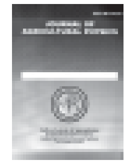
Vol. 9, pp. 1-8 (2009)
Journal of Agricultural Physics
http://www.agrophysics.in



Management Options for Improving Soil Physical Environment for Sustainable Agricultural Production: A Brief Review

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ABSTRACT

Sustaining the productivity at higher level to meet the increasing demands of food and fiber for the growing population from the limited land and water resources is the key issue in Indian agriculture. Unless the soil physical environment is maintained at its optimum level, the genetic yield potential of a crop cannot be realized even when all the other requirements are fulfilled. In this paper an attempt has been made to review how different technologies like optimal uses of manures and fertilizers, tillage practices and mulching can favourably modify the soil physical parameters like bulk density, porosity, aeration, soil moisture, temperature, soil aggregation, water retention properties and water transmission properties and soil processes like evaporation, infiltration, runoff and soil loss for better crop growth and yield. The improvement of soil health through these eco-friendly site specific technologies will lead to efficient use of inputs and help in sustaining agricultural production at higher level.

Key words: Sustainable agriculture, Soil physical environment, Manure, Fertilizer, Tillage, Mulching

Sustainable agriculture aims at meeting the needs of present generation without endangering the resource base for posterity. Unfortunately unsustainable productivity, yield decline, environmental pollution, decreasing soil organic matter storage, decreasing factor productivity under high intensity agriculture in the post green revolution era has been a matter of great concern today. Sustaining the productivity at higher level is therefore the key issue in Indian agriculture to meet the increasing demands of food and fiber for the growing population. Maintaining soil health/ quality is indispensable for sustaining the agricultural productivity at higher level. Soil quality is defined as the capacity of soil to function within ecosystem and land use boundaries, to sustain biological productivity, maintain the environmental quality and promote plant, animal and human health (Doran and Parkin, 1994). Soil quality includes three groups of mutually interactive attributes i.e. soil physical, chemical and biological quality, which must be restored at its optimum to sustain productivity at higher levels in the long run. It is high time to appreciate the fact that unless the soil physical environment is maintained at its optimum level, the genetic yield potential of a crop cannot be realized even when all the other requirements are fulfilled.

The nature and extent of physical constraints are however, not static. Mechanization of farm operations, frequent tillage in intensive cropping systems, unscientific and indiscriminate use of inputs and decline in soil organic matter etc. are adding new problems to the existing area. The current scenario calls for appreciating the fact that once degraded, it is difficult, if not impossible to restore the soil to its good physical condition. Persistent efforts are therefore warranted to

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arrest further aggravation of soil degradation, to alleviate soil physical constraints and also to understand the respective causal processes for the sake of holistic, safe and resilient agricultural production system. Therefore, our sincere efforts must be to improve and maintain soil physical environment at its optimum condition with minimal risks to environment.

Management Options for Improving Soil Physical Environment

It is estimated that out of the 328 m ha of the total geographical area in India, 173.65 m ha are degraded, producing less than 20% of its potential capacity (GOI, 1990) and out of this 89.52 m ha suffers from one or the other form of physical constraints viz., shallow depth, soil hardening, slow and high permeability, sub-surface compacted layer, surface crusting, temporary water logging etc. (Painuli and Yadav, 1998).

Soil physical environment can be improved by following site specific technologies for optimal use of manures, crop residues, fertilizers, water, tillage practices and following appropriate cropping systems.

Improving Soil Physical Environment through Optimal Use of Manures and Fertilizers

Application of organic manures viz., compost, farmyard manure and green manure improve soil physical properties through improvement of soil organic matter. The increased plant biomass produced by fertilizer, results in increased return of organic material to soil in the form of decaying roots, litter and crop residues. Thus mineral fertilizers indirectly influence soil organic matter content by increasing crop productivity and thereby increasing the amount of organic matter returned to soil in various crop residues. The effect of mineral fertilizers may therefore be compared to that of straw incorporation (Hati and Bandyopadhyay, 2010). Increasing soil organic matter content characteristically leads to a decrease in bulk density, and surface crusting and an increase in water holding capacity, macroporosity, infiltration capacity, hydraulic conductivity and aggregation. These aspects are discussed below:

