Geoderma, 22 (1979) 275—295

EFFECTS OF DEEP TILLAGE AND PROFILE MODIFICATION ON SOIL PROPERTIES, ROOT GROWTH, AND CROP YIELDS IN THE UNITED STATES AND CANADA*[1]

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(Received September 11, 1978, accepted April 12, 1979)

ABSTRACT

Unger, P.W., 1979. Effects of deep tillage and profile modification on soil properties, root growth, and crop yields in the United States and Canada. Geoderma, 22: 275—295.

Unfavorable conditions of soil profiles, through their adverse effects on the growth, proliferation, and activity of roots, may severely limit the yield of crops at some locations in the United States and Canada. A review of the literature showed that deep tillage and modification of soils having unfavorable profiles may increase crop production by providing larger, more favorable zones of soil for the growth, proliferation, and activity of roots. The improved conditions may result from disrupting dense, high-strength horizons; leaching or burying salts or toxic materials; increasing the capacity of sandy soils to retain water; and reducing the erodibility of soil. When the horizons causing problems were adequately disrupted or altered, yields of crops were generally increased. Benefits from the treatments were greater when precipitation or irrigation were limited than when they were adequate. There are many soils on which no benefits can be expected from deep tillage and profile modification.

INTRODUCTION

Unfavorable conditions of soil profiles, through their adverse effects on the growth, proliferation, and activity of roots, may severely limit the yield of crops at some locations in the United States and Canada. On soils where conditions of the profile are unfavorable for the development of roots and yield of crops, the objective of deep tillage and profile modification is to increase crop production, principally by providing a larger, more favorable zone in the soil for increased growth, proliferation, and activity of roots. Deep tillage and profile modification may also alter the conditions at the soil surface, which may reduce damage to plants resulting from water and wind erosion. Because conditions of the soil that limit production differ

*[1] Contribution from Agricultural Research, Science and Education Administration, USDA, in cooperation with The Texas Agricultural Experiment Station, Texas A&M University.

widely, we should thoroughly understand the nature of these conditions. Then we can select equipment and methods that can best provide for a more desirable soil condition. Although deep tillage and profile modification can improve some soils, it is recognized that use of these practices will not be beneficial on other soils.

Definitions

The meaning of "deep tillage" changed as power for tillage changed from horses or mules to tractors, and as more powerful tractors became available. Early deep tillage with tractors meant plowing 20 to 40 cm deep, but now it means plowing 40 to 90 cm or deeper (Burnett and Hauser, 1967).

Differentiation between "deep tillage" and "profile modification" is not precise. Burnett (1969) stated that any tillage operation that alters any part of the soil profile can be considered as a form of profile modification. Generally, however, profile modification means some form of tillage, with or without chemical or physical amendments, to depths greater than ordinary plowing. Plowing to depths greater than 25 cm, subsoiling, and vertical mulching are types of profile modification. More drastic types include installing subsurface barriers, completely disrupting and homogenizing the profile, and modifying particular zones of the profile by trenching. In this review, I will restrict my discussion to tillage and profile modification to depths of 25 cm or more. Distinction between deep tillage and profile modification will be based largely upon usage by the authors whose work I will review.

Problems to be overcome

The soil conditions that cause problems with growth, proliferation, and activity of plant roots and that can possibly be overcome by deep tillage and profile modification are: (a) soil layers that restrict the growth of roots and movement of water; (b) undesirable substances on or near the surface; and (c) coarse-textured materials at the surface or to great depths.

Layers of soil that restrict growth of roots and movement of water are fragipans, plowpans, claypans, and horizons high in clay. Specific problems resulting from these conditions of the soil include reduced penetration of roots; restricted drainage of excess water; poor leaching of salts; and low infiltration, low storage, and poor distribution of water.

Undesirable substances on or near the surface of a soil may be salts, waste products, or toxic materials, such as radioactive fallout. These substances may cause poor growth of plants, poor leaching of salts, poor soil—water relations, and plants with high concentrations of undesirable substances.

Sandy soils, with coarse-textured materials at the surface and possibly to great depths, may result in poor growth of roots and plants because of excessive percolation of water, low fertility, excessive leaching of plant nutrients, low capacity to store water, and high erodibility by wind.

The above conditions are prevalent in many important agricultural soils in the United States and Canada. The total extent of soils with the conditions causing problems in the production of crops is not known, but some indications of the extent will be given in succeeding sections when effects of treatments on specific conditions of the soil are discussed.

Selection of equipment and treatments

For deep tillage and profile modification to be effective in correcting a soil problem, the equipment used must be capable of reaching the problem zone in the soil. For maximum effectiveness, the equipment should be selected on its ability to alter the condition of the soil and the operation should be performed at near—optimum conditions of soil water for the equipment used.

As power for tillage has increased, the size of equipment has also increased. Moldboard plows are available that can plow to at least a 90-cm depth. Robinson and Luthin (1968) reported that slip plowing reaches depths of 1.2 to 1.8 m in California. Trenching machines have been used to completely mix profiles to depths of 1.5 m or more on a limited-area basis, to install drains, and to open soil slots for vertical mulching. Subsoilers and chisels are widely used to loosen or shatter dense horizons at various depths.

A detailed discussion of all the problems and all the methods of overcoming them is not attempted in this report. I have, however, chosen some examples to illustrate what has been done to cope with the different kinds of soil problems that are potentially amenable, at least to some extent, by deep tillage and profile modification. Effects of the treatments on soil properties, root growth, and crop yields are included.

