Technologies for Improved Soil Water Use

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Abstract

A dense and compact layer below a surface soil is often observed in agricultural soils and causes unstable crop production. The dense and compact layer is either formed naturally or artificially and is characterized by high mechanical impedance for root growth and low water transmission in the soil matrix. Soil water in a surface soil is not drained but remains during rain events unless bypass flow through macropores occurred. The surface soil is easily dried up by soil evaporation due to insufficient upward water movement through the matrix of the dense and compact layer. In addition, most plant roots hardly penetrate the dense and compact layer and shallow root systems are formed. Due to such physical conditions, crops become susceptible to both excess water injury and drought damage. To alleviate such adverse soil conditions, agronomic and physical approaches have been adopted. Subsoil disruption by deep tillage and subsoiling is effective for soil profile modification. Subsoiling perpendicular to the envelope of a drainpipe is effective to collect residual ponding water to the drainpipe in clayey soils. Subsoiling has also been carried out to expand the soil volume for root water uptake. Soils in Northeast Thailand are sandy soils with impervious dense layers. Subsoiling in a wet season promoted deep percolation and reduced water erosion, and a large amount of water was stored in the subsoil compared to conventional tillage. This resulted in vigorous sugarcane growth starting near the end of the wet season. Deep rooted plants were able to extract stored soil water in deeper layers during the dry season. However, the effect of biopores by deep rooted plants on subsequent crop growth has not been elucidated.

Introduction

Adequate water supply and soil physical conditions as well as chemical and biological conditions are essential for better crop production. In some regions, however, dense and compacted soil layers are formed either naturally or artificially below the surface soil. Field operations such as plowing, harvesting, etc. destroy the soil structure below the plow layer by compaction and smearing. The dense and compacted layer formed by such activities is referred to as plow pan or traffic pan. Dense and compacted layers hinder deep percolation and root growth and result in excess water injury and drought for crops. The soils with dense and compacted layers are classified into two types: clayey non-structured soils and coarse-textured soils. The former soils shrink by dehydration and the development of drying cracks that contribute to deep drainage, aeration and plant root penetration can be expected. The latter soils in contrast display a non-plastic behavior, and shrinkage and swelling associated with the changes of soil water content do not occur.

Improvement of the dense and compacted layers has been carried out biologically and mechanically. Creation of biopores by plants that are able to penetrate dense and compacted soils may enhance the drainage ability and contribute to the root development of the succeeding crops, resulting in a higher crop yield. Cresswell and Kirkegaard (1995) reviewed the effect of plant roots on the subsoil structure and benefits to

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subsequent crops. However, the beneficial effect could not be confirmed due to the lack of quantitative information.

Mechanical disruption of the dense and compacted layers either by deep tillage or subsoiling has been carried out in many countries. Unger (1979) investigated various areas in the United States and Canada where deep tillage and profile modification had been implemented and summarized the observations as follows. 1) When the horizons causing problems were adequately disrupted or altered, yields of crops generally increased. 2) Benefits from the treatments were greater when precipitation or irrigation was limited than when the two were adequate. 3) In many soils, no benefits could be expected from deep tillage and profile modification.

When dense and compacted layers are thick, a large amount of investment is necessary to implement the profile modification and most of the farmers are not able to conduct such operations by themselves. However, farmers can destroy the plow pan formed at 20 to 40cm depth from the soil surface by using a tractor equipped with a subsoiler. Subsoiling was often introduced to enhance subsurface drainage of wetland rice fields where drainpipes had been installed. This is effective especially for clayey soils to dry and strengthen the surface soil for the use of a harvesting machine. Subsoiling for dryland crops grown in fields converted from a wetland rice field was also effective to increase the rooting volume and alleviate drought damage in Japan (Hasegawa, 1992). Coarse-textured dense soils derived from pyroclastic flow sediments become hard when dry and muddy when wet, and subsoiling itself is not effective due to the rather rapid recementation. Subsoiling by mixing wood tips (bark compost) has been found to be effective for the aeration and drainage ability of such soils, and field operations by a tractor could begin earlier after a rain event and the yield of wheat increased by 30% after the implementation (Yokoi *et al.*, 1995).