***a. Structure and aggregation*:** Soil aggregation is the process by which aggregates of different sizes are joined and held together by different organic and inorganic binding agents. In surface soils, organic matter is the main binding agent responsible for the water stability of soil aggregates with the formation of clay humus complex. The aggregate stability is positively correlated with the soil organic carbon content (Hati *et al*., 2007). So it is expected that addition of materials rich in organic carbon such as manure or sludge leads to an improvement of the aggregation status of soil (Bandyopadhyay et al., 2010). Long-term fertilizer studies have shown that application of fertilizers to soil induces an increase in number and size of water stable aggregates.

Addition of inorganic fertilizers can have physico-chemical effects on soils which influence soil particle aggregation. Phosphatic fertilizers and phosphoric acid can also favour aggregation with the formation of Al or Ca phosphate binding agents. Where fertilizer NH_4^+ accumulates in the soil in high concentrations, it behaves like Na^+ and causes dispersion of clay colloids.

***b. Bulk density and porosity*:** Long term application of organic manures normally reduces the bulk density of the soil due to higher organic matter content of the soil, better aggregation and a consequent increase in volume of pores, soil aeration and increased root growth. Furthermore, addition of large quantity of organic manure or wastes reduces the bulk density of the soil due to a dilution effect caused by mixing of the added organic material with the denser mineral fraction of the soil (Khaleel *et al*., 1981). The organic matter content and bulk density of a soil amended with inorganic fertilizer and farmyard manure normally shows a negative linear relationship (Hati *et al*., 2007; Bandyopadhyay *et al*., 2010). Addition of organic manure leads to an increase in total pore volume of the soil, besides changes in pore size distribution with fertilization. Organic matter addition through sludge and compost increases the percentage of transmission (50-500 µm) and storage (0.5-50 µm) pores while reduces the percentages of fissure (>500 µm) (Metzer and Yaron, 1987).

***c. Water retention properties*:** Water retention by soils is known to be controlled primarily by: (i) the number of pores and pore-size distribution of soils; and (ii) the specific surface area of soils. Because of increased aggregation with application of organic manures, total pore space is increased. Furthermore, as a result of decreased bulk density, the pore-size distribution is altered and the relative number of small pores increases, especially for coarse textured soils. Organic manure application improves water retention properties of soil through its effect on pore size distribution and soil structure and increases soil-water retention more at lower suctions due to increase in micro-pores and inter-aggregate pores caused by enhanced soil organic matter content and higher activity of soil fauna e.g. earthworms and termites. At higher tensions close to the wilting point (1.5 MPa) nearly all pores are filled with air and the surface area and the thickness of water films on soil particle surfaces determine moisture retention. Following the addition of organic matter, specific surface area increases resulting in increased water holding capacity at higher tensions.

***d. Water transmission properties*:** Application of organic manure also indirectly influences the water transmission properties of the soil through aggregation and porosity. As good structural conditions are usually associated with adequate water transmission properties, it can be inferred as a thumb rule that organic manure will generally also improve the water transmission properties.

i. **Hydraulic conductivity:** Addition of organic manure and mineral fertilizer results better aggregation, increase in effective pore volume and an increase in continuity of pores due to enhanced root growth and formation of biopores, increased faunal activity and earthworm population and burrows. As soil permeability is a function of effective pore volume, increased pore volume has a direct influence on the saturated hydraulic conductivity of the soil (Hati et al., 2006). Combined application of organic and inorganic fertilizers to soil increased the hydraulic conductivity of a Vertisol under soybean-wheat system (Bandyopadhyay et al., 2010).

ii. **Infiltration:** Infiltration through the soil surface depends on soil surface features and the hydraulic conductivity in the underlying soil mass. The application of organic manures generally improves the initial and steady state infiltration rate due to increase in water stability of soil aggregates, reduction in crust formation and consequent increase in hydraulic conductivity (Acharya et al., 1988).