METHODS, RESULTS, AND DISCUSSION

Soils with dense, compact layers in the profile

For plants to benefit from water and nutrients in soil, plant roots must reach them. Extension and proliferation of roots, however, may be restricted or prevented by compact, high-density layers or horizons in the profile. These layers may have resulted from natural processes or from operations performed for crop production. Many studies have been conducted to determine the potential of deep tillage and profile modification for reducing the harmful effects of dense and compacted layers of soil on growth and yields of plants.

The penetrating ability of roots, according to Taylor and Gardner (1960), differs with plant species. Major factors influencing the penetration of roots include density, aeration, water tension, and strength of soil. Taylor and Gardner (1963) showed much higher penetration of roots into a soil with given density when the water tension was -1/5 bar than when it was -2/3 bar.

As the bulk density of soil increased, penetration of the roots at a given tension of water decreased. The ability of roots to penetrate was related to soil strength, which for a given bulk density, increased as tension of the water increased. Penetration of cotton (*Gossypium hirsutum* L.) roots stopped when the strength of Amarillo fine sandy loam (fine-loamy, mixed, thermic family of Aridic Paleustalfs), as determined with a penetrometer, reached about 30 bars.

Soils with fragipans, hardpans, claypans, or plowpans

A fragipan is a natural subsurface horizon with a bulk density higher than that of the soil above it. It is seemingly cemented when dry but is weakly to moderately brittle when moist. Fragipans restrict movement of air and water, have high strength, may be extremely acid, may cause aluminum toxicity to plants and, thus, limit the development of plant roots. In addition, saturated conditions above fragipans during periods of high rainfall may damage roots, whereas droughty conditions during dry periods reduce yields due to limited rooting of plants and consequent water stress. These results are common when the fragipans are near the surface. If the fragipans lie deep in soils, no adverse effects may occur and they may even be beneficial because of decreased percolation of water and leaching of nutrients. Where the fragipans are deep in the soil, deep tillage and profile modification are not expected to be beneficial.

As with fragipans, the degree of influence of hardpans, claypans, and plowpans on the development of plant roots and on their potential amelioration by deep tillage and profile modification depends on their depth below the surface of the soil. Hardpans and claypans are naturally dense, compact layers resulting from processes of soil formation. Plowpans form as a result of the action of tillage implements in a soil, usually just below the maximum depth of tillage. Soils may also be compacted by forces at the surface, such as traffic by tractors, implements, and livestock. USDA Handbook 436 (Soil Survey Staff, 1975) should be consulted for complete descriptions of the different types of pans in soils.

Hardpans and claypans may form at any depth in soils whereas plowpans usually are relatively near the surface where they are within reach of conventional tillage implements. Therefore, deep tillage or profile modification (>25 cm) generally is not required for loosening plowpans.

Bradford and Blanchar (1977) modified the profile of Hobson silt loam (fine-loamy, siliceous, mesic family of typic Fragiudalfs) to a depth of 152 cm in Missouri in 1974 with a wheel-type trenching machine. This soil has a dense, sandy fragipan at a depth of about 50 to 70 cm. Treatments besides modification included the addition of lime, fertilizer, and sawdust. The modification greatly reduced bulk density of the soil; increased the hydraulic conductivity; and caused a more uniform distribution of sand, silt, and clay, and of soil pores throughout the profile. Associated with these improved conditions were greater storage of available soil water and prolifer-

TABLE I

Effects of profile modification of soil with a fragipan on grain sorghum yields (from Bradford and Blanchar, 1977)

Modification	Grain yield (kg/ha)
Outside trench area	1,840
Nontrench area	3,230 d*
Trench	4,320 c
Trench and lime	4,910 bc
Trench and lime and fertilizer	5,150 b
Trench and lime and fertilizer and sawdust	5,990 a

*Means for treatments within trench area followed by the same letter or letters are not significantly different at the 5% level (Duncan's Multiple Range Test).

ation of roots to greater depths. As a consequence, yields of grain sorghum [*Sorghum bicolor* (L.) Moench] were significantly increased (Table I). Re-excavation in 1975 of a pit in Hobson silt loam that was excavated and refilled in 1959 with the same soil showed little indication of reformation of the fragipan during 16 years. In contrast, Fritton and Olson (1972) in New York found that modification of Erie channery silt loam (coarse-loamy, mixed, mesic family of Aeric Fragiaqualfs) by mechanical disturbance alone (trenching for a pipeline) resulted in the reformation of a dense fragipan within 11 years.

Van Doren and Haynes (1961) evaluated the effects of subsoiling and chiseling of Ohio soils having fragipans at depths of 36 to 90 cm. Subsoiling or chiseling to 38- or 46-cm depths, respectively, did not increase corn (*Zea mays* L.), oats (*Avena sativa* L.), and clover (*Triticum aestivum* L.) yields. Apparently, yields were not increased because the tillage operations disrupted only a small part of the fragipan and because the climate and the nutrient conditions of the soil were favorable for relatively good yields, even though the soil was not deeply loosened.

