Role of soil physical properties in soil health management and crop productivity in rainfed systems–II. Management technologies and crop productivity

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In this article we review how different management technologies like integrated nutrient management, tillage practices, mulching, addition of clay, surface compaction, conservation tillage, use of polymers, etc. can favourably modify the soil physical properties like bulk density, porosity, aeration, soil moisture, soil aggregation, water retention and transmission properties, and soil processes like evaporation, infiltration, run-off and soil loss for better crop growth and yield. We suggest that if appropriate soil management technologies are adopted in rainfed areas for the improvement of soil physical health, the productivity of rainfed crops can be significantly improved.

Keywords: Crop productivity, management technologies, rainfed agriculture, soil physical properties.

KNOWLEDGE of the physical properties of soil is essential for defining and/or improving soil health to achieve optimal productivity for each soil/climatic condition. The physical characterization of soil in the field depends strongly on its spatial and temporal variability. If large agricultural fields are to be described successfully from the physical point of view, better ways of handling this variability have to be found. There is a strong growing realization that yields are limited by the physical conditions rather than plant nutrient status in the soil. Among many climatic and edaphic crop production constraints, substantial reduction in the production capacity of rainfed areas could be attributed to soil physical constraints like surface crusting and hardening, subsurface hard pan and compactness, high permeability, slow permeability and extremes of consistence, soil water-related constraints, wind and water erosion, etc. This envisages that for increasing crop production, soil must be maintained in such a physical condition so as to allow adequate crop growth. 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. No doubt, if these soils are managed properly for good physical health, the yield potential of different crops can be increased significantly. However, the soil physical management technologies are location-specific and the benefits from their adoption are highly variable depending on the rainfall intensity, slope and texture of the soil besides the prevailing crop/cropping system. We summarize the impact of management technologies for alleviating the soil physical constraints for the enhancement of crop yield in rainfed regions of India.

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Management technologies for rainfed soils

Management technologies for soil crust formation constraint

In rainfed soils, particularly in Alfisols, Entisols and Aridisols soils, crust formation at the soil surface by the beating action of rain results in poor germination of crops, reduced infiltration and enhanced rainfall run-off. Misra[1] reported poor seedling emergence, decreased shoot and root growth of pearl millet seedlings and increased seedling under crust with the crust strength of 4.6 g cm^{-2} in rainfed pearl millet. To overcome the problem of crusting several researchers reported that mechanical breaking of crust by hoeing and continuous incorporation of stubble or crop residues to the land helped in minimizing crust formation in these soils. Phogat and Dahiya[2] reported that application of farmyard manure (FYM) on seed lines as mulch increased the seedling emergence over the crusted soil by three- and tenfold in pearl millet and cotton respectively (Table 1). Upon mulching, the yield of pearl millet increased from 2.63 to 3.42 t ha^{-1}, whereas in cotton the increase was from 0.35 to 1.49 t ha^{-1}. Thus, FYM seed line mulch reduces the impact of rain drops and prevents the formation of the crust, improves seedling emergence and yield of crops. Similarly, Oswal[3] showed that emergence of pearl millet significantly improved by 33% and 30% with seed line application of FYM @ 1 t ha^{-1} and broadcast of

Table 1. Effect of farmyard manure seed line mulch on seedling emergence and yield of pearl millet and cotton on sandy loam and loamy sand soils[2]

Treatment	Seedling emergence (%)		Grain yield (t ha^{-1})	
	Pearl millet	Cotton	Pearl millet	Cotton
Crusted	16.4	03.6	2.63	0.35
Uncrusted	48.2	35.5	3.26	1.47
Seedline mulch	43.1	20.2	3.42	1.49
CD at 5%	6.6	7.6	0.40	0.33