Subsoiling is thus not fully effective and requires more power than conventional tillage. Subsoiling including timing and persistence must be carefully considered before implementation.

In this paper, the role of the disruption of dense and compacted layers was discussed from the viewpoints of root development and water movement. Plow pan disruption by subsoiling and the introduction of deep-rooted crops for water harvesting on sandy soils in Northeast Thailand were also introduced.

Root growth and soil physical conditions

Table 1 Some physical properties of plowed layer and plow pan

Origin	Alluvial clay soil[1]		Pyroclastic sediment[2]		Undulating plateau[3]	
Site	Tsukuba, Ibaraki		Biei, Hokkaido		Khon Kaen, Thailand	
	Plow layer	Plow pan	Plow Layer	Plow pan	Plow Layer	Plow pan
Soil texture	HC	HC	CL	CL	S	S
BD (Mg/m^3)	1.15	1.46	1.34	1.52	1.54	1.63
RAW (%)	12	3	16	7	15	9
TAW (%)			18	13	19	13
K_s (cm/s)	$0.6\text{-}2.0 \times 10^{-3}$	$0.6\text{-}1.0 \times 10^{-6}$	3×10^{-6}	6×10^{-8}		

BD: Dry bulk density
RAW: Readily available water (-6(-3) to -100 (-50) kPa)
TAW: Total available water (-6 kPa to -1.5 MPa)
K_s : Saturated hydraulic conductivity
[1] Inoue (1992), [2] Kitagawa *et al.* (2001), [3] Miura *et al.* (1992)

Table 1 shows some of the physical properties of the plow pan and plow layer. Dry bulk density of coarse soils in the plow pan was very high resulting in higher mechanical impedance, less available water to plants and lower hydraulic conductivity compared to the plow layer.

Plant roots develop under conditions of sufficient soil water, adequate soil aeration and low soil mechanical impedance. A large number of studies has shown that the root elongation rate decreases with the increase of the soil mechanical impedance which depends on the soil bulk density. Plow pan restricts root penetration and results in the formation of a shallow root system of the crops. Due to the limitation in the available soil water in the plow layer, the crops are susceptible to drought under erratic rainfall. Mechanical impedance of the soil decreases with the increase of the soil water content, but root respiration is hindered by a high degree of water saturation. Eavis (1972) showed that there were optimum soil water conditions for root elongation for certain values of the soil bulk density. Figure 1 shows the effects of the soil water potential, relative gas diffusivity and mechanical impedance of a soil on the top and root development of maize plants grown in a pot (Osozawa, 1994). The top weight and the root growth were influenced significantly by poor aeration. Upland crops cannot develop roots in saturated soil or below a groundwater table unlike aquatic plants such as rice. Lety (1985) introduced the concept of non-limiting water range (NLWR) for root growth as shown in Fig. 2. In NLWR, roots develop without restriction of water, aeration and soil mechanical impedance. The range of NLWR becomes narrower with increasing soil bulk density and