Some soils of the southeastern Coastal Plains from Virginia to eastern Texas have physical properties that restrict development of roots to shallow depths. Limited rooting and low capacity of the soil to store water, combined with periods of low rainfall, cause severe water stress in plants. Physical properties involved are the size-distribution of soil particles, strength of soil, and retention and transmission of water in the soil. Soils studied were the Norfolk series (fine-loamy, siliceous, thermic family of Typic Paleudults) and Varina sandy loam (clayey, kaolonitic, thermic family of Plinthic Paleudults). Chiseling the soils to a 38-cm depth disrupted the high-density horizons, which reduced the impedance to root growth, increased the infiltration of water, and increased the depth of rooting (Campbell et al., 1974). Disrupting the restricting layer increased the amount of water available to plants by

TABLE II

Effects of profile modification of Houston Black Clay on cotton and grain sorghum yields (from Burnett and Tackett, 1968)

Crop and treatment	Yield (kg/ha)		
	1964	1965	1966
Lint cotton			
Conventional tillage	210 b*	270 c	400 b
Roto-tilled 60 cm	560 a	380 b	630 a
Profile modified 60 cm	—	370 b	630 a
Profile modified 120 cm	—	500 a	660 a
Sorghum grain			
Conventional tillage	4,080 b	4,370 b	5,330 b
Roto-tilled 60 cm	4,660 a	5,800 a	6,380 a
Profile modified 60 cm	—	4,270 b	5,690 a
Profile modified 120 cm	—	5,060 a	5,990 a

*Means for a crop within a year column followed by the same letter are not significantly different at the 5% level (Duncan's Multiple Range Test).

lowering the water content at which the soil strength restricted development of the roots, thus permitting extraction of water to lower residual levels. Deeper proliferation of roots enabled plants to extract water from a larger volume of soil, which minimized stress and increased yields. During drought in 1 year, chiseling without irrigation increased yields of crops by 38 to 81%. With frequent rainfall, chiseling had no beneficial effects on yields.

Soils with dense clay layers

Soils with high percentages of montmorillonitic clay in the profile restrict drainage, aeration, penetration of water, and development of roots, especially of annual crops. One such soil is Houston Black clay (fine, montmorillonitic, thermic family of Udic Pellusterts), which with associated soils covers about 2 million ha in central Texas. Burnett and Tackett (1968) modified this soil to depths of 60 and 120 cm by rototilling or by mixing with a trenching machine. Mixing the profile to the 120-cm depth, as compared with mixing to the 60-cm depth or with normal tillage, caused greater and more uniform aeration to the 180-cm depth, which increased proliferation of roots. Although roots penetrated to the 150-cm depth on unmodified soil, branching in the lower profile was much more extensive on the modified soil. Yields of cotton and grain sorghum were generally increased by mixing the profile to the 60- or 120-cm depth as compared with conventional tillage (Table II). Also, improved aeration, which reduced CO_2 concentrations in the profile, greatly reduced the incidence of cotton root rot.

Low infiltration rate of water after initial wetting of the surface is a dominant feature of Pullman clay loam (fine, mixed, thermic family of Torrertic Paleustolls) and associated soils, which occupy about 4.8 million ha in the High Plains of Texas, New Mexico, and Oklahoma. Pullman clay loam has a very slowly permeable horizon of swelling clay below the depth of normal tillage. The upper boundary is located at about a 23-cm depth, which is the depth of primary tillage on cultivated soils. The depth of the lower boundary varies from place to place, but it is typically located at about the 68-cm depth. After initial wetting, the rate of infiltration decreases to about 1.3 mm/h. Consequently, complete refilling of the water reservoir of the soil, whether by irrigation or precipitation, is very slow. A major reason for studies involving deep tillage and profile modification on Pullman clay loam soil, therefore, has been to devise techniques for increasing the infiltration rate of water and for more completely refilling the profile with water.

Jensen and Sletten (1965) conducted a tillage study on Pullman clay loam from 1955 to 1961. Chiseling at 50- to 60-cm intervals to the 38-cm depth after harvest, when the soil was dry, doubled the rate of water infiltration during the first irrigation after chiseling, as compared with conventional tillage. The rate of infiltration in chiseled plots in the fourth year after chiseling was only 20% greater than in conventionally tilled plots. Because the plots had borders and because all added water eventually entered the soil or evaporated, chiseling increased yields of wheat grain only about 6% and did not affect yields of grain sorghum.

Hauser and Taylor (1964) compared disk plowing to a 60-cm depth; chiseling at 2-m intervals to a 60-cm depth, with and without vertical mulching; and conventional tillage on Pullman clay loam. Chiseling without vertical mulching, as a one-time operation, significantly increased infiltration of water only the first year because spacing of chisels was too wide to effectively loosen a significant volume of soil. Rates of infiltration with disk plowing and chiseling with vertical mulching were 1.9 and 1.5 times greater, respectively, than with conventional tillage after 3 years. Plowing to the 60-cm depth significantly decreased the bulk density of plowed layers. Yields of grain sorghum were significantly higher with deep tillage than with other treatments in only 1 year, apparently because adequate water was applied to sorghum on the bordered plots so that a deficiency of water did not limit yields. Vertical mulching also decreased the density and increased the aggregation, the infiltration rate and the volume of water stored, and the rooting depth and growth of plants on soils in South Texas (Heilman and Gonzalez, 1973), South Dakota (Kingsley and Shubeck, 1964) and Indiana (Parr, 1959).