Improving Soil Physical Environment through Optimal Use of Tillage Practices

Tillage practices change the initial state of soil to a new state, with changes in the physical, chemical and biological environment of soil. These in turn, influence crop growth and yield and thereby, the input use efficiency of crops. Tillage either loosens or compacts the soil and changes its volume and mass relationship. One property of soil that is likely to get changed by tillage is bulk density of soil (Cassel, 1982). A decrease in bulk density increases the total porosity and the proportion of macropores. The changes in total porosity, pore size distribution and particle-to-particle contact affect all (physical) state variables of soil, which in turn, induce behavioural changes in soil properties and processes, modifying the edaphic environment. Thus, all physical parameters affecting seedling emergence and root growth, i.e. soil wetness, aeration, temperature and penetration resistance are affected by the tillage (Gajri et al., 1997).

a. Bulk density, porosity, aggregation and mechanical impedances: Loosening of soil decreases and its compaction increases the bulk density. The deep tillage in a sandy soil decreased the bulk density of tilled zone than what is achieved by conventional tillage (Gajri et al., 1997). No tillage generally increases the bulk density of soil in the surface layer. Unger and Jones (1998) reported that bulk density and soil strength increased in the 0-100 mm layer of Pullman clay loam after 12 years of imposition of no tillage compared with stubble mulch. Abid and Lal (2008) reported a significant decrease in the bulk density and increase in the total porosity under no till than in conventional tillage.

Tillage increases macro-porosity whereas compaction increases micro-porosity of the soil. It has been reported that there was significant increase in the proportion of noncapillary pores under mouldboard plough and disc harrow compared to no tillage in a lateritic sandy loam soil. In contrast to conventional tillage, conservation tillage system results in more continuous pore system because of increase in earthworm activity, old root channels and vertical cracks between peds. Ekeberg and Riley (1997) reported significantly greater macro pores (>30 μm) in the top 30-70 mm soil layer after 10-year imposition of minimum tillage.

Conventional tillage significantly reduces macro-aggregates with a significant redistribution of aggregates into micro-aggregates. Thus conventional tillage leads to the formation of carbon depleted micro-aggregates at the cost of carbon rich macro-aggregates. Increased macro-aggregate turnover under conventional tillage is the primary mechanism for loss of soil organic carbon (Six et al. 1998, 1999). Increase in water stable aggregates and mean weight diameter of water stable aggregates under no till than conventional tillage has been reported by Abid and Lal (2008).

Conservation tillage usually increases the soil strength in the surface layers. Loosening of soil by tillage also decreases cohesiveness and particle-to-particle contact and hence reduces soil strength in the tilled layer.

b. Soil wetness: Tillage affects the soil water status and the capacity of plants to utilize it. It alters surface and subsurface soil conditions that govern infiltration, runoff and evaporation of water, weed growth, root proliferation and crop establishment. Shallow tillage at tillable wetness after rain/irrigation reduces evaporation loss from the soil. Tillage not only helps conserve moisture in the profile but also in carrying over the moisture in the seed zone (Acharya et al., 1998). Conservation tillage helps in conserving soil moisture. Decrease in bulk density increases the amount of water held at higher water potentials and decreases it at low water potentials, which in turn, influence its availability. On the other hand, water retention of a highly permeable sandy soil at field capacity can be increased by compaction.

c. Soil aeration: Tillage increases the proportion of macro-pores in a tilled layer, which can drain out water rapidly after heavy rains or irrigation and is able to restore adequate porosity free from water. A decrease in the volume-water fraction increases the volume of water free pores, enhancing soil aeration. Tillage is likely to also affect the oxygen diffusion rate (ODR). Ball (1981) reported that the gas diffusion in untilled soil is 2-6 times less than in tilled soil.

d. Soil temperature*:* The changes in surface roughness and plant residue cover, affected by tillage influence the thermal regimes of a soil. A change in bulk density alters the specific heat capacity of a soil, primarily by changing the relative amount of water and mineral matter per volume of soil (Wierenga et al., 1969). Compaction increases thermal conductivity of soil because of decreased porosity and increased contact between the particles. Conservation tillage system, that leaves residue on the soil surface, lowers the soil temperature. Lal (1976) reported that no tillage that left substantial residue on the surface reduced the maximum soil temperature at 5 cm depth by 11^{o}C and 9^{o}C in two weeks old maize and soybean, respectively in Nigeria.

Improving Soil Physical Environment through Optimal Use of Mulching Practices

Mulch means a layer of dissimilar material separating the soil surface from the atmosphere and mulching is the artificial application of mulch, practiced to obtain beneficial changes in soil physical environment. Mulching improves physical conditions, chemical environment and biological activities of soil. Favorable modification of the soil hydrothermal regime, improvement of soil aggregation and retardation of erosion and soil loss, improve the physical condition of soil under mulch.

a. Soil moisture regime: Mulching favorably influences the soil moisture regime by controlling evaporation from soil surface, improving infiltration and soil moisture retention and facilitating condensation of water at night due to temperature reversals (Acharya *et al.*, 2005).

(i) **Controlling evaporation from soil surface:** Direct evaporation of water from soil surface is an important process, particularly in case of bare soils or in areas where summer fallow is practiced. Mulching reduces evaporation from soil surface by retarding the intensity of the radiation and wind velocity on mulched surface. It is effective in retarding the evaporation mainly during the initial energy limited stage of drying. However, mulching is not very effective in controlling evaporation during the falling rate or supply controlled stage of evaporation. During this stage, the soil surface dries under the mulch and the vapor transfer of water to the atmosphere is inhibited more by the dry soil than by the overlying vegetative mulch. Higher mulch rate retards the energy reaching the soil surface and hence limits the evaporation at the constant rate stage. The retardation of initial evaporation can also enhance the process of internal drainage and thus allows more water to migrate downward into the deeper layers of the soil profile, where it is conserved longer and is less likely to be lost by evaporation.

Mulching also affects the pattern of evaporation by offering resistance to water vapor flow from the soil surface to atmosphere and by increasing the thickness of relatively non-turbulent air zone above the soil, thus changing the boundary layer conditions of the soil-air interface. Relative magnitude of evaporation reduction for different mulch rates is much greater under high evaporative demand. The magnitude of maximum reduction in evaporation and the time when reached depends on the rate of mulching, soil type, magnitude of evaporative demand and the method of residue application. The orientation of the residue i.e. flat or matted versus standing affects the porosity and thickness of the layer and thus the rate of evaporation from the soil surface. As the amount of standing residue increases, greater wind speed is needed to initiate water loss through evaporation, in addition the water loss rate at a given wind speed decreases with increased amounts of standing residue. Residue position also affects soil temperature, which in turn affects the evaporation rate through its influence on vapor pressure of the soil water.

Water saving under mulching is prominent if rains are frequent. However, under extended length of dry spell mulch may keep the soil surface moist for longer period and prolong the first stage of evaporation without net saving of water.

(ii) **Improving infiltration rate:** Mulching with organic materials improves the infiltration rate because it serves as a barrier for runoff, which allows more opportunity time for water to infiltrate into the profile. Secondly, mulch intercepts the rainwater and protects the soil from erosion under the impacts of rain drops. It prevents the crust formation due to clogging of soil pores, which increases infiltration rate. Furthermore, organic mulches improve the macro porosity and stability of the structural aggregates of soil and thereby improve the water transmission properties, which facilitate better infiltration and recharge of the soil profile (Lal, 1987). Straw mulch application increases soil water storage and storage efficiency. The amount of water storage in the soil profile, the storage efficiency, total water use and water use efficiencies of dryland crops increase with increase in the mulch rate (Unger, 1990). The increase in infiltration that results from mulch is found to be more important in some situations than its effect on reduction in evaporation for conservation of water in the profile.

(iii) **Soil moisture retention:** Mulching improves moisture retention properties of soil through its effect on pore size distribution and soil structure. Higher mulch rate increases soil-water retention more at lower suctions (Lal, 1987) due to increase in macro-pores and inter-aggregate pores caused by enhanced soil organic matter content and higher activity of soil fauna e.g. earthworms and termites in mulched plots.

(iv) **Water condensation at night:** Stone and gravel mulches induce lateral movement of heat and vapour, which could in turn collect water under the stones due to condensation of vapor at night, in amounts sufficient enough to serve as the source of water for some species of desert plants and soil fauna.

b. Controlling runoff and soil erosion: Mulching invariably decreases soil erosion and often reduces runoff rate and its amount. Mulch cover protects the soil from raindrop impact and surface sealing, increases the infiltration rate and decreases run-off velocity through physical resistance to water flow. In general, loss in water through runoff decreases exponentially with increase in mulch rate (Erenstein, 2002).

For some type of soils mulch does not substantially decrease runoff but drastically reduces soil erosion. The runoff water gets filtered through the mulch and is often clear with little sediment. Mulching decreases sediment concentration in runoff water through the protective effect of crop residues against raindrop. Experimental evidence shows that adequate quantity of crop residue mulch can mitigate the effect of the degree of slope in reducing runoff and soil loss.

Mulching is also effective in reducing soil erosion by wind by reducing the wind velocity on soil surface when the mulch is fixed to soil so that it does not get blown up by the wind. Standing crop residues serve as barriers to wind and are more effective than flattened surface mulches in reducing wind erosion. The effectiveness of standing crop residues depends upon the plant density of the crop harvested and their size above the ground.

c. Modification of soil thermal regime: Mulch has a moderating influence on the soil thermal regime and the effect varies among the soils, climate, kind of mulch materials used and rate of application. It increases soil temperature during cooler weather and decreases it during hot spells. In general, mulch has a damping effect on the amplitude of the diurnal fluctuations in soil temperature. Organic mulching enhances the soil temperature at night and early morning hours but it decreases the daytime temperature as compared to unmulched plots.

Transparent polythene mulch raises the maximum soil temperature whereas organic mulches like pine needle and grass mulches lower it. Black polythene mulch, however, does not alter the maximum soil temperature appreciably. The application of straw mulch can lower maximum soil temperature due to interception of the incoming solar radiation, high reflectivity and low heat conductivity, the magnitude of which depends upon soil wetness, incidental radiation, rate of mulch application as well as period of the year (Prihar, 1986). The lowering of maximum soil temperature by straw mulching during early stage of growth of sugarcane can significantly improve the yield.

d. Soil aeration: Crop residue mulch improves soil aeration by promoting free exchange of gases between the soil and the atmosphere. This is facilitated by improvement of structural stability, total porosity and macroporosity, decrease of surface crusting and by improving the overall soil drainage. Oxygen diffusion rate is higher under mulch than under unmulched condition. The gaseous composition of soil air under mulch depends on the nature of the mulch material (C:N ratio), its rate of decomposition, the soil moisture regime and the climatic condition. Plastic mulch is practically impervious to carbon dioxide (CO_2), a gas that is of prime importance for photosynthesis. Very high levels of CO_2 build up takes place under the plastic, as the film does not allow it to escape. It has to come through the holes made in the plastic for the plants and a "chimney effect" is created, resulting in localized concentrations of abundant CO_2 for the actively growing leaves that accelerate the growth of the crop.

e. Soil structural improvement: Mulching improves soil structural properties directly and indirectly by promoting the biological activity. Organic mulching improves the total porosity, macro porosity and mean weight diameter of water stable aggregates, because of addition of organic matter upon decomposition by soil microorganisms. The mean weight diameter of water stable aggregates increases with increase in the mulch rate (Lal, 1987).

In general, under mulched condition, bulk density of the soil is lower than that under unmulched condition. Bulk density decreases with increase in residue mulch rate. One of the reasons for decrease in bulk density with increase in mulch rates is high earthworm activity in mulched plots.

Conclusions

Thus these eco-friendly site specific technologies viz., efficient use of organic manures and fertilizers, optimum tillage practices and mulching can improve the soil physical environment, which in turn will lead to efficient use of inputs and help in sustaining agricultural production at higher level.

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