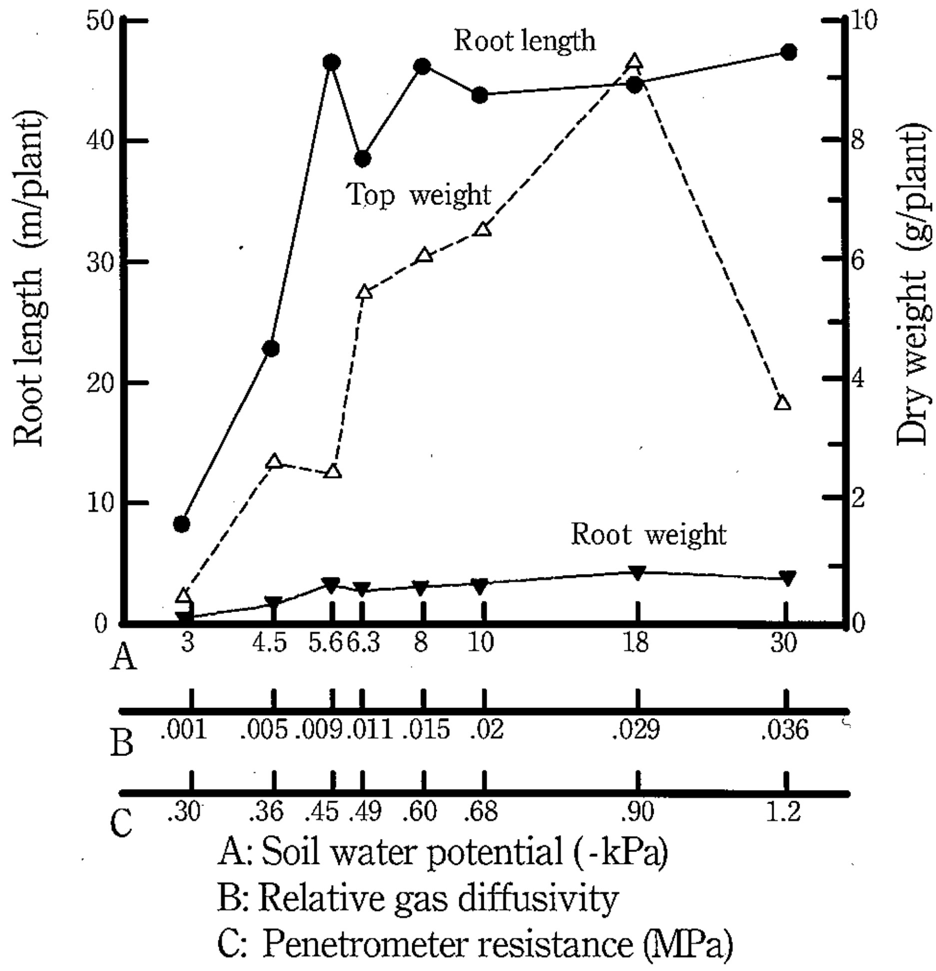

Fig. 1 Effect of soil water potential, relative gas diffusivity and penetrometer resistance of a soil on maize root growth (after Osozawa, 1994).

deterioration of the soil structure. Under field conditions, mechanical impedance of the soil changes with the soil water content, which enables the crops to develop roots under adequate soil water conditions. Therefore, the soil water conditions at the time of germination to young stages are critically important for crop development.

Plant roots are often observed in macropores such as fissures, drying cracks and tubular pores created by previous decayed roots. Roots elongate in these macropores with the absence of mechanical impedance and proliferate due to sufficient air supply. Hasegawa and Sato (1987) measured the root length of soybean developed on the subsoil cracks of a clayey soil, and they estimated that these roots extracted one-third of the amount of daily transpiration. As roots in macropores are not in contact with the soil surface completely, water and nutrient absorption by these roots has not been evaluated thoroughly. Cresswell and Kirkegaard (1995) concluded that the benefit of biopores for succeeding crops was not evident because the introduction of deep-rooted crops for crop rotation in some cases reduced crop diseases and improved soil nutrients by nitrogen fixation.

Soil water movement

In homogeneous soils, water moves through pores in the soil matrix. This phenomenon is referred to as "matrix flow" and it follows Darcy's law. In structured soils with macropores such as drying cracks and tubular pores formed by decayed roots, water bypasses the pores in the soil matrix but moves preferentially through macropores. This phenomenon is referred to as "bypass flow". Natural soils more or less have macropores and bypass flow may occur near saturation or under ponding water. Well-drained conditions are attained by deep percolation exceeding 10 mm d^{-1}, which is equivalent to a hydraulic conductivity of the order of 10^{-5} cm d^{-1}. As the plow pan formed by compaction or by smearing of wet soil has lost macropores and exhibits finer pores in the soil matrix, hydraulic conductivity is usually lower than 10^{-6} cm s^{-1} (Table 1).