In 1966, Pullman clay loam was plowed to 40-, 60-, and 80-cm depths with a moldboard plow. Conventional tillage was to a 20-cm depth. The 40-cm deep-plowing loosened parts of the slowly permeable layer of soil, the 60-cm deep-plowing mixed most of this layer with surface soil, and the 80-cm deep-plowing mixed the slowly permeable layer with surface soil and

TABLE III

Effects of deep tillage of Pullman clay loam on infiltration of irrigation water and grain sorghum yields (from Schneider and Mathers, 1970)

Tillage (cm) depth (cm)	Infiltration (cm)		Average grain yield (kg/ha)	
	1966	1968	one irrig.	two irrig.
20	19.8	15.2	3,830	5,620
40	22.1	14.7	4,870	7,100
60	29.7	14.7	5,280	6,600
80	29.5	14.7	5,820	6,200

*Based on average infiltration for treatment receiving two growing-season irrigations.

with some of the more permeable layer below the slowly permeable layer. Several studies were conducted on these plots which were furrow-irrigated. Tillage to the 40-, 60-, or 80-cm depth, as compared with conventional tillage, increased the infiltration rate of irrigation water in 1966, but not in 1968 (Table III). Lack of response to deep tillage in 1968 was attributed to compaction of the surface soil during harvest of sugarbeets (*Beta vulgaris* L.) in 1967 while the soil was wet. This condition was corrected by conventional tillage to the 20-cm depth after the 1968 crop. Grain sorghum was planted on the plots in 1966 and 1968. With one irrigation during the growing season, yields of grain with tillage to 80-cm were 1,990 kg/ha higher than with conventional tillage. With two irrigations during the growing season, yields were highest when the soil was plowed 40 cm deep (Table III). Greater storage of water and subsequently greater depletion of the water permitted sorghum on deep-tilled plots to produce satisfactory yields of grain with limited irrigations during the growing season. Where water for irrigation is limited, as in parts of the Southern Great Plains, deep tillage reduces the demand for irrigation water during critical periods of growth for grain sorghum. To obtain the greatest efficiency of water use by grain sorghum, Musick and Dusek (1971, 1975) showed that the lower portion of the slowly permeable horizon of Pullman clay loam should be left intact. Complete penetration of the slowly permeable horizon by deep tillage allowed excessive infiltration and deep percolation of irrigation water.

For sugarbeets grown on the deep-tilled plots in 1967 with adequate irrigation, yields of roots and sugar were significantly higher with tillage to the 40-cm depth than with conventional tillage (Table IV). Tillage to 60- and 80-cm depths did not further increase yields (Mathers et al., 1971).

In 1964, Eck and Taylor (1969) modified the profile of Pullman clay loam to 90- and 150-cm depths by mixing the soil with a large wheel-type ditching machine. They then grew grain sorghum on the plots with limited and full irrigation. With limited irrigation, grain yields for 3 years averaged

TABLE IV

Effects of deep tillage of Pullman clay loam on sugarbeet root and sugar yields (from Mathers et al., 1971)

Tillage depth (cm)	Yields*	
	root (m.tons/ha)	sugar (kg/ha)
20	41.3	6,900
40	49.6	8,280
60	45.1	7,350
80	44.9	7,480

*Based on the average for 0, 112, and 224 kg/ha nitrogen treatments.

2,810, 4,670, and 5,060 kg/ha for the 0-, 90-, and 150-cm depth treatments, respectively. The increases over the unmodified treatment were statistically significant. With full irrigation, yields were 7,100, 7,100, and 7,640 kg/ha for the 0-, 90-, and 150-cm depth treatments, respectively, but the differences were not statistically significant. Yield trends for stover were similar to yield trends for grain. As compared with no profile modification, modification to 90- and 150-cm depths significantly increased the efficiency of water use for the production of grain and total dry matter. Profile modification permitted storage of water at greater depths where the water was less subject to loss by evaporation. This increased storage of water, coupled with depletion of water to about the 240-cm depth on modified plots as compared with a 150-cm depth on unmodified plots, resulted in higher efficiencies of water use. A subsequent study on these plots showed that profile modification increased the yields and efficiency of water use by alfalfa (*Medicago sativa* L.). Because infiltration of water was more rapid and ponding was not a problem, profile modification also simplified the management of irrigation for the alfalfa by permitting one large application of water between harvests, whereas two smaller irrigations were required on unmodified soil to obtain similar yields (Eck et al., 1977). Infiltration rates of water due to profile modification were still greater in 1976, 12 years after the profile was modified.

Analyses of samples obtained in 1967 from the plots used for the profile modification study showed that modification treatments decreased the density and resistance to penetration (measured with a penetrometer) of soil within the modified layers. The differences were statistically significant. Modification also resulted in a more uniform distribution of soil particles and a greater volume of air-filled pores and tended to increase the hydraulic conductivity of soil cores. The retention of water and the amount of water available to plants were not altered by the treatments, but infiltration of water was much more rapid into modified than into unmodified field plots

(Unger, 1970). The modification did not increase the capacity of the water storage reservoir but provided for filling the reservoir more readily.

Deep tillage also increased the infiltration rate of rainwater, which more readily refilled the water storage reservoir of Commerce silt loam (fine-silty, mixed, nonacid, thermic family of Aeric Fluvaquents) in the cotton-growing area of the Mississippi River Delta Plains in Louisiana (Saveson et al., 1961). In isolated parts of the field, the soil has natural "hardpans" at depths of about 13—45 cm below the surface and plants experience water stress well before those on surrounding areas. Lint yields of cotton were substantially increased by deep tillage in years when rainfall was limited but were not affected when rainfall was adequate.

Soils with salts or other undesirable substances in the profile

Salt-affected soils

Soils affected by salts are found in subhumid to arid regions of the United States and Canada. Although the characteristics differ for the different types of these soils, they generally have a layer somewhere in the profile that is high in adsorbed or exchangeable sodium. The soil may be high in sodium throughout the profile or it may be high in sodium in a layer beneath the A horizon. Furthermore, some of the salt-affected soils have saline layers at or below the surface, and some but not all of these soils contain gypsum. Soils that are high in sodium are largely classified in the Aridisol and Mollisol order of the U.S. system and in the Solonetzic order of the Canadian system.

Rasmussen et al. (1964) conducted studies on the Chilcott-Sebree complex of soils in Idaho. The Sebree (fine-silty, mixed, mesic family of Xerollic Nadurargids) is a saline-sodic soil. It occurs in close association with less salt-affected or nonsaline soils of the Chilcott (fine, montmorillonitic, mesic family of Abruptic Xerollic Durargids) and other series. Growth of plants on Sebree soil is very poor because of unfavourable physical conditions and because of extremely low infiltration of water during irrigations. The low infiltration results from the poor soil structure caused by the highly exchangeable sodium, primarily in the shallow clayey subsoil.

In a field study established in 1959, treatments were subsoiling to a 71-cm depth and tillage with a moldboard plow to 61- and 76-cm depths. On the Sebree soil, the effect of added gypsum (27 metric tons/ha) was also evaluated. Deep tillage greatly increased the total infiltration and depth of penetration of water in 24 h on both soils. Infiltration and penetration of water were also increased by subsoiling the Chilcott but not the Sebree soil after the first year. Applying gypsum, with and without subsoiling, increased infiltration and penetration of water on the Sebree soil. Associated with the increased infiltration were increased leaching, water storage, root penetration, and crop yields (Table V). Yields of wheat were doubled by tilling the Chilcott soil to the 61-cm depth and tripled by a combination of tilling the Sebree

TABLE V

Effects of deep tillage of soils of the Sebree-Chilcott complex on wheat grain and alfalfa yields (from Rasmussen et al., 1964)

Soil and treatment	Yields	
	wheat (kg/ha)	alfalfa (m.tons/ha)
Chilcott		
Check	1,190	9.9 bc*
Subsoiled 71 cm	1,820	10.9 abc
Plowed 61 cm	2,500	12.7 ab
Plowed 76 cm	2,080	13.2 a
Sebree		
Check	780	3.4 d
Gypsum	990	9.7 c
Subsoiled 71 cm	1,050	3.7 d
Subsoiled 71 cm + gypsum	1,810	12.4 abc
Plowed 61 cm	1,860	11.7 abc
Plowed 61 cm + gypsum	2,580	12.2 abc
Plowed 76 cm	1,970	12.2 abc
Plowed 76 cm + gypsum	2,510	12.9 a

*Alfalfa yield differences for both soils followed by the same letter or letters are not significantly different at the 5% level (Duncan's Multiple Range Test).

soil to a 61-cm depth and adding gypsum. Average yields of alfalfa were increased 33% by tilling the Chilcott soil to a 76-cm depth and 275% by tilling the Sebree soil to the 76-cm depth and adding gypsum. The yields on the Sebree soil resulting from depths of tillage and subsoiling, with and without added gypsum, were similar, except for subsoiling only, which did not increase yields over those from the check.

Bowser and Cairns (1967) conducted deep-tillage studies on Duagh silt loam and silty clay loam soils in Alberta, Canada. The Duagh series is a Solonetzic soil with a hydraulic conductivity usually less than 0.3 mm/h, an electrical conductivity of 10 mmhos/cm, and a profile that contains considerable gypsum and sodium and magnesium sulfate. The soil was tilled 56 cm deep with a moldboard plow in the fall of 1959. Deep tillage increased the rate of water infiltration and greatly decreased the content of total salts in the soil. In 1966, contents of soluble sodium in the profile averaged 4.30 and 0.34 mequiv./100 g in the check and deep-tilled plots, respectively. Deep tillage had less effect on the contents of soluble calcium and magnesium.

Alfalfa and bromegrass (*Bromus* sp.) were grown on the plots in 1966. Most alfalfa roots in check plots penetrated only to the 30-cm depth with few penetrating to the 50-cm depth. In deep-tilled plots, roots penetrated to a 76-cm depth, with some penetrating to a 90-cm depth. Because of the more extensive root system and greater plant growth, extraction of water was greater and soil of the deep-tilled plots contained only 14–15% water when the crops were harvested. On check plots, the water content at harvest was 18 to 20%. The difference was statistically significant. Average yields of wheat and barley (*Hordeum* sp.) from 1960 to 1965 were 2,320 and 2,400 kg/ha on deep-tilled and check plots, respectively. The difference was not statistically significant.

During relatively dry years, preparation of a seedbed was not difficult after Solonetzic soils were deep-tilled. Considerable difficulty was encountered during wet years, however, resulting in uneven emergence of crops. The uneven emergence resembled that usually associated with normally-tilled Solonetzic soils (Cairns, 1976). From analyses of samples obtained from the upper 10 cm of normal and deep-tilled Kavanagh loam and Duagh silt loam, Cairns (1976) found that the condition of the seedbed was related to the amounts of extractable sodium and calcium in the soils. Generally, higher amounts of extractable sodium resulted in a poorer seedbed and higher amounts of extractable calcium in an improved seedbed. Within sites, there was a good relationship between the extractable calcium:sodium ratio and condition of the seedbed. Where emergence was good, the ratio invariably exceeded 4. The finding that one seedbed was moderately good with a Ca:Na ratio of 1.5 whereas another was poor with a ratio of 2.9 was attributed to conditions of soil water at the time of preparing the seedbed. Only soils with an extractable Ca:Na ratio greater than four seemed to be sufficiently stable to assure good seedbeds under various conditions.

Slip plows have been used extensively since 1962 to improve drainage of shallow perched water tables and leaching of salts in soil profiles in stratified deposits in the Imperial Valley of California. The slip plow is a modified soil chisel with a 20- to 30-cm wide flat plate attached to the back of the chisel from its point to the above-ground portion. The plate extends upward from the chisel point at an angle of 60°–70°. Common operating depths are 120–180 cm. The plow lifts and loosens impermeable layers and interrupts any pronounced stratification.

Robinson and Luthin (1968) studied effects of chiseling and slip-plowing of a nonstratified clay on the infiltration rate of water and on soil salinity. The study area had tile drains at a 1.8-m depth at 36-m intervals. Chiseling and slip-plowing were done at 56- and 120-cm depths, respectively. Infiltration rates of water were 11.6, 12.0, and 14.8 mm/day for normal tillage, chiseling, and slip-plowing treatments, respectively, when water was ponded on the soil. Greater infiltration with slip-plowing resulted in the greatest reduction in conductivity at the midpoint between tile drains (Table VI). In the trench for the tile drain, however, untreated and chiseled areas had the lowest conductivity. Apparently, slip plowing opened the soil profile enough so that leaching from all points at the same depth proceeded at similar rates.

TABLE VI

Effects of chiseling and slip plowing a nonstratified clay on conductivity at the midpoint between tile drains (from Robinson and Luthin, 1968)

Depth (cm)	Conductivity (mmho/cm)		
	untreated	chisel (56 cm)	slip plow (120 cm)
0—30	-1.46	+0.23	-1.60
30—60	+0.69	-1.00	-1.79
60—90	-0.63	-1.17	-1.75
90—120	-0.65	-0.99	-1.72
120—150	-0.12	-1.88	-1.52

*Minus signs indicate reduction in conductivity; plus signs indicate gain.

Kaddah (1976) compared chiseling and slip plowing of Rositas loamy fine sand (mixed, hyperthermic family of Typic Torripsamments), which overlies Imperial silty clay [fine, montmorillonitic (calcareous), hyperthermic family of Vertic Torrifluvents], at 90-cm depths in one and two directions with disking to a 20-cm depth. The bulk density of soil between plowed slits and in many slits did not differ greatly among treatments. Penetration tests showed similar strengths of soil at the 0—30-cm depths in all plots, but lower strengths at the 30—90-cm depths in slip-plowed plots than in disked plots. Examination of plant rooting in open pits after harvest showed greater penetration and density of roots in deeply loosened soil than in disked soil and along slits as compared with areas between slits. Chiseling and slip-plowing treatments significantly increased yields of wheat grain and straw as compared with the disking treatment (Table VII).

TABLE VII

Tillage effects on wheat yields on a stratified soil (from Kaddah, 1976)

Treatment	Yields (m.tons/ha)	
	grain	straw
Disking 20 cm	4.50 d*	9.54 d
Chisel 90 cm, one direction	5.15 c	10.55 c
Chisel 90 cm, two directions	5.62 b	11.65 b
Slip plow 90 cm, one direction	5.73 b	11.67 b
Slip plow 90 cm, two directions	6.32 a	13.40 a

*Column values followed by the same letter are not significantly different at the 5% level (Duncan's Multiple Range Test).

Soils contaminated with radioactive materials

During the 1950's and 1960's, there was much interest in reducing the uptake of radioactive materials if soils became contaminated with radioactive fallout. To reduce uptake of these materials, Menzel et al. (1968) conducted a study on Pullman clay loam. Strontium-85 was applied to the surface of the soil at a rate of 110 $\mu c/m^2$. Treatments were roto-tilling 20 cm deep, moldboard-plowing 90 cm deep, and applying Na_2CO_3 at 22.4 metric tons/ha before moldboard-plowing 90 cm deep. The plow had an attached scraper that moved the treated surface soil to the bottom of the furrow behind the moldboard. This soil was then covered by the next pass of the plow. The Na_2CO_3 was intended as a root-growth inhibitor to reduce the uptake of strontium. Crops grown were sugarbeet, sudangrass (*Sorghum sudanese*), soybean (*Glycine max*), and cabbage (*Brassica oleracea*).

Deep tillage placed most of the contaminated surface soil at 90 cm below the surface. Concentrations of strontium in plants late in the season were greatly reduced by deep tillage as compared with roto-tilling to the 20-cm depth (Table VIII). Concentrations of strontium were reduced even more when Na_2CO_3 was placed in the bottom of the plow furrow with the strontium. Yields of crops were greatly increased by deep tillage and were little affected by plowing under the Na_2CO_3. The bulk density of soil was about 25% less after deep tillage than before. Yield, distribution, and activity of roots were studied in the rototilled and deep-tilled soil by Eck and Davis (1971). Deep tillage tended to decrease root yields of sudangrass, sugarbeets, and soybeans, but had little effect on cabbage. Root yields decreased with depth on rototilled or deep-tilled soil, but tended to be evenly distributed throughout the profile when 22.4 metric tons/ha of Na_2CO_3 were placed at the 90-cm depth. The activity of roots, as measured by top:root ratios, was increased by deep tillage (Table VIII). Because root yields were not greatly affected by deep tillage, the higher top:root ratios resulted from increased top yields on deep-tilled plots.

Sandy soils

Deep, sandy soils have a low capacity to retain water, often are infertile, and may be subject to erosion by wind. These soils can be improved by placing barriers that restrict downward movement of water in the profile or by deep tillage or profile modification if finer-textured materials can be brought to the surface.

Studies with a layer of asphalt placed 60 cm below the surface of Lakeland fine sand (thermic, coated family of Typic Quartzipsamments) in Florida showed that rooting below the barrier by tomatoes (*Lycopersicon esculentum* Mill.) and corn was less than that at the same depth without a barrier. However, the concentration of corn roots was greater in the top 60 cm of soil, both with and without irrigation (Saxena et al., 1973). Treatments involving irrigation, asphalt layers, and asphalt layers plus irrigation increased

TABLE VIII

Effects of tillage and sodium carbonate on strontium concentration, dry matter yield, and top:root ratio of various crops (from Menzel et al., 1968; Eck and Davis, 1971)

Crop	Treatments		
	Roto-tilled 20 cm	Plowed 90 cm	Plowed 90 cm + Na_2CO_3
Relative strontium concentration			
Sugarbeet			
Top	100	23.7	2.9
Root	100	40.5	4.2
Sudangrass			
Fodder	100	36.6	4.8
Seed	100	50.5	5.9
Soybean			
Straw	100	35.3	2.7
Seed	100	37.6	4.2
Cabbage	100	29.6	6.4
Dry matter yield (kg/ha)			
Sugarbeet			
Top	1,100 b*[1]	2,320 a	2,270 a
Root	3,970 b	8,250 a	7,810 a
Sudangrass			
Fodder	2,890 b	4,600 a	4,060 a
Soybean			
Straw	580 b	1,260 a	1,090 a
Seed	480 b	990 a	990 a
Cabbage	930 a	1,560 a	2,060 a
Top:root ratio			
Sugarbeet*[2]	3.72	8.52	6.53
Sudangrass	1.35	2.51	1.81
Soybean	0.79	1.93	1.47
Cabbage	0.74	1.40	1.99

*[1] Row values followed by the same letter are not significantly different at the 5% level (Duncan's Multiple Range Test).
*[2] For sugarbeet, the ratios are based on roots other than the fleshy, sugarbearing root.

TABLE IX

Effects of asphalt barriers and irrigation on corn yields on Lakeland fine sand (from Robertson et al., 1973)

Treatment	Yields (kg/ha)	
	fodder	grain
Check	14,680 c*	5,140 b
Irrigation	20,470 a	7,590 a
Asphalt layer	17,900 b	5,020 b
Irrigation + asphalt layer	20,430 a	8,150 a

*Column values followed by the same letter are not significantly different at the 5% level (Duncan's Multiple Range Test).

yields of fodder over those of the check (Table IX), but yields of grain for the nonirrigated treatment with the asphalt layer were similar to those of the check because of a drought when the corn was in the early silking stage. Irrigation, with and without an asphalt barrier, significantly increased yields of grain (Robertson et al., 1973).

Various responses to an asphalt layer, depending on the distribution of rainfall, were reported for vegetable crops in Michigan by Erickson et al. (1968). Favorable rainfall increased yields of cucumber (*Cucumis sativus*) and cabbage with the asphalt-layer treatment, whereas irrigation decreased

TABLE X

Effects of asphalt barriers and irrigation on crop yields on sandy soil with favorable and unfavorable rainfall (from Erickson et al., 1968)

Rainfall, location and crop	Yields (m.tons/ha)			
	control	control with irrigation	asphalt layer	asphalt layer with irrigation
Favorable rainfall—Allegan Co., Mich.:				
Cucumbers	18.7 b*	19.5 b	24.9 a	25.5 a
Cabbage	23.0 b	18.5 c	32.7 a	23.8 b
Unfavorable rainfall—Montcalm Co., Mich.:				
Potatoes	24.3 b	37.3 a	25.6 b	38.6 a
Beans	13.8 b	25.1 b	14.4 b	25.3 a

*Row values followed by the same letter are not significantly different at the 5% level (Duncan's Multiple Range Test).

TABLE XI

Effects of subsurface barriers on yields and water requirements for rice in India (from Rao et al., 1972)

Barrier depth (cm)	Yield (kg/ha)		Water used (cm)	
	early crop	late crop	early crop	late crop
None (check)	4,980 c*	3,920 a	317.3 a	70.6 a
20	7,200 a	4,260 a	96.5 b	48.5 b
30	6,310 b	4,320 a	85.4 b	47.2 b
40	7,600 a	4,420 a	86.9 b	47.2 b

*Column values followed by the same letter are not significantly different at the 5% level (Duncan's Multiple Range Test).

yields of cabbage, possibly due to leaching of nutrients (Table X). With less favorable rainfall, the asphalt layer did not increase yields of potatoes (*Solanum tuberosum*) and beans (*Phaseolus* sp.) without irrigation. Subsurface barriers of bitumen (asphalt) or concrete significantly increased rice (*Oryza sativa*) yields in India (Table XI). In addition, the requirement of water was drastically reduced and the efficiency of water was increased by the subsurface barriers (Rao et al., 1972).

Miller and Aarstad (1972) plowed Hezel soil (sandy over loam, mixed, nonacid, mesic family of Xeric Torriorthents) in Washington to a 1-m depth with a moldboard plow. This soil has a sandy loam texture to a 46-cm depth and a silt loam texture in a 46- to 91-cm layer. After tillage, the texture was silt loam in the 0–15-cm layer and loam in the 15–30-cm layer. Although variable because of incomplete mixing, the capacity of the surface 30 cm of soil to hold plant-available water was increased about 70% by deep tillage because of the change in texture. Below the 30-cm depth, differences between unplowed and plowed soil were slight.

Sandy soils in arid and semiarid regions that contain less than about 8% clay in the surface layer may be highly susceptible to erosion by wind when planted to row crops. About 2.6 million ha of such soils occur in western Texas and eastern New Mexico. Other extensive areas of sandy soils in semiarid regions occur in western Kansas and Nebraska. If soils contain more than about 8% clay, a cloddy condition that is resistant to erosion by wind can be produced by cultivation (Harper and Brensing, 1950). Because soil clods reduce erosion and cloddiness is related to clay content of the soil, the goal of deep moldboard- or disk-plowing of sandy soils with respect to controlling erosion is to adequately increase the clay content of the surface layer. When Harper and Brensing (1950) tilled sandy soils to about the 40-cm depth at several locations in Oklahoma, the clay content of the surface layer was increased from less than 4% to an average of over 12%.

The subsoil contained about 20% clay before deep tillage. Harper and Brensing (1950) advised against deep tilling sandy soils that had subsurface layers with very high percentages of clay because it places too much clay in the surface soil, which could decrease infiltration of water. Deep-tilling soils with little clay in the subsoil would be of no value for controlling wind erosion because the clay content of the surface layer could not be increased sufficiently.

During the 1950's, Chepil et al. (1962) evaluated the potential of deep tillage for reducing wind erosion on sandy soils in Texas and Kansas. In Texas, tilling Amarillo loamy fine sand 25 or 43 cm deep with a large disk plow increased the clay content from about 4 to 14% and thus reduced the potential for erosion. However, within 5 years after deep tillage, the sand content had increased and the clay content had decreased to about the same levels as before tillage. Severe wind erosion because of a prolonged drought in Texas during that period removed or buried most of the clay initially brought to the surface, and potential loss of soil after 5 years was very high.

Deep tilling of sandy soils in southwestern Kansas decreased the average content of sand in the surface soil from 86 to 72% and increased the content of clay from about 5 to 12%. The percentages of sand and clay remained practically unchanged for 6 years after tillage when little or no wind erosion occurred. With severe wind erosion, the clay content decreased rapidly.

The deep-tillage operations in Kansas brought soil clods to the surface, which greatly reduced the soil's susceptibility to wind erosion. One-half year after tillage, the percentage of clods on the surface of the deep-tilled soil averaged twice that on soil that was not deeply tilled. The difference decreased rapidly for about 2 years and less rapidly to the end of 6 years. Cloddiness was directly proportional to the amount of clay brought to the surface.

PREDICTION OF EFFECTS

Ideally, all changes in soil resulting from deep tillage and profile modification should be completely predictable. In addition, it would be beneficial to know the longevity of these changes. Effects of deep tillage and profile modification on soil sand, silt, and clay contents can be predicted with a fair degree of accuracy. Also, Rasmussen and McNeal (1973) devised a procedure for estimating the effects of solution of mixed salts on the hydraulic conductivity of soil to predict the relative hydraulic conductivity of separate horizons from saline–sodic soils. The results permitted them to predict the optimum depth of tillage for improving saline–sodic soils. For other factors, however, the effects are generally less predictable because different soils, when similarly treated, behave differently because of differences in texture, structure, organic matter, profile characteristics, and the like. Also, the water content during the operations of deep tillage or profile modification and the degree of profile mixing obtained greatly influence the effectiveness of the operations.

CONCLUSIONS

Accurate predictions of the immediate and long-term effects of deep tillage and profile modification on the physical properties of soils, on the growth of roots, and on the yields of crops is not possible. We can, however, draw some general conclusions.

Soils with dense, compact layers in the profile

Tillage and modification of profiles at depths greater than 25 cm can improve soils with compact layers if those are sufficiently near the surface to be disrupted by the tillage or modification operation. For soils with thick fragipans or thick, dense clay layers that restrict growth of roots and penetration of water, responses are related to depth of operation and degree of disruption of the restricting layer. Generally, improvement of soil increases as the depth of operation and the degree of loosening of the problem layer increases. In some cases, however, loosening the entire clay layer causes excessive infiltration of water when the soils are irrigated. On soils with fragipans or other dense layers, benefits from modification are greater in years with limited precipitation or with limited irrigation than when water is adequate. The effectiveness of treatments can be prolonged by mixing organic materials or materials from other horizons of the soil with the horizons causing problems. Generally, benefits are more enduring from deep tilling with disk or moldboard plows and from complete mixing of profiles than from chiseling or subsoiling. Chisels and subsoilers often do not effectively loosen or disrupt sufficient volumes of the layers of soils that cause problems. When soils are wet, use of chisels and subsoilers is of little value.

Soils with salts or other undesirable substances in the profile

Deep tillage and profile modification are usually effective practices for improving soils containing high concentrations of sodium. Adding gypsum or mixing gypsum from subsurface horizons with the horizon high in sodium usually is necessary for improving these soils. Deep tillage increases the infiltration and drainage of water, thus decreasing the salt content of soil by increased leaching. Deep burial of radioactive materials by tillage can greatly decrease the immediate uptake by plants of these materials when they contaminate the surface of the soils. Uptake of these materials by plants may be decreased even more by plowing down substances, such as sodium carbonate which inhibit the growth of roots.

Sandy soils

Subsurface barriers, such as asphalt layers, increase the storage of water above the barriers and the yields of crops on deep, sandy soils with irrigation or when rainfall is adequate. The barriers also decrease the water requirements of crops and increase the efficiency of water use. With limited water, barriers have little or no effect on yields of crops. For soils with sand overlying horizons of clay, deep tillage that reaches the clay horizon increases the content of clay and clods in the surface soil, thus decreasing susceptibility to erosion by wind. However, the content of clay and clods in the surface soil generally decreases with time.The rate of decrease is related to the amount of clay initially brought to the surface and to wind erosion in the problem area. Chepil and Moldenhauer (1962) considered deep tillage of sandy soils as one aid for controlling wind erosion because deep tillage alone could not control erosion.

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