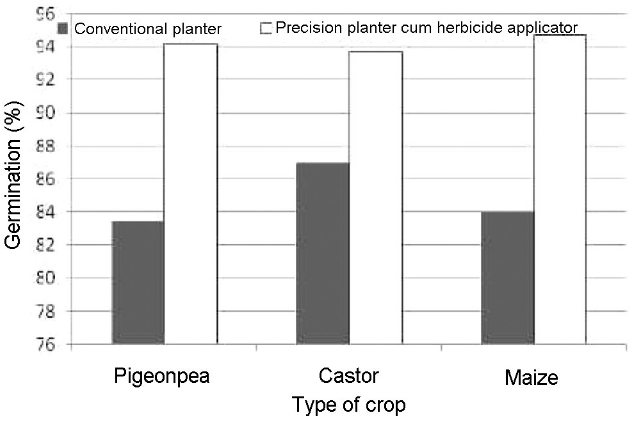

Figure 1. Germination of different crops with conventional and precision planter in undulating lands[5].

FYM @ 2 t ha^{-1} before sowing respectively, over the control. He also reported that application of FYM @ 4 t ha^{-1} or 2 t ha^{-1} wheat straw increased the emergence of cotton by 4–10 times, while that of pearl millet by 2–3 times. Rapid and irreversible hardening of red chalka soils upon drying is a major constraint in the production of rainfed crops. Addition of slow decomposing residues like paddy husk, coir pith, etc. fallowed by appropriate tillage has proved useful. In these soils, addition of paddy husk @ 5 t ha^{-1} increased the yield of sorghum and castor by 18% and 23% respectively, in the farmer's field over control[4]. Also, application on seed line as mulch of organics such as wheat busha, rice husk and FYM @ 2–3 t ha^{-1} was most effective in reducing the crust strength and increasing the crop yield. At Hisar, the increase in yield of pearl millet, cotton, sorghum and maize was 49%, 75%, 85% and 62% respectively. The slow decomposing amendments have proved useful for these soils. The efficiency of various amendments at different rates was evaluated for major crops of the area and their efficiency was found in the order: FYM @ 10 t ha^{-1} > coir pith @ 20 t ha^{-1}> powdered groundnut shell @ 5 t ha^{-1}> gypsum @ 4 t ha^{-1}> paddy husk @ 5 t ha^{-1}. The effect of added amendments directly or indirectly modified soil moisture and soil temperature by reducing the evaporation losses. The amendments also reduced the impact of raindrop and prevented the formation of the crust. In black soil, addition of gypsum @ 2–5 t ha^{-1} increased the infiltration rate by 4–7 times over the control rate of 0.25 cm h^{-1} (ref. 3).

It was observed that in rainfed Alfisols at Hyderabad, the germination percentage in precision planter sown plot was 10.5% higher than the conventional planter in different crops (Figure 1)[5]. In the undulating topography of the red Alfisols, seed germination was poor because seeds were placed at a depth less than that recommended, as the rainfed soils which opened once lose moisture at a fast rate during the sowing season because of high wind velocity. Similarly, the seeds dropped below the recommended depth could not come up because of more soil shear strength influenced by the low moisture availability in the topsoil. Researchers have emphasized on timely sowing and proper use of the implements in rainfed regions to increase seed germination and productivity in rainfed crops[6–8].

Sowing of rainfed crops on shoulders of ridges under ridge–furrow system of cultivation helps in lowering the crust problem encountered in seeding emergence. Using this system of cultivation, the crust is formed in the furrow as the soil particles responsible for soil crusting are transported from ridge side to furrow bottom with rainwater. Also due to inter-row water harvesting of the rain, the furrow remains wet for a longer time, thus preventing the development of crust strength critical to seeding emergence. Surface crust can be broken by special equipment before and after seeding. Preserving organic material in and on the soil surface can be achieved by conservation farming. Soil moisture contents close to field capacity are most favourable for seed emergence in crusty soils. Thus, timely sowing of the rainfed crops could be one of the strategies for higher crop productivity.

Management technology for highly permeable rainfed soils

Compaction

In light texture soils, about 25–40% of rainfall can percolate down below the root zone of crops. Consequently, a small quantity of rainfall could be conserved *in situ*. Under such conditions, the rainfed crops are unable to sustain even short (>10 days), dry spells. Soil compaction by giving a few passes of heavy duty roller has been attempted by several researchers[9–11]. Compaction by 12 passes of half tonne roller could increase bulk density of

Table 2. Effect of compaction on soil moisture content (%) and saturated hydraulic conductivity (cm h^{-1}) in soil layers at different stages of crop growth in cowpea[11]

	Moisture content (%) and saturated hydraulic conductivity (cm h^{-1}) (saturated hydraulic conductivity values presented in brackets)					
	Just after compaction		At flowering		At harvest	
Soil depth (cm)	C_O*	C_2*	C_O	C_2	C_O	C_2
0–15	9.4 (10.4)	11.6 (8.9)	10.0 (10.6)	12.63 (9.1)	7.2(10.7)	9.1 (9.3)
15–30	9.9 (9.6)	12.1 (7.2)	10.6 (9.7)	12.94 (7.4)	7.7(9.9)	9.9 (7.5)
30–45	10.5 (8.7)	12.0 (7.4)	11.0 (8.8)	12.68 (7.6)	7.8 (8.9)	9.5 (7.7)

C_O*, No compaction; C_2*, Two passes of 500 kg iron roller.

top 30 cm soil layer from 1.55 to 1.67 mg m^{-3}, and increased the yield of pearl millet at Jobner (Rajasthan) by 33% over the control yield. Similar results were obtained by Indoria *et al.*[11] in rainfed cowpea crop, who recorded 23% more seed yield and 9% more stover yield with the passing of 500 kg iron roller two times over uncompacted soil. In other crops like barley, cluster bean, cotton, mustard, pearl millet and wheat, the yield increase was to the tune of 34%, 25%, 7%, 13%, 31% and 32% respectively, over uncompacted soil[3]. Indoria *et al.*[11] reported that compacted soil retained 15–33% more moisture in different soil layers under rainfed condition. They also reported that the saturated hydraulic conductivity decreased by 13–25% compared to the control, which may be due to increase in the bulk density because of compaction (Table 2). Agrawal *et al.*[12] reported that surface compaction to the depth of 30–40 cm increased the soil moisture retention and reduced the infiltration rate and hydraulic conductivity. However, reduction in hydraulic conductivity due to increase in bulk density was less in alluvial, red and laterite soil compared to black soil[13].

Compaction increased the volumetric water content at different tensions and the available water content of the rainfed soils. Majumdar[10] reported after an exhaustive study on highly permeable loamy sand soils that crop raised after compaction shows remarkable increase in moisture content, and bulk density, and reduced the hydraulic conductivity of soil compared to uncompacted soil. As water flux decreases exponentially with an increase in the bulk density of the soil by compaction, this benefits rainfed crops[14]. Singh and Mishra[15] reported that water flux will also be affected by the length of compacted soil layer because of its effect on the hydraulic head gradient. Thus, it could be viable technologies in highly permeable rainfed soils where water retention is the limiting factor for crop production.

Addition of clay and tank silt

Many studies in the rainfed regions of Aridisols and red Alfisol soils revealed that mixing of clay in the soil could improve the yield potential of the rainfed crops. Application of 2% clay in red sandy loam soils of Andra Pradesh increased the yield by more than ten times[4]. Application of tank silt @ 60 t ha^{-1} showed increased available water retention in the soil to the extent of 2%, as reported by Rao *et al.*[16] in red Alfisol soil of Andhra Pradesh. Osman[17] reported that addition of tank silt @ 50, 100, 150 and 375 tractor loads/ha improved the available water content by 0.002, 0.007, 0.012 and 0.032 g g^{-1} soil respectively. The moisture retention also increases to support the crop for additional 4–7 days, which plays an important role during the period of prolonged dry spells and intermittent droughts. This could be possibly due to the formation of aggregate in light soils which helps in retaining more water and nutrient by reducing the percolation due to addition of clay. This technology is viable where fine-textured soil is available for application either from ponds or nearby fields.

Compaction plus clay addition

In the arid regions of Rajasthan, compaction was imparted after addition of 2% clay. In this case the results in terms of water and nutrient retention and yield sustainability have been phenomenal in desert soil, and hence, the name to desert technology. A low-cost roller (JRIC roller) was designed and fabricated at Jobner for implementing this technology. Yadav and Majumdar[18] indicated that four passes of 500 kg iron roller after mixing of 2% clay increased the moisture retention capacity and reduced saturated hydraulic conductivity and infiltration rate of loamy sand soil over control. This technology was successfully demonstrated at adaptive farmer's field for wheat and pearl millet crop and 29% and 37% yield increase was observed[4].

Management technologies for subsurface mechanical impedance and compactness

Formation of a hard pan below the ploughing depths restricts infiltration of rainwater into the subsoil besides restricting root proliferation[19,20]. Mechanical shattering of these hard pans by chiselling or mould-board ploughing helps in improving infiltration (Table 3) and water storage capacity of the solum, besides good improvement in the yield of different crops in rainfed regions (Table 4)[3]. In black soils, the addition of gypsum @ 2–5 t ha increased infiltration rate by 4–7 times over the control rate of 0.25 cm h^{-1}.

Similar results were reported by Painuli and Yadav[4], indicating that chiselling of mechanical impedance resulted in increase in the production of major crops at ORP and farmer's field. Due to application of chisel technology (up to 45–50 cm interval) in red soil at Coimbatore, there was 18.6–64.1% yield increase over farmer's practices in different rainfed crops, viz. sorghum, maize, groundnut, tomato, black gram, etc. Similarly, in black soil at Nizamabad (Andra Pradesh), 12% yield increase was noticed with the chisel technology (30 cm soil depth at 60 cm interval). At the same location, with chisel-plus-amendment (gypsum @ 5 t ha^{-1} or FYM @ 25 t ha^{-1}), 25.4% yield increase was noticed in sugarcane at farmer's field. In sandy loam soil at Hisar (Haryana), there was 14%, 17% and 41% yield increase in wheat, cotton and raya respectively, due to chieselling (up to 40 cm depth at 50 cm interval)[3].

Not only in highly permeable soils like Entisols, Inceptisols and Aridisols, but also in Vertisols, deep tillage helped in improving water infiltration. Mohanty *et al.*[21] reported that in Vertisols of Central India, erratic rainfall and prevalence of drought during crop growth, low infiltration rate and the consequent ponding of water at the surface during the critical growth stages are the possible reasons for poor yield (<1 t ha^{-1}) of soybean (*Glycine max* (L.) Merr.) in rainfed situation. Ameliorative tillage practices, particularly deep tillage (subsoiling with chisel plough), can improve water storage of soil by facilitating infiltration, which may help in minimizing water stress in this type of soil. The basic infiltration rate was greater after subsoiling every year (5.65 cm h^{-1}) in relation to conventional tillage (1.84 cm h^{-1}). Similar trend was observed in water storage characteristics (0–90 cm depth) of the soil profile. The faster infiltration rate and water storage of the profile facilitated higher grain yield and enhanced water use efficiency (WUE) for soybean under subsoiling than conventional tillage. Conventional tillage + subsoiling in alternate years registered significantly higher WUE (17 kg ha^{-1} cm^{-1}) over conventional tillage + subsoiling every year (16 kg ha^{-1} cm^{-1}) and conventional tillage (14 kg ha^{-1} cm^{-1}). On an average, subsoiling recorded 20% higher grain yield of soybean over conventional tillage, but the yield did not vary significantly due to conventional tillage + subsoiling during alternate years and also every year. They also reported a decrease in the surface and subsurface penetration resistance as well as bulk density due to subsoiling.

Table 3. Effect of deep ploughing on basic infiltration rate of soil[3]

	Infiltration rate (cm h^{-1})		
Treatment	Desertic	Alluvial	Black
Control	5.2	2.1	0.18
Ploughing with local plough	5.7	2.2	0.20
Deep ploughing	7.6	3.3	0.39

Table 4. Effect of deep ploughing on yield of some dryland crops[3]

		Yield (t ha^{-1})	
Soil type	Crop	Local plough	Deep plough
Alluvial	Maize	2.22	2.65
	Pearl millet	2.24	2.56
	Wheat	2.38	2.81
Red	Castor	4.00	6.00
	Groundnut	1.80	2.40
	Pigeonpea	5.90	7.60
Black	Castor	4.2	6.00
Desertic	Pearmillet	1.34	1.58
	Mung bean	0.47	0.58

Management technologies for water retention

Although the amount of soil organic carbon in Indian soils is relatively low (0.1–1.0%), its influence on physical health is of great significance. However, maintenance of soil organic carbon under tropical conditions, particularly in arid, semi-arid and sub-humid conditions, is difficult due to extremely high temperature and moisture stress. Soil organic matter is integral to managing water cycles in ecosystems and its depletion has significant negative impacts on soil physical properties (infiltration, aggregate stability, porosity, water content, bulk density) and plant productivity. Thus, organic matter is one of the most important biophysical elements that can be managed to improve soil physical health and resilience. Incorporation of organic matter either in the form of crop residues or FYM has been shown to improve soil structure (aggregate stability) and water retention capacity[22], increase the initial and steady infiltration rates and decrease bulk density[23], resulting in reduction in crust formation and consequent increase in water productivity. Thus, organic matter plays a vital function in buffering yields in rainfed regions under climatic extremes and uncertainty. Prasad[24] reported that neither inorganic nor organic amendments alone can maintain organic matter status of soil and sustain productivity in the semi-arid tropics. Several studies have been conducted to monitor the long-term impact of INM, tillage practices and residues application on soil quality indicators and indices at network centres of All India Coordinated Research Project for Dryland Agriculture at Hyderabad[25,26]. These studies have clearly shown the positive impact of INM practices on soil aggregates and bulk density, resulting in higher yield in rainfed crops.

Table 5. Seed yield and water-use efficiency (WUE) of soybean as influenced by nutrient management[27]

	Seed yield (kg ha^{-1})				WUE (kg ha^{-1} cm^{-1})			
Treatment	1998	1999	2000	Mean	1998	1999	2000	Mean
Control	848^c	935^c	915^c	899	20.4^b	21.4^c	23.8^c	21.9
NPK (@ RDF)	1593^b	1552^b	1584^b	1576	37.1^a	34.5^b	33.1^b	34.9
NPK (@ RDF) + FYM (10 Mg ha^{-1})	1723^a	1853^a	1905^a	1827	38.6^a	39.3^a	37.5^a	38.5

The difference between values in a column followed by the same superscripts is not significant at ($P < 0.05$).

Table 6. Percentage of water stable aggregate, mean weight diameter of water stable aggregate, bulk density, hydraulic conductivity and soil organic carbon in *rainfed* Vertisols[28]

Treatment	Water stable aggregate (%)	Mean weight diameter (mm)	Bulk density (Mg m^{-3})	Hydraulic conductivity (m s^{-1})	Soil organic carbon (g kg^{-1})
Control	69.28	0.68	1.50	1.65×10^{-4}	4.2
NPK	68.06	0.74	1.44	2.66×10^{-4}	4.7
NPK + FYM	73.88	0.77	1.36	3.23×10^{-4}	6.1
LSD	NS	0.05	0.07	1.14×10^{-4}	0.7

LSD, Least significant difference ($p < 0.05$).

Thus, greater focus is needed on integrated nutrient management strategies for improving the soil physical health and water productivity in the soils. Hati *et al.*[27] showed that an integrated supply of nutrients through organic and inorganic sources could be an effective practice of nutrient management for increasing WUE and yield of rainfed soybean in Vertisols of central India by improved soil physical conditions through better aggregation, increased saturated hydraulic conductivity, reduced mechanical resistance and bulk density, and enhanced root proliferation of rainfed soybean (Table 5).

Bandyopadhyay *et al.*[28] reported that integrated nutrient management strategies decreased the bulk density (9.3%), soil penetration resistance (42.6%), and increased the hydraulic conductivity (95.8%), mean weight diameter of the water stable aggregates (13.8%) and soil organic carbon content (45.2%) compared to control (Table 6). Annual application of FYM @ 4 t ha^{-1} along with recommended dose of fertilizers (NPK) significantly improved the grain yield of rainfed soybean by 14.2% over NPK and by 50.3% over control treatment. They further reported that integrated use of NPK + FYM resulted in higher WUE (19.28 kg/ha cm) than NPK (17.04 kg/ha cm) and control (13.63 kg/ha cm; Table 6). Studies have also reported higher WUE rainfed soybean under integrated use of fertilizers and FYM in Vertisols[29–31].

The effect of organic matter is somewhat more pronounced in soils containing less than 25% clay[32,33]. As the clay content in rainfed Alfisols, Entisols and Inceptisols is less, hence in these soils, addition of organic matter helps in improving soil aggregates. A rapid increase in the granulation occurs after the addition of organic matter, but it declines with time[34]. This emphasizes the importance of frequent replacement of organic matter to maintain good soil structure in these soils. The decrease of soil organic matter, along with the associated faunal activities (aggravated by the use of pesticides and tillage practices), favours the collapse of soil aggregates, which results in crusting and sealing of the soil surface[35].

Rainwater and soil moisture conservation practices for rainfed soils

In the Deccan Plateau, under normal cultivation, soil slope, low rate of infiltration and high intensity rainfall cause run-off. In general, the run-off is between 12% and 20% with a concurrent upper soil loss of 10–14 t ha^{-1} y^{-1} due to erosion. During the rainy season, in the cropped fields, about 10% of the rainfall is lost as run-off from black and about 25% from red soils[36]. First, it was realized that the land needed some kind of vegetal cover to minimize the run-off and soil loss. Secondly, various practices have been recommended for soil and moisture conservation in rainfed regions. Some crops such as pearl millet, horse gram and pigeonpea provide cover to the soil, thus resulting in considerable reduction in run-off and soil loss. Deep ploughing, soil stirring and mulching help conserve soil moisture. Fallowing is also useful. The Vertisols of rainfed regions are prone to erosion due to their low infiltration rates, high intensity of rainfall and slopes; hence some kind of mechanical obstacle is essential. For slope about 1.5%, contour bunds with arrangement of surplus water are effective in black soils. Comparison of graded and live bunds revealed that the latter could reduce run-off by about 34% compared to sowing across the major slope and soil loss was reduced by about 74%. Compared to graded bunds, the run-off was not reduced in live bund, but the soil loss was reduced by 70% (ref. 37). In deep black soils with gentle slopes and other land surface configurations, such as ridges and furrows, tied ridges and compartments help hold rainwater, increase infiltration, and reduce run-off and soil loss. Beneficial results on soil conservation due to surface

Table 7. Yield and economics of finger millet + pigeonpea (10:2) cropping system as influenced by soil and conservation practices (mean of two years, 2007–08 and 2008–09)[38]

	Yield						
	Finger millet				Return Rs ha^{-1}		
Treatment	Grain	Straw	Pigeonpea	Fodder jowar	Gross	Net	B : C ratio
Finger millet + pigeonpea (10 : 2) staggered moisture conservation furrow	2251	5370	280	–	26,669	14,918	2.26
Farmers practices (finger millet and fodder jowar)	1237	2700	–	885	12,283	1,633	1.15

configuration have been reported for different land situations. Ramachandrappa[38] reported that during 2007–08 and 2008–09, under rainwater management, finger millet+pigeonpea (10 : 2) cropping system with staggered moisture conservation furrow (covered about 56 farmers with 23 ha area) recorded higher net returns of Rs 14,918 ha^{-1} with B : C ratio of 2.26 compared to farmers practice (B : C ratio 1.15; Table 7). Despite long dry spells of 25 days during grain-filling stage, the farmers harvested good yield and were convinced about the technology. Various conservation tillage practices, viz. ridge and furrow, broad bed furrow, and raised and sunken beds of different widths were also evaluated on black soils of low (Prabhani) and high (Jabalpur) rainfall areas to avoid waterlogging during rainy season. These practices were found effective to various extents depending upon topography, crop and rainfall. Painuli and Yadav[4] reported that in sorghum 27.2% yield increased due to ridge and furrow at Jabalpur, and 17.3% yield increased at Prabhani over farmer's practices. Similarly, due to broad bed and furrow, there was 18.3% and 25.2% yield increased in greengram and sorghum respectively, at Prabhani over farmer's practices. Raised and sunken beds were also found to increase the yield by 5.2–55.2% in various crops (paddy, cotton soybean, black gram, pigeonpea, sesame, etc.) at Prabhani[4]. This might be due to availability of more moisture under these practices.

Kurothe *et al.*[39] showed that tillage is an important tool for tackling water-induced erosion hazards, promoting *in situ* water conservation and stabilizing crop yield from rainfed production system of semi-arid and subtropical agro-ecosystem of Gujarat region. They reported that ridge farming tillage, no tilllage and stubble mulch farming tillage reduced run-off by 69.4%, 16.2% and 59.6% respectively, compared to conventional tillage. They also reported that average soil loss in no tillage was 32.7% less than conventional tillage. The highest average yield of all the crops (pearl millet, cowpea, mustard, pigeonpea and castor), except green gram was recorded under stubble mulch farming tillage. Poor structure and extreme rainfall densities often cause ponding and increased erosion hazards in these soils. Broad bed and furrow is the technology package proposed by ICRISAT for medium-textured Alfisols in land that is exposed to harsh monsoon climate with distinct dry seasons.

Surface residue management

Surface management and crop residue management practices alter the pattern of water entry into the soil. As these practices yield different soil surface roughness, surface residue distribution, organic carbon concentration, aggregate-size distribution and aggregate stability; these will in turn influence water infiltration and deep percolation[40,41]. There is no doubt that application of the surface residues improves the soil moisture status and the effect of surface residues impact is more in rainfed regions. Rao *et al.*[42] reported that the application of *Gliricidia* loppings in rainfed areas improved the water holding capacity and reduced soil erosion. Studies conducted at CRIDA, Hyderabad showed that in rainfed situation where only a single crop is grown in a year, it is possible to raise a second crop with residual soil moisture by covering soil with crop residues[43]. Aujla and Cheema[44] observed that evaporation retardants and straw mulch are useful in conserving more soil moisture in the 180 cm deep soil profile. These moisture conservation practices improved plant stand, profile water use and yield of rainfed chickpea. Gupta *et al.*[45] reported significant improvement in cowpea seedling growth under arid condition by improving the soil physical properties. Organic mulches reduce run-off and soil loss. They improve surface soil conditions in two ways. First, by reducing rain drop impact and secondly, by increasing biological activity, particularly by termites that build channel and increase the number of continuous tubular pore in the topsoil, which facilitates water entry into the soil. These mulches also retard the formation of surface crust in micro depression or tied furrows and therefore increase the infiltration of water into the subsoil. Polythene mulch also showed increase in profile water storage leading to higher yields compared to control (without mulch) treatment.

Conservation (minimum) tillage

Conservation tillage may be more appropriate under rainfed agriculture than conventional tillage. Tillage alone without residue retention may not be of much utility in these areas. Sharma *et al.*[46] reported that graded level of sorghum residue application on the surface in combination with minimum tillage on long-term basis helped in increasing the infiltration rate and available water content in rainfed Alfisols under sorghum–cowpea rotation. In the rainfed hills of northwest India, maize (*Zea mays* L.)–wheat (*Triticum aestivum* L.) is the dominant cropping system. However, rainfed wheat suffers from lack of optimum moisture at sowing. Researchers have suggested that mulches and conservation tillage are useful in rainfed wheat in mitigating this problem. Acharya *et al.*[47] reported that in case of wheat shown after the harvest of maize, mulches (@ 10 mg ha^{-1} dry weight basis) of weeds like *Lantana camara* (lantana) or *Eupatorium adenophoru*m plus conservation tillage resulted in higher moisture (0.06 ± 0.10 m^3 m^{-3}) in the seed-zone compared to conventