DEEP TILLAGE OF SOLONETZIC AND NON-SOLONETZIC SOILS IN SASKATCHEWAN

M.C.J. Grevers
Saskatchewan Institute of Pedology
University of Saskatchewan, Saskatoon, Sk.

Abstract

The effect of deep tillage on soil conditions and crop growth was studied over a 5-year period, involving 15 farm sites, 4 soil zones, and both Solonetzic and Chernozemic soils, as well as Solonetzic/Chernozemic intergrades. Deep ripping reduced soil bulk density for up to 2.5 years for Solonetzic soils and for up to 1.5 years for non-Solonetzic soils. Soil loosening by paraplowing was much less dramatic than that of deep ripping and involved only one Site (Solonetzic soil), where the effect lasted only up to 1 year. Deep ripping of Solonetzic soils increased soil water recharge for up to three years following the deep tillage operation. Increased soil-water recharge in the paraplowed plots was found only in the first year. Crop emergence on some of the Solonetzic soils was decreased in the first year on the deep ripped plots due to poor seedbed conditions. Deep ripping increased crop production on Solonetzic soils by up to 4 years, and on Solonetzic/Chernozemic soils by up to 3 years, but had no effect on crop production on Chernozemic soils. Paraplowing also increased crop production on both the Solonetzic soils and on the Solonetzic/Chernozemic intergrades; however the effect was much less dramatic than that of deep ripping and lasted only up to 2 years. The increased crop production was the result of greater spring soil NO_3-N levels and greater crop water-use efficiency. Deep ripping and paraplowing reduced soil sodicity and salinity under irrigated conditions, but not under dry-land conditions.

Introduction

Deep tillage has received much attention in the media over the past 6 to 7 years. Articles have appeared in farm publications such as Country Guide (November 1984) and GRAINEWS (September 1986), which indicated that with deep ripping crop production had been increased at particular farm sites. Furthermore, farmers have frequently reported on improved crop production in parts of their field following the installation of pipelines. In Saskatchewan, soil disturbance from the installation of pipelines has been found to increase soil productivity of Solonetzic soils (de Jong and Button, 1973). There has been much discussion amongst the farm community in Saskatchewan regarding the deep tillage work in Alberta, such as on so-called "alkali soils" around Vegreville. However, deep tillage (deep plowing and/or deep ripping) in general is not recommended as a farm practice in semi-arid regions (Lutz 1962), particularly in areas sensitive to soil erosion and in areas with soil salinity problems. There was thus a need to investigate the feasibility of deep ripping under Saskatchewan conditions.

Deep ripping, compared to deep plowing is considerably less expensive than deep plowing, but may cause insufficient mixing of soil layers to result in significant improvement in the productivity of Solonetzic soils (Alzubaidi and Webster, 1982). Bole (1986) found increased soil-water infiltration following deep ripping; however, the effect lasted for only two years. Alzubaidi and Webster (1982) found that deep ripping had resulted in increased deep leaching of salts. There has been little evidence to suggest that deep ripping results in considerable increases in crop yield of Solonetzic soils (Lavado and Cairns, 1980). Lickacz (1986) reported that deep ripping of Solonetzic soils was less beneficial in terms of increasing crop production in areas with severe moisture deficits, than in "wetter" areas. For example, he reported average wheat yield increases due to deep ripping of 130 kg/ha in the Brown soil zone compared to 400 kg/ha in the Dark Brown and Black soil zones.

Deep rippers or subsoilers, are used to loosen the soil without inverting it, and are used primarily to break through and shatter compact sub soils. Under most conditions subsoilers will break out a slot of soil that is slightly wider that the tool point (Cooper, 1971). The loosened soil resembles a triangular shaped trench (Bowen, 1981; Trouse and

Humbert, 1959). Another type of subsoiler is the paraplow, which has been described as a "slant legged soil loosener" (Pidgeon, 1982). This tillage implement was originally designed to alleviate soil compaction in zero-tilled soils (Davies et al, 1982). Soil loosening is achieved through a lifting action along the legs of the plow, which results in the formation of cracks along natural planes of weakness (Davies et al, 1982). Soil loosening apparently is almost uniform with depth (Ehlers and Baeumer, 1988). Soil loosening with the paraplow is thus quite different from that with conventional subsoilers or deep rippers, where the soil is displaced forwards, sideways and upwards, leaving a V-shaped trench.

The objective of this research project was to investigate the effect of deep ripping and of that of paraplowing on the physical and chemical conditions of the soil and on crop production, under both dry-land and irrigated conditions. A range of soil types were included, such as soils with varying degrees of solonetzic characteristics, having different textures and occurring in different soil zones. The investigation was carried out over a five-year period.

Materials and Methods

A total of 15 farm sites are included in the study, involving both deep ripping and paraplowing. The sites involve Solonetzic (5) soils, Chernozemic (5) soils and Solonetzic/Chernozemic intergrades (5), representing the Brown, the Dark Brown, the Black and the Dark Gray soil zones.

The experimental plots consisted of 6 strips; each strip was between 15 and 30 m wide and 800 m long. Alternate strips were selected to be subsoiled, while the other strips remained non-subsoiled (control). The tillage strips were divided into 3 replicate blocks; each block consisting of one subsoiled and one adjacent control plot. In this manner, some of the effect of field variability could be isolated from possible deep tillage effect on soil properties and crop growth. At the sites where subsoiling consisted of both deep ripping and paraplowing, 9 tillage strips were used. One replicate block thus consisted of 3 tillage strips; one deep ripped, one paraplowed and one control strip.

In all cases deep ripping and paraplowing were carried out in the fall. Deep ripping was done with a KELLO-BILT subsoiler, pulled with a 1150 VERSATILE tractor (450 HP), travelling between 5 and 6 km per hour. Paraplowing was done with a HOWARD 3-bottom paraplow (courtesy of Agriculture Canada @ Swift Current). The paraplow was pulled with a DEUTSCH DX130 tractor (~120 HP), travelling between 6 and 8 km per hour. At Tisdale, A BELARUS tractor (~250 HP) was used to pull the paraplow. The depth of deep ripping ranged from 40 cm to 76 cm and that of paraplowing ranged from 40 cm to 46 cm (Table 1). The spacing of the ripper shanks varied from 60 cm to 152 cm, and the spacing of the paraplow bottoms was 46 cm. Approximate cost of the deep ripping and subsequent secondary tillage operations were: $ 50 per acre on Solonetzic soils and between $ 15 and $ 25 per acre on non-Solonetzic soils. The costs associated with paraplowing were not computed since the unit is commercially unavailable in Saskatchewan. Secondary tillage operations, such as discing and harrowing to smooth down the deep-tilled fields were considerable, in particular at the Tisdale, Arborfield and Carrot River Sites. At the Morgan site, large depressions were left in the field, with subsequent exposed subsoil in some areas. At the Arborfield and Carrot River sites, subsequent secondary tillage operations in the spring had left the top 10 cm of the soil in a very dry and powdery condition for seeding.

Soil samples were collected at the time of deep ripping from the control strips. Samples were taken to a depth of 120 cm, in increments of 0-15, 15-30, 30-45, 45-60, 60-90 and 90-120 cm. The samples were air-dried and then analyzed for pH, electrical conductivity (EC), water soluble cations, sodium adsorption ratio (SAR), cation exchange capacity (CEC), exchangeable cations (Ca, Mg, Na,K). Samples were collected for NO_3-nitrogen content to a depth of 60 cm from all the tillage strips in each year of the project. In the fall of 1989 (1990 for the D.Eliason, J. Eliason and Riopka Sites), additional samples were collected for soil chemical analysis: 6 depth increments, 6 replicates, 6 to 9 tillage strips. The samples were analyzed for pH, EC, SAR, and water-soluble cations and anions.

Soil physical parameters that were measured include soil moisture and soil bulk density. Soil water content was measured by neutron thermalization, using a DEPTH MOISTURE GAUGE (Troxler Electronic Laboratories Inc.). Soil bulk density was measured by gamma backscattering using a DEPTHPROBE CPN 501 (Hoskins Scientific), which had become available in the spring of 1988. The scanning zone of the CPN probe has a vertical dimension of approximately 15 cm and is therefore not sensitive to "picking up" thin dense layers in the soil. Aluminum access tubes (2 per tillage plot) had been installed to a depth of 120 cm to facilitate the measurements of the soil bulk density and the soil moisture content in-situ, using the depth probes. Readings were taken prior to seeding (1 to 2 weeks) and at harvest time.

Crop yield was determined by taking square meter samples, in a series of paired row samples, 6 pairs in each tillage strip. At some sites, crop yields were also determined using weigh wagons. The crop samples were transported to the University, where the samples were dried, weighed, threshed and grain weights were taken. Crop water use (mm) was determined from the difference between the soil moisture content at seeding and at harvest, plus the growing season precipitation (data from the nearest weather station or from rain gauges installed in the field plots). Crop water-use efficiency was determined by dividing the grain yield by the total crop water use (kg/ha/cm).

Results and Discussion

Classification of the field sites according to soil chemical criteria

Classification of Solonetzic soils in Canada is based upon the characteristic morphological features of the Solonetzic Bn or Bnt horizon and related soil chemistry. Soil chemical criteria used to differentiate Solonetzic soils from Chernozemic soils are the exchangeable Ca:Na ratio and/or the % water soluble Na. A soil is considered to be Solonetzic if the exchangeable calcium to sodium ratio of the B horizon is equal to or less than 10 (Canada Soil Survey Committee, 1987). Bennett (1988) indicated that a saturation extract SAR value of 5 corresponded to exchangeable calcium to sodium ratio of 10 for a Brown Solonetzic soil, and could therefore be used to differentiate Brown Solonetzic soils from Brown Chernozemic soils. A Solonetzic soil can also be identified if the % water soluble Na (WSS) in the B horizon is equal to or greater than 50% (Ballantyne and Clayton, 1962).

Most of the soils were mapped as Solonetzic, the rest as Chernozemic (Table 1). However when the above criteria for differentiating Solonetzic from Chernozemic soils were applied, some of the Solonetzic soils were found to be non- or partly Solonetzic. Five soils were classified as Solonetzic (at least 2/3 of the field plot was Solonetzic): the Boxall, Cragg, J. Eliason, Morgan and Warner Sites. Five were classified as Solonetzic/Chernozemic Intergrades (1/3 to 1/2 of the field plot was Solonetzic): the Chabot, D. Eliason, Harrington, Millar and McEwen Sites. The remaining five Sites were classified as Chernozemic (none or less than 1/3 of the field plot was Solonetzic): the Foisy, Jessiman, Norrish, Rice and Riopka Sites. The soil chemical characteristics for all three farm sites are shown in Table 2.

Soil Bulk Density

The soil bulk density in the deep tillage plots in the spring of 1988 is listed in Table 2. Deep ripping had resulted in soil loosening to a depth of 40 cm in both the Solonetzic and non-Solonetzic soils. By the fall of 1989 there were no significant differences in density between the ripped plots and the control plots for any of the depths that were measured, with the exception of the J. Eliason Site. The above indicates that soil loosening of Solonetzic soils lasted up to 2.5 years after the deep ripping, and that soil loosening of non-Solonetzic soils lasted up to 1.5 years after the deep ripping. Soil loosening by paraplowing was much less dramatic than by deep ripping, and at only one Site (Boxall) significantly reduced the density of the soil for one year.

Soil-Water Recharge

Over-winter soil-water recharge was calculated from the soil moisture readings taken at harvest time (Aug/Sep) and in spring (April). The relative amount amount of soil-water recharge during this period therefore is indicative of differences in soil-water infiltration from rainfall and from melting snow, and of soil-water conservation during this period. The relative gain (cm H_2O) in soil moisture in the deep tillage plots compared to the gain in soil moisture in the control plots for the first three years following the deep tillage operations is listed in Table 3. The deep ripped Solonetzic soils gained an additional 1.2 cm in the second year and 1.4 cm in the third year following deep ripping. There was no consistent effect of deep ripping on improving soil-water recharge of the Solonetzic/Chernozemic Intergrades nor on the Chernozemic soils. Paraplowing improved soil-water recharge of all the soils by an average of 3 cm in the first year, but had no consistent effect on improving soil-water recharge in subsequent years.

Soil NO_3-Nitrogen levels in the spring

The soil disturbance associated with deep ripping and paraplowing (e.g. lower bulk density levels and increased soil aeration porosity) could increase the rates of soil organic matter decomposition, nitrogen mineralization and nitrification. The levels of nitrate-nitrogen (NO_3-N) as measured in the spring of 1988, 1989 and 1990 are shown in Table 4. The NO_3-N levels were higher in the deep tillage field plots compared to the non-ripped field plots. The increased soil NO_3-N levels were 16, 14 and 28 kg/ha in the second, the third and the fourth year after deep ripping, respectively. The increased soil NO_3-N levels in the paraplowed plots was only found in the second year: 20 kg/ha

Crop Production

There was a substantial difference in the effect of deep tillage on crop production between the Solonetzic soil and the non-Solonetzic soils (Fig. 1, Table 4). Deep ripping increased crop production on Solonetzic soils by 19%, 62%, 22% and 10%, in the 1'st, 2'nd, 3'rd, and the 4'th year following deep ripping, respectively. Similarly, deep ripping increased crop production on the Solonetzic/Chernozemic Intergrades by 30%, 18%, and 24% in the 1'st, 2'nd, and 3'rd year following deep ripping, respectively. However, deep ripping did not increase crop production on Chernozemic soils. There were considerable plant emergence problems in the first year after deep ripping, particularly of Solonetzic soils. Secondary tillage operations required to "smooth down" the seedbed in the ripped field plots had resulted in relatively poor seedbed conditions. In 1986, timely spring rains alleviated the crop emergence problems at the Boxall, McEwen and Morgan sites. The crop in the ripped areas recovered and eventually out-yielded the crop in the control areas at these sites. In 1987, rainfall was relatively poor in the spring, and the crop in the ripped areas at Cragg's and at Chabot's was unable to fully recover, and as a consequence some of the crop never emerged and some of the crop was still quite green at the time of harvest. The same problems existed in 1988 at the Norrish site.

The effect of paraplowing on crop production was less dramatic than that of deep ripping and involved only 2 Sites; a Solonetzic soil (Boxall in the first year) and a Solonetzic/Chernozemic Intergrade (McEwen in the second year). There were no significant yield increases due to paraplowing of Chernozemic soils.

Water-Use Efficiency

The water-use efficiency (WUE) values were generally greater in the deep ripped plots compared to the non-ripped plots (Table 4). Deep ripping had increased crop WUE on Solonetzic soils by 43%, 11% and 33% in the second, third and fourth year following deep ripping, respectively. On Solonetzic/Chernozemic Intergrades, deep ripping increased the WUE by 18% in the second year and by 26% in the third year after deep ripping. On Chernozemic soils deep ripping increased the WUE only in the second year, by an average of 17%. There was little effect of paraplowing on the WUE of crops grown on either Solonetzic or Chernozemic soils.

Soil salinity in the deep tillage plots

Soil disturbance with deep ripping and paraplowing improved soil-water penetration, as indicated by improved soil-water recharge (Table 3), which should result in increased leaching of salts. Soil chemical characteristics measured in the fall of 1989 (in 1990 for the D. Eliason, J. Eliason and Riopka Sites) revealed significant differences between the deep tilled and the control plots under irrigated conditions (Table 6), but not under dry-land conditions (Table 5). At the J. Eliason Site, deep ripping lowered the electrical conductivity in the top 90 cm, the sodium adsorption ratio in the top 45 cm and the percentage water-soluble sodium in the op 15 cm. The leached salts included mostly

Na_2SO_4 and $MgSO_4$. The lowering of soil sodicity in irrigated deep ripped Solonetzic soils indicates a long-term soil amelioration.

At the start of the experiment it was hypothesized that soil loosening should result in leaching of soluble salts from Solonetzic soils in the "wetter" regions of Saskatchewan (i.e. the Tisdale-Carrot area). However, this area experienced unusually dry years over the duration of the tillage experiment, especially in the fall and winter periods. The data from the irrigated plots do indicate that significant amounts of soluble salts, especially N-salts can be leached following either deep ripping or paraplowing of Solonetzic soils. This would imply that when deep tillage of Solonetzic soils is followed by relatively "wet" periods, Na-salts may also be leached under dry-land conditions, which would increase the longevity of the beneficial effects of deep tillage on soil structure and, consequently, on crop production.

Conclusions

Deep ripping reduced soil bulk density for up to 2.5 years for Solonetzic and for up to 1.5 years for non-Solonetzic soils. The effects were most pronounced in deep ripped Solonetzic soils. Soil loosening by paraplowing was much less dramatic than that of deep ripping and involved only one Site (Solonetzic soil), where the effect lasted only up to 1 year.

Deep ripping of Solonetzic soils increased soil water recharge for up to three years following the deep tillage operation. Increased soil-water recharge in the paraplowed plots was found only in the first year.

Crop emergence on some Solonetzic soil was decreased in the tillage plots, due to poor seedbed conditions, created as a result of the secondary tillage operations in spring that were required to smooth down the soil surface.

Deep ripping increased crop production on Solonetzic soils by up to 4 years, and on Solonetzic/Chernozemic soils by up to 3 years, but had no effect on crop production on Chernozemic soils. Paraplowing increased crop production on both the Solonetzic soils and on the Solonetzic/Chernozemic intergrades; however the effect was much less dramatic than that of deep ripping and lasted only up to 2 years. The increased crop production was the result of greater spring soil NO_3-N levels and greater crop water-use efficiency.

Under irrigated conditions deep ripping reduced the salinity as well as the soil sodicity of the soil, and paraplowing reduced the soil sodicity of the soil. Neither deep ripping nor paraplowing affected the salinity or the sodicity of the soil under dryland conditions.

Acknowledgement

This project was supported by grants from the Agriculture Development Fund and from the Saskatchewan Water Coorporation

List of references

Alzubaidi, A and G.R Webster. 1982. Effect of tillage in combination with chemical amendments on reclamation of a Solonetzic soil. Can. J. Soil Sci. 62:641-649.

American Society of Agricultural Engineers. 1971. Terminology for soil tillage and soil-tool relationships. ASAE. Recommendation: ASAE R291. 1971 Agric. Engineers Yearbook. St Joseph, Mich.

Ballantyne, A.K. 1983. Five years of soil analyses and yield data on deep-plowed Solonetzic soil. Can. J. Soil Sci. 63:191-197.

Ballantyne, A.K. and J.S. Clayton. 1962. The relationship of water-soluble cations to field separations of Chernozemic and Solonetzic soils. Can. J. Soil Sci. 43:359-369.

Bole, J.B. 1986. Amelioration of a calcareous Solonetzic soil by irrigation, deep ripping, and acidification with elemental sulfur. Can. J. Soil Sci. 66:347-356.

Bowen, H.D. 1981. Alleviating mechanical impedance. In Modifying the Root Environment to Reduce Crop Stress. (Ed's G.F. Arkin and H.M. Taylor). ASAE Monograph No. 4. A.S.A.E. St. Joseph, Mich. pp: 21-57.

Bowser, W.E. and R.R. Cairns. 1967. Some effects of deep plowing of a solonetz soil. Can. J. Soil Sci. 47:239-244.

Cairns, R.R. 1961. Some chemical characteristics of a Solonetzic soil sequence at Vegreville, Alberta, with regards to possible amelioration. Can. J. Soil Sci. 41:24-34.

Cairns, R.R. and W.E. Bowser. 1977. Solonetzic soils and their management. Publ. 1391. Agric. Can. 37 pp.

Canada Soil Survey Committee. 1978. The Canadian System of Soil Classification. Research Branch, Agriculture Canada. Publication 1646.

Cooper, A.W. 1971. Effects of tillage on soil compaction. In *Compaction of Agricultural Soils*. A.S.A.E. Monograph. St Joseph, Mich. pp: 315-364.

Davies, D.B., J.D. Pidgeon, E. Lord and M. Gowman. 1982. Responses to deep loosening by "Paraplow" in continuous cereal production. Proc. 9th Conf. ISTRO. Osijek, Jugoslavia: 591-596.

De Jong, E. and R.G. Button. 1973. Effects of pipeline installation on soil properties and productivity. Can. J. Soil Sci. 53:37-47.

Ehlers, W. and K. Baeumer. 1988. Effect of the paraplow on soil properties and plant performance. Proc. 11th Conf. ISTRO. Edinburgh, Scotland: 637-642.

Lavado , A.S. and R.R. Cairns. 1980. Solonetzic soil properties and yields of wheat, oats and barley as affected by deep plowing and deep ripping. Soil & Tillage Res. 1:69-79.

Lickacz, J. 1986. Management of Solonetzic soils. Agdex 518-8, Alta Agric., 10 pp.

Lutz, J.F. 1962. Mechanical impedance and plant growth. Pages 43-67 *In* B.T. Shaw (ed.) Soil physical conditions and plant growth. Agronomy no. 2. Am. Soc. Agron., Madison, Wis.

McConkey, B.G. 1987. Subsoiling for soil and water conservation. Proc. Soils and Crops Workshop. Feb 1987. Saskatoon Univ. of Saskatchewan. Saskatoon, Sask.

Pidgeon, J.D.1982. "Paraplow"- A rational approach to soil management. Proc. 9. Conf. of ISTRO, Osijek, Jugoslavia: 633-638.

Russell, W.E. 1973. Soil Conditions and Plant Growth. 10th Edition Longman Group Ltd. NY, NY.

Toogood, J.A. and R.R. Cairns. 1978. Solonetzic soils technology and management. Bull. B-78-1 University of Alberta. Edmonton, Alta. 105 pp.

Trouse, A.C., Jr. and R.P. Humbert. 1959. Deep tillage in Hawaii. I. Subsoiling. Soil Sci. 88:150-158.

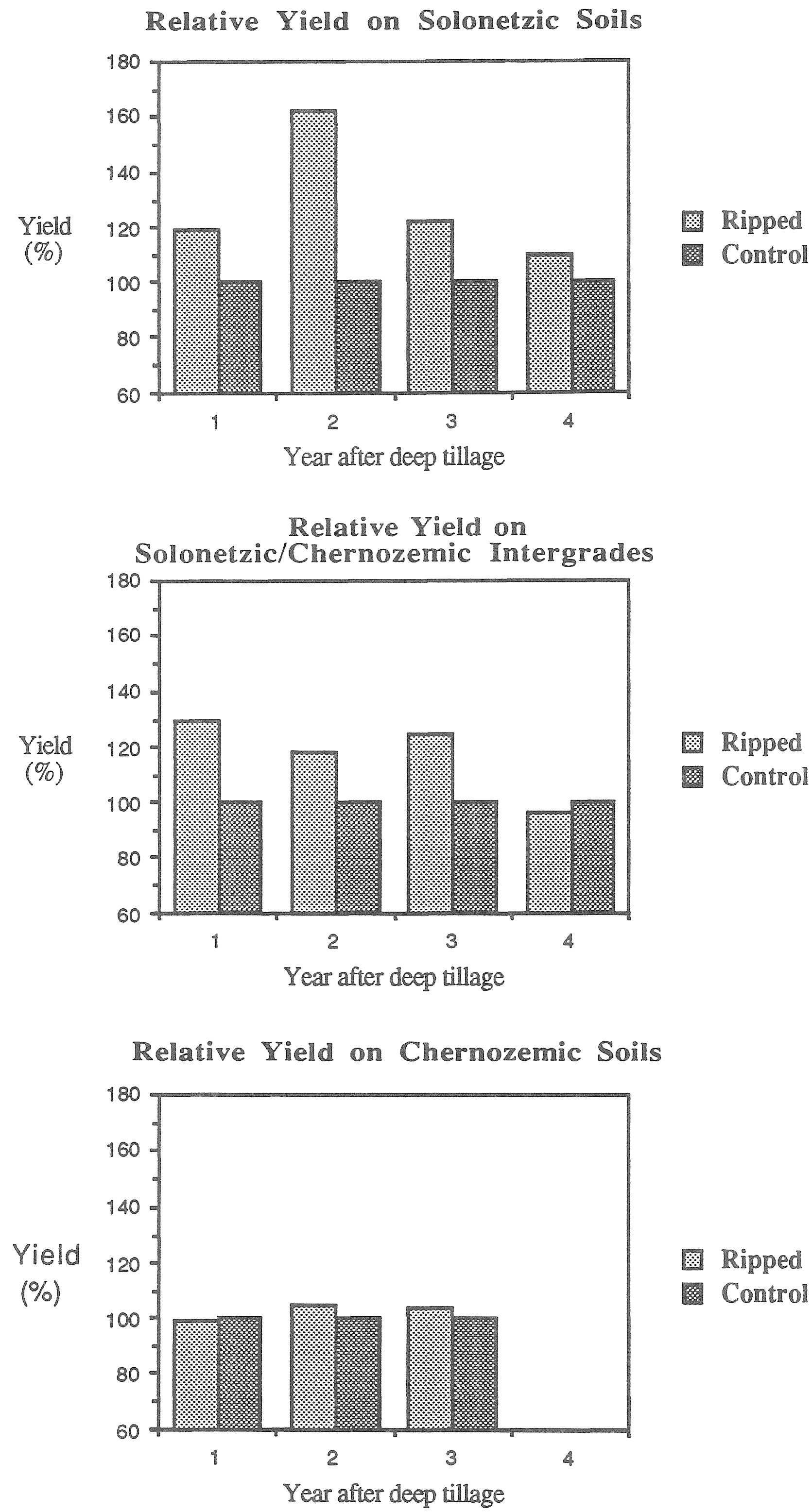

Fig. 1. Relative crop yields following deep ripping as a percentage of the crop yields on the non-ripped field plots for the first 4 years after deep ripping

Table 1. Soil descriptions and tillage details of the deep tillage plots.

Farm site	Soil Zone	Soil Order	Soil Association	Tillage	Year	Depth	Spacing
			Solonetzic Soils†				
Boxall	D.Gray	Solonetz	Arborfield C-CL	Rip Ppl	1985 1986	76 46	60 46
Cragg	D.Gray	Solonetz	Arborfield C	Rip	1986	76	60
J. Eliason	D. Brown	Solonetz	Tuxford C	Rip	1987	60	112
Morgan	D.Gray	Solonetz	Arborfield C	Rip	1985	76	60
Warner	D.Gray	Solonetz	Arborfield C	Rip	1987	61	112
			Solonetzic/Chernozemic Intergrades†				
Chabot	D.Gray	Solon/Chern	Arborfield C	Rip	1986	76	60
D. Eliason	D. Brown	Solonetz	Tuxford C	Rip	1987	60	112
Harrington	D.Brown	Solonetz	Tuxford C	Ppl	1986	46	38
Millar	Brown	Chernozem	Fox Valley CL	Ppl	1986	46	46
McEwen	D.Gray	Solon/Chern	Arborfield C-CL	Rip Ppl	1985 1986	76 46	60 46
			Non-Solonetzic Soils†				
Foisy	Black	Chernozem	Oxbow L	Rip Ppl	1986 1986	40 46	152 46
Jessiman	Brown	Chernozem	Sceptre HC	Rip Ppl	1986 1986	46 46	46 46
Norrish	D.Gray	Chernozem	Tisdale C	Rip	1987	61	60
Rice	D.Gray	Chernozem	Tisdale SiC-SiCL	Rip	1986	76	60
Riopka	D. Brown	Solonetz	Tuxford C	Rip	1987	60	112

Solon/Chern = mixed Solonetzic-Chernozemic

† Classification according to soil chemical criteria for SAR and WSS

Table 2. Soil bulk density in the spring of 1988 and in the fall of 1989

Site	Depth	Spring 1988			Fall 1989		
		Rip	Check	Ppl.	Rip	Check	Ppl.
	cm	g/cm^3					
Boxall	25	1.31	1.42	1.39	1.44	1.47	1.31
	40	1.43*	1.49	1.37*	1.50	1.50	1.42
	60	1.47	1.50	1.47	1.48	1.51	1.49
Chabot	25	1.05	1.29		1.12	1.24	
	40	1.33	1.44		1.39	1.41	
	60	1.51	1.50		1.47	1.45	
Cragg	25	1.30	1.43		1.26	1.40	
	40	1.26	1.38		1.37	1.46	
	60	1.47	1.43		1.48	1.48	
D. Eliason	25	1.33	1.62		1.26	1.63	
	40	1.43	1.44		1.50	1.51	
	60	1.66	1.52		1.64	1.54	
J. Eliason	25	1.43*	1.60		1.29*	1.44	
	40	1.40	1.30		1.47	1.40	
	60	1.47	1.50		1.54	1.53	
Foisy	25	1.48	1.38		1.47	1.42	1.31
	40	1.69	1.70		1.65	1.71	1.48
	60	1.68*	1.84		1.76	1.79	1.62
Harrington	25		1.58	1.33		1.59	1.48
	40		1.61	1.38		1.55	1.36
	60		1.78	1.49		1.73	1.43

* Indicates: mean of deep tillage plot is significantly (P <0.05) different from that of the control plot.

Table 2. Continued

Site	Depth	Spring 1988			Fall 1989 or 1990†		
		Rip	Check	Ppl.	Rip	Check	Ppl.
	cm	g/cm^3					
Jessiman	25	1.08*	1.40	1.26	1.24	1.41	1.32
	40	1.34*	1.51	1.45	1.35	1.51	1.42
	60	1.57	1.57	1.58	1.54	1.55	1.49
McEwen	25	1.09	1.22	1.28	1.26	1.32	1.42
	40	1.41*	1.49	1.37	1.39	1.39	1.43
	60	1.51	1.54	1.51	1.43	1.46	1.51
Millar	25		1.41	1.18		1.61	1.54
	40		1.51	1.53		1.71	1.57
	60		1.64	1.62		1.71	1.73
Morgan	25	1.23	1.31		nd	nd	
	40	1.40*	1.50		1.43	1.57	
	60	1.46	1.47		1.50	1.51	
Norrish	25	1.31	1.48		1.33	1.31	
	40	1.42	1.46		1.47	1.48	
	60	1.42	1.45		1.42	1.44	
Rice	25	1.14	1.15		nd	nd	
	40	1.48*	1.69		1.50	1.53	
	60	1.60	1.51		1.66	1.55	
Riopka	25	1.46	1.55		1.43	1.55	
	40	1.37	1.47		1.42	1.55	
	60	1.59	1.58		1.54	1.53	
Warner	25	1.44	1.60		1.43	nd	
	40	1.30	1.36		1.56	1.44	
	60	1.37	1.34		1.52	1.48	

* Indicates: mean of deep tillage plot is significantly (P <0.05) different from that of the control plot.

Table 3. Increase in soil water recharge in the deep tillage plots relative to that in the control plots for the first three years following the deep tillage operations.

Site	Year #1	Year #2	Year #3
	----------- cm H_2O -------------		
	Deep Ripped Solonetzic Soils		
Boxall	n.d.	0.0	0.8
Cragg	n.d.	1.7	0.9
J. Eliason	n.d.	1.6	1.0
Morgan	n.d.	4.0	1.1
Warner	n.d.	-1.1	3.3
	Deep Ripped Solonetzic/Chernozemic Intergrades		
Chabot	n.d.	0.1	0.0
McEwen	n.d.	1.0	-1.8
	Deep Ripped Chernozemic Soils		
Foisy	-1.7	-1.3	0.6
Jessiman	1.8	2.0	0.5
Rice	n.d.	-1.2	-1.4
Riopka	n.d.	-3.7	1.5
	Paraplowed Soils		
Boxall	7.0	1.0	n.d.
Foisy	1.1	-1.3	2.6
Harrington	-1.8	n.d.	n.d.
Jessiman	5.1	0.5	0.5
Millar	0.0	0.9	n.d.
McEwen	6.8	1.5	-3.3.
Average	3.4	1.2	n.d.

n.d. = no data

Table 4 Spring soil moisture and nitrate-nitrogen, crop yield and water-use efficiency.

Farm	Year/crop	Tillage	Spring seeding		Yield		WUE
			SMC	NO_3-N	Total	Grain	
			(%)	(kg/ha)	(kg/ha)	(Bu/A)	(kg/ha/cm)
			Solonetzic soils				
Boxall	1986 Wheat	Control	ND	ND	4262	34.3	ND
		Ripped	ND	ND	5795*	43.1*	ND
	1987 Wheat	Control	41	ND	3548	18.4	47
		Ripped	43	ND	5042*	34.8*	90
		Parapl.	44	ND	4574*	29.5*	69
	1988 Wheat	Control	47	94	Crop Failure		
		Ripped	50	135	Crop Failure		
		Parapl.	48	130	Crop Failure		
	1989 Wheat	Control	36	107	5673	37.4	131
		Ripped	34	198	6420	42.1	177
		Parapl.	33	75	5522	35.3	152
Cragg	1987 Wheat	Control	53	ND	6249	41.8	68
		Ripped	52	ND	5968	34.9*	54
	1988 Barley	Control	53	18	4319	23.8	73
		Ripped	53	16	5183	35.4*	102
	1989 Smf	Control	39	27	Fallow		
		Ripped	39	32	Fallow		
	1990 Durum	Control	53	81	9634	60.7	ND
		Ripped	55	101	10269	64.3	ND
J. Eliason	1988 Durum	Control	33.6	26	6392	39.6	ND
		Ripped	33.6	30	7667	49.7*	ND
	1989 Beans	Control	27.9	30	4184	33.0	53.5
		Ripped	30.1	66	5527*	38.0	65.7*
	1990 Wheat	Control	33.7	21	9014	56.2	111
		Ripped	35.7	32	9772	57.7	110
Morgan	1986 Barley	Control	ND	ND	5362	48.6*	ND
		Ripped	ND	ND	6264*	56.5*	ND
	1987 Flax	Control	37	ND	2963	23.0	69
		Ripped	37	ND	4246*	27.1*	81

SMC= soil moisture content, WUE= water use efficiency, ND = no data available
*, and ** indicate that the means of the tillage plots are significantly different from that of the control plots at $P < 0.05$, and $P < 0.01$, respectively.

Table 4. Continued.

Farm	Year/crop	Tillage	Spring seeding SMC	Spring seeding NO3-N	Yield Total	Yield Grain	WUE
			(%)	(kg/ha)	(kg/ha)	(Bu/A)	(kg/ha/cm)
Solonetzic soils							
Morgan	1988 HY320	Control	48	31	1825	14.3	51
		Ripped	49	69	2393*	19.0*	63
	1989 HY320	Control	35	68	5948	37.8	2126
		Ripped	35	212	7240	43.3	160
Warner	1988 Canola	Control	65	8	2683	12.8	88
		Ripped	65	30	4228*	20.2*	132
	1989 Barley	Control	42	9	3014	25.8	95
		Ripped	41	19	7713*	61.1**	269
	1990 Canola	Control	50.0	15	2785	10.9	26
		Ripped	54	18	3138	15.0*	36
Solonetzic/Chernozemic Intergrades							
Chabot	1987 Peas	Control	46	ND	5979	31.2	64
		Ripped	46	ND	6977	28.6	52
	1988 Flax	Control	51	85	1910	9.8	28
		Ripped	48	102	1964	9.8	28
	1989 Smf	Control	40	140	Fallow		
		Ripped	38	162	Fallow		
	1990 Canola	Control	58	136	7392	45.2	120
		Ripped	60	135	6581	40.5	96
D.Eliason	1988 Lentils	Control	36.5	21	1564	11.2	ND
		Ripped	38.8	23	2089	17.0	ND
	1989 Durum	Control	33.2	30	7483	54.1	117
		Ripped	38.8	32	10868*	75.4*	169*
	1990 Durum	Control	32.9	83	8110	58.2	111
		Ripped	35.5	84	9573*	65.6*	131*
Harringt	1987 Wheat	Control	29	ND	2872	20.0	50
		Parapl.	31	ND	2840	19.8	48
	1988 Mustard	Control	26	14	Crop Failure		
		Parapl.	36	45	Crop Failure		

SMC= soil moisture content, WUE= water use efficiency, ND = no data available
*, and ** indicate that the means of the tillage plots are significantly different from that of the control plots at $P < 0.05$, and $P < 0.01$, respectively.

Table 4. Continued.

Farm	Year/crop	Tillage	Spring seeding		Yield		WUE
			SMC	NO3-N	Total	Grain	
			(%)	(kg/ha)	(kg/ha)	(Bu/A)	(kg/ha/cm)
Solonetzic/Chernozemic Intergrades							
Harringt	1989 Smf	Control	23	30	Fallow		
		Parapl.	31	43	Fallow		
McEwen	1986 Peas	Control	ND	ND	2899	22.7	ND
		Ripped	ND	ND	4217*	32.9*	ND
	1987 Flax	Control	44	ND	3195	21.0	46
		Ripped	46	ND	3830*	24.0*	50
	1987 Flax	Control	49	ND	3704	22.5	39
		Parapl.	51	ND	3652	23.1	8
	1988 Barley	Control	45	126	3927	30.3	74
		Ripped	45	139	5071	40.8*	99
	1988 Barley	Control	43	95	3851	25.0	65
		Parapl.	45	133	5039	37.2*	90
	1989 Flax	Control	44	112	2716	11.5	22
		Ripped	43	84	2913	12.1	23
	1989 Flax	Control	44	112	2716	11.5	22
		Parapl.	41	86	2438	10.0	19
Millar	1987 Flax	Control	32	ND	6403	34.7	76
		Parapl.	32	ND	6271	35.0	78
	1988 Wheat	Control	28	32	5539	35.5	ND
		Parapl.	30	44	5273	37.7	ND
Chernozemic Soils							
Foisy	1987 Lentils	Control	27	ND	7667	40.4	91
		Ripped	28	ND	7346	41.1	95
		Parapl.	28	ND	7326	42.3	85
	1988 Peas	Control	24	45	No yield data		
		Ripped	24	32	No yield data		
		Parapl.	24	37	No yield data		

SMC= soil moisture content, WUE= water use efficiency, ND = no data available
*, and ** indicate that the means of the tillage plots are significantly different from that of the control plots at $P < 0.05$, and $P < 0.01$, respectively.

Table 4. Continued.

Farm	Year/crop	Tillage	Spring seeding		Yield		WUE
			SMC	NO3-N	Total	Grain	
			(%)	(kg/ha)	(kg/ha)	(Bu/A)	(kg/ha/cm)
			Chernozemic Soils				
Foisy	1989 Canola	Control	23	140	3351	16.6	40
		Ripped	23	140	3270	17.1	42
		Parapl.	25.2	110	3751	18.4	42
Jessiman	1987 Wheat	Control	36	ND	6423	44.1	126
		Ripped	37	ND	6587	44.1	111
		Parapl.	43	ND	7040	46.4	117
	1988 W.wheat	Control	36	20	Crop Failure		
		Ripped	37	31	Crop Failure		
		Parapl	41	31	Crop Failure		
	1989 Barley	Control	26	17	3759	30.9	66
		Ripped	28	20	4220	33.7	67
		Parapl.	32	46	4154	30.2	65
Norrish	1988 Canola	Control	49	47	5055	30.4	65
		Ripped	52	48	4616	25.9	56
	1989 Canola	Control	34	81	5118	25.7	87
		Ripped	35	147	5192	24.8	95
	1990 Barley	Control	43	29	8878	80.4	ND
		Ripped	42	25	9396	79.1	ND
Rice	1988 Wheat	Control	35	113	3795	29.1	60
		Ripped	301	131	4345	33.0	75
	1989 Flax	Control	27	120	3461	14.4	30
		Ripped	24	168	3501	15.0	33
Riopka	1988 Wheat	Control	35.6	43	3732	21.9	ND
		Ripped	32.5	41	3968	21.8	ND
	1989 Wheat	Control	33.7	20	7113	46.7	ND
		Ripped	29.2	18	7588	48.7	ND
	1990 Wheat	Control	41.6	22	7034	36.4	ND
		Ripped	39.7	18	8002	38.2	ND

SMC= soil moisture content, WUE= water use efficiency, ND = no data available
*, and ** indicate that the means of the tillage plots are significantly different from that of the control plots at P <0.05, and P <0.01, respectively.

Table 5. Soil chemical characteristics after subsoiling field plots under dryland conditions

Depth	EC		pH		SAR†		WSS‡	
	Check	DT	Check	DT	Check	DT	Check	DT
cm	-- dS/m --						----- % ----	
Boxall Site: Ripped versus Control								
(0-15)	1.42	1.73	6.4	6.9	1.3	2.8	29.4	43.8
(15-30)	1.02	1.20	7.0	7.1	2.0	3.1	44.8	51.5
(30-60)	1.72	4.07	8.1	8.0	4.1	5.4	57.7	52.0
(60-90)	6.90	7.20	8.0	8.0	7.4	8.1	49.6	51.7
Boxall Site: Paraplowed versus Control								
(0-15)	1.42	1.17	6.4	6.1	1.3	0.8	29.4	21.6
(15-30)	1.02	0.60	7.0	7.2	2.0	1.5	44.8	39.5
(30-60)	1.72	1.13	8.1	8.0	4.1	2.8	57.7	50.2
(60-90)	6.90	5.55	8.0	7.9	7.4	4.8	49.6	39.0
Chabot Site: Ripped versus Control								
(0-15)	0.73	0.67	5.7	5.8	0.9	0.8	27.1	24.4
(15-30)	0.60	1.17	6.0	6.1	1.7	2.0	44.0	41.7
(30-60)	0.57	0.40	7.0	6.5	2.7	2.4	61.9	64.2
(60-90)	1.80	0.90	7.9	7.6	4.2	3.5	56.3	60.7
Cragg Site: Ripped versus Control								
(0-15)	1.17	0.80	6.4	6.9	4.6	4.2	65.7	68.7
(15-30)	1.03	0.97	7.5	7.6	7.4	7.3	80.8	82.3
(30-60)	3.40	2.00	8.0	8.0	10.4	10.5	76.2	82.5
(60-90)	6.20	4.70	8.0	7.9	11.5	11.9	67.5	74.0
Foisy Site: Ripped versus Control								
(0-15)	1.03	0.90	5.2	5.0	0.2	0.2	4.8	4.7
(15-30)	0.47	0.50	6.0	6.0	0.2	0.2	9.4	10.5
(30-60)	0.60	0.60	6.9	6.9	0.6	0.6	17.6	19.0
(60-90)	1.70	0.50	7.8	8.1	1.6	1.5	28.4	42.5
Foisy Site: Paraplowed versus Control								
(0-15)	1.03	1.17	5.2	5.2	0.2	0.2	4.8	4.5
(15-30)	0.47	0.43	6.0	6.0	0.2	0.2	9.4	10.5
(30-60)	0.60	0.23	6.9	6.3	0.6	0.3	17.6	13.8
(60-90)	1.70	0.50	7.8	7.5	1.6	0.5	28.4	17.6

There are no significant differences ($P < 0.05$) between the means of the deep tillage (DT) plots and the means of the control (Check) plots

Table 5. Continued.

Depth	EC		pH		SAR†		WSS‡	
	Check	DT	Check	DT	Check	DT	Check	DT
cm	-- dS/m --						----- % ----	
Harrington Site: Paraplowed versus Control								
(0-15)	0.77	0.73	7.3	7.7	1.3	2.6	31.4	47.6
(15-30)	0.60	0.80	8.0	8.2	3.3	4.7	57.2	66.7
(30-60)	3.43	4.73	8.3	8.3	8.6	9.1	66.3	66.9
(60-90)	7.00	9.60	8.3	8.2	10.6	12.2	62.8	60.7
Jessiman Site: Ripped versus Control								
(0-15)	0.50	0.40	7.3	7.1	0.3	0.3	10.8	9.5
(15-30)	0.33	0.33	7.8	7.8	0.4	0.4	17.3	20.0
(30-60)	0.37	0.47	8.0	8.0	1.0	1.0	33.2	38.7
(60-90)	1.00	0.70	8.1	8.1	2.7	3.5	64.6	48.2
Jessiman Site: Paraplowed versus Control								
(0-15)	0.50	1.13	7.3	6.7	0.3	0.3	10.1	9.5
(15-30)	0.33	0.47	7.8	7.2	0.4	0.5	17.7	20.0
(30-60)	0.37	0.40	8.0	8.0	1.0	1.2	37.5	38.7
(60-90)	1.00	1.30	8.1	8.1	2.7	2.8	50.0	48.2
McEwen Site: Ripped versus Control								
(0-15)	1.48	1.43	5.5	5.3	0.7	1.0	17.4	22.9
(15-30)	0.63	0.47	6.7	6.5	1.6	2.5	42.7	57.9
(30-60)	0.98	1.57	7.5	7.7	3.0	3.8	51.2	56.2
(60-90)	2.50	5.20	7.9	7.8	4.5	4.1	52.5	35.8
McEwen Site: Paraplowed versus Control								
(0-15)	1.48	0.73	5.5	5.6	0.7	0.6	17.4	20.3
(15-30)	0.63	0.43	6.7	6.5	1.6	1.4	42.7	43.1
(30-60)	0.98	0.73	7.5	7.7	3.0	2.9	51.2	51.8
(60-90)	2.50	2.10	7.9	8.0	4.5	4.6	52.5	56.2
Morgan Site: Ripped versus Control								
(0-15)	1.15	1.50	5.9	5.6	5.7	4.6	69.2	63.5
(15-30)	1.15	1.05	7.2	6.6	8.0	6.6	80.6	78.8
(30-60)	4.00	2.50	8.2	8.2	10.7	10.7	77.1	81.9
(60-90)	5.00	8.10	8.1	8.1	10.9	10.9	70.0	60.0

There are no significant differences ($P < 0.05$) between the means of the deep tillage (DT) plots and the means of the control (Check) plots

Table 5. Continued.

Depth	EC		pH		SAR†		WSS‡	
	Check	DT	Check	DT	Check	DT	Check	DT
cm	-- dS/m --						----- % ----	
			Norrish Site: Ripped versus Control					
(0-15)	0.77	1.00	7.0	6.7	0.3	0.3	8.2	7.4
(15-30)	0.50	0.63	6.9	6.7	0.4	0.3	12.9	9.0
(30-60)	0.73	0.80	7.1	7.1	0.7	0.4	19.2	12.0
(60-90)	1.80	1.70	7.7	7.4	0.7	0.7	13.1	13.2
			Rice Site: Ripped versus Control					
(0-15)	1.10	0.97	6.6	6.5	0.4	0.3	10.5	8.7
(15-30)	0.57	0.60	7.1	7.1	0.6	0.3	20.1	12.2
(30-60)	0.43	0.43	7.6	7.8	0.6	0.6	21.7	20.2
(60-90)	0.60	0.40	8.1	8.1	1.3	1.2	38.0	37.8
			Warner Site: Ripped versus Control					
(0-15)	1.23	1.00	5.2	5.6	5.9	4.2	74.1	65.4
(15-30)	1.67	1.13	6.3	6.1	7.3	7.0	74.3	79.5
(30-60)	4.10	2.90	7.5	7.5	9.1	9.2	67.6	74.5
(60-90)	6.20	5.90	8.0	7.9	9.6	8.3	60.8	56.5

There are no significant differences ($P < 0.05$) between the means of the deep tillage (DT) plots and the means of the control (Check) plots

Table 6. Soil chemical characteristics after subsoiling field plots under irrigated conditions

Depth	EC		pH		SAR†		WSS‡	
	Check	DR	Check	DR	Check	DR	Check	DR
cm	-- dS/m --						----- % ----	
			D. Eliason Site: Ripped versus Control					
(0-15)	0.69	0.77	7.3	7.2	1.7	1.9	34.1	35.2
(15-30)	0.73	1.32	7.8	7.8	4.2	4.4	54.0	51.8
(30-45)	3.86	2.80	8.2	8.2	8.9	6.8	51.1	54.5
(45-60)	6.52	4.08	8.3	8.2	7.3	7.8	44.7	50.9
(60-90)	7.47	6.95	8.3	8.3	10.0	10.6	50.9	55.3
(90-120)	8.34	8.24	8.2	8.2	11.1	12.2	50.8	52.4
			J. Eliason Site: Ripped versus Control					
(0-15)	1.01	0.64**	6.9	6.9	4.2	1.8**	53.1	34.7**
(15-30)	2.21	0.65	7.9	7.1	7.3	2.9**	60.0	46.7
(30-45)	4.46	1.36*	8.2	7.5	9.4	4.6*	56.6	50.2
(45-60)	7.08	2.89*	8.2	8.0	9.4	7.7	43.5	52.7
(60-90)	9.51	4.56*	8.2	8.1	10.0	8.2	40.6	49.8
(90-120)	9.08	5.79	8.2	8.1	11.6	9.4	48.4	49.9
			Millar Site: Paraplowed versus Control					
(0-15)	0.77	1.27	7.2	7.3	1.5	1.2	36.2	26.0
(15-30)	0.60	1.17	7.7	7.7	1.5	1.0*	42.0	22.5*
(30-60)	0.97	0.90	8.2	8.2	3.6	2.3	58.3	45.5
(60-90)	2.60	5.40	8.5	7.7	7.3	3.3	69.1	29.9
			Riopka Site: Ripped versus Control					
(0-15)	0.78	0.73	7.6	7.4	1.6	1.9	30.1	34.4
(15-30)	0.78	0.81	8.1	7.9	2.6	3.7	42.1	48.3
(30-45)	1.40	1.87	8.2	8.1	4.3	5.6	51.4	54.6
(45-60)	2.86	2.54	8.2	8.4	6.6	8.1	53.7	62.8
(60-90)	5.42	4.52	8.1	8.3	7.8	9.0	47.6	55.4
(90-120)	7.63	6.88	8.0	8.0	10.4	9.2	50.8	47.2

† SAR is sodium adsorption ratio

‡ WSS is percentage water-soluble sodium

*,** Significant differences between check and DR at $P < 0.05$, $P < 0.01$, repectively