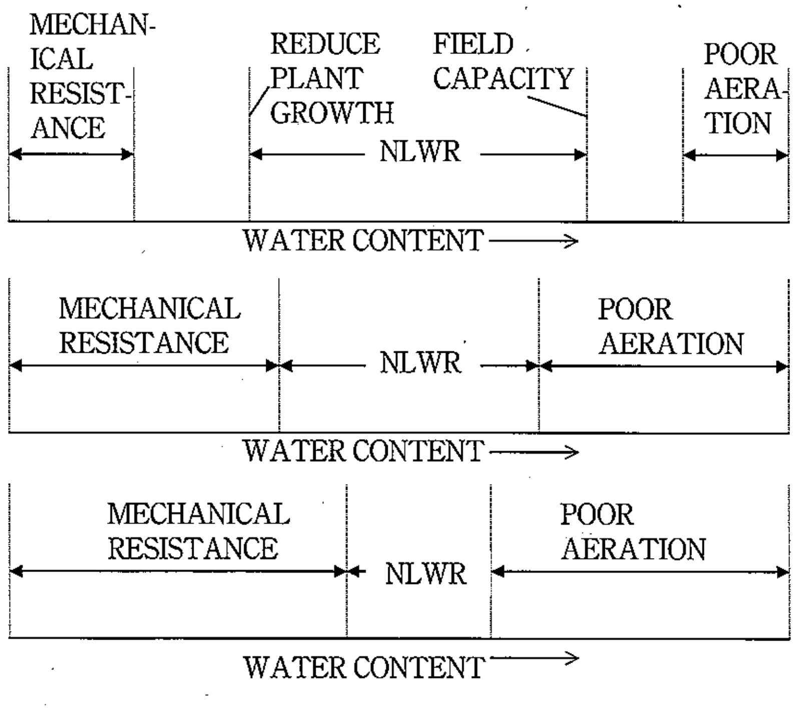

Fig. 2 Generalized relationships between soil water content and restricting factors for plant growth in soils with increasing bulk density and decreasing structure from A to C (after Lety, 1985).

Percolation through the plow pan, therefore, is far below the above value and results in ill-drained conditions. Therefore, the formation of macropores is necessary to promote deep drainage to the subsoil.

On the contrary, upward soil water movement caused by soil evaporation occurs exclusively through the pores in the soil matrix and macropores do not contribute to the water movement. As saturated as well as unsaturated hydraulic conductivity of the plow pan is too low to supply a sufficient amount of water to meet the evaporative demand, the surface soil dries up rapidly while the subsoil remains wet. Gardner (1958) analyzed the matric potential at the soil surface when a steady state upward water movement occurred from a water table at a given depth. When the groundwater table was located at only 10 cm below the soil surface and the evaporative demand was 3 mm d^{-1}, the matric potential at the soil surface reached a value of around -100 kPa, if the hydraulic conductivity at a matric potential of -30cm was of the order of 10^{-7} cm s^{-1}. Such surface dry conditions were also observed for sandy soils in which the hydraulic conductivity decreased remarkably with the decrease of the matric potential. If the crop roots are not able to penetrate into the subsoil, crops wilt and abundant available soil water remains in the subsoil in such soils. Rapid drying of the surface soil also impairs the emergence of the crops. Introduction of deep-rooted crops that are able to penetrate into a plow pan is one option to alleviate drought damage through the extraction of the available soil water contained in the subsoil.

Plow pan disruption

Deep tillage or subsoiling is implemented to disrupt dense and compacted layers or the plow pan. The objective of the disruption is to create macropores artificially for the improvement of deep drainage or the expansion of root systems, but the disruption itself does not increase the amount of storage pores or available soil water for the plants. Deep tillage which disrupts thoroughly the plow pan must be more effective to ameliorate the physical properties of the soil and may remain effective for a longer period than subsoiling, but deep tillage requires more power and cost to disrupt the pan, and subsoiling, which requires less draft power, is practiced by small farmers. Subsoiling applied by small farmers destroys soil layers to depths of 30 to 40 cm and is not effective if the deteriorated soils are located at a deeper depth.

Subsoiling for deep drainage has been carried out in wetland rice fields with a permeable subsoil or a drainpipe for subsurface drainage. Wetland rice cultivation destroys the soil structure of the surface soil by puddling. Sedimentation of fine soil particles dispersed by the puddling below the puddled layer as well as repeated runs of agricultural machines generate a plow pan with a lower hydraulic conductivity. As the surface of paddy fields is level, residual ponding water remains on the surface. Subsoiling, therefore, enables to carry the residual ponding water to the envelope of a drainpipe through man-made fissures within one or two days. This method was often applied when upland crops were introduced to previously puddled rice fields. Clayey soils become more brittle with decreasing water content. Shattering by subsoiling is more effective under dry conditions with a spacing of 2 to 3 m. Promotion of subsurface drainage usually accompanies the development of drying cracks to a deeper depth in clayey soils. Thus, acceleration of the drainage can expand the root systems through the cracks and may alleviate drought damage of upland crops. Above subsoiling method corresponds to a partial disruption of the pan and is applied by many farmers because rice transplanting after upland use can be performed satisfactorily by the support of undestroyed parts of the plow pan. In-row subsoiling which enables crops to elongate roots at deeper soil depths without restricting the mechanical impedance is also implemented to expand the soil volume for water extraction. This method aims at the improvement of drainage and drought damage at the same time.

Upland soil in the Kamikawa district in Hokkaido is a coarse soil derived from pyroclastic flow sediments. This soil is characterized by a high dry bulk density (1.34 to 1.52 Mg m^{-3}), low amount of available soil water and contains 40 to 54% of sand fraction. The soil is muddy under saturation and too rigid to be tilled and pulverized when it is dried. Subsoiling was not effective in ameliorating the soil physical conditions due to easy recementation. Subsoil improvement of this soil has been carried out by removing the surface soil by plowing and crushing of the subsoil to depths of 20 to 30 cm using a tine and

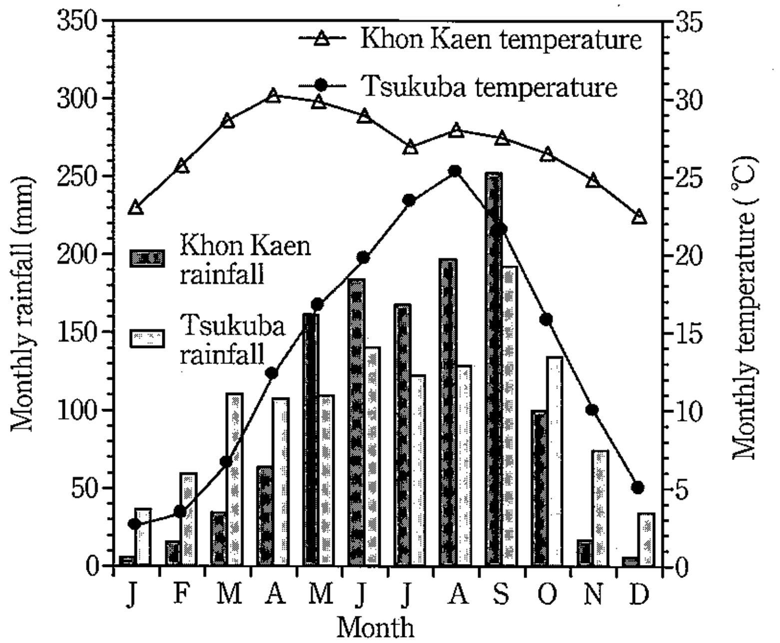

Fig. 3 Monthly rainfall and temperature at Khon Kaen and Tsukuba.

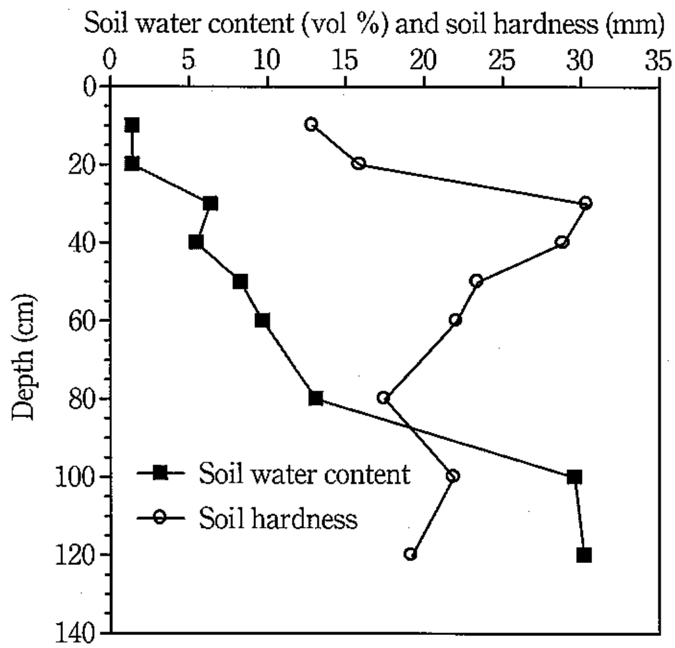

Fig. 4 Changes in soil water content and soil hardness with depth in a soil in Northeast Thailand.
Soil hardness was measured with Yamanaka's penetrometer, 20 mm=0.6 MPa, 30 mm=3.7 MPa (after Ishikawa *et al.*, 1999).

then the pulverized clods were mixed with wood tips as soil amendment before returning the surface soil (Kitagawa *et al.*, 2001). As this profile modification requires special machines and more than 100 t ha^{-1} wood tips for the amelioration, it may not be applied in other areas without subsidies from the local government. However, this method suggests that the incorporation of organic materials is important to ameliorate the physical properties of such soils.

Sandy soils cover large areas in Northeast Thailand. Clay content of these soils is less than 10% but farmland shows ill-drained conditions in the wet season. Annual rainfall is around 1,200 mm, a value comparable to the annual precipitation at Tsukuba of around 1,250 mm (Fig. 3). However, during about half a year from October to April, the dry season occurs with a high evaporative demand due to the low humidity and high temperature. Only a few crops such as sugarcane and cassava are cultivated in the dry season and annual crops can not survive in this season. In the dry season, the soil forms a strong pan below 30 cm depth, while soil layers deeper than 100 cm contain available soil water (Ishikawa *et al.*, 1999, Fig. 4). In contrast, crops experience excess water injury in the wet season due to poor drainage. One of the subjects of JIRCAS research project in Northeast Thailand is focused on the exploitation of soil water contained in deep soil layers by crops.

At the beginning of the wet season in May, subsoiling with 100 cm spacing was implemented to destroy the shallow pan for maize cropping. The results showed that subsoiling decreased water erosion during the wet season and the soil water content in deeper layers was higher than in the conventional method. Furthermore, in-row subsoiling was considered to be a promising measure for crop water use.

Introduction of crops that can penetrate into deep hard soil layers is another option to exploit soil water in deeper soil layers. Erianthus and napier grass were planted at the beginning of the wet season. Soil matric potential at 1 m depth under Erianthus cultivation was lower than that under fallow conditions during the dry season, suggesting that deep-rooted crops were able to extract water in deep layers that otherwise would not be used in conventional cropping systems. However, the effect of biopore formation by deep- rooted plants on subsequent crop growth has not been elucidated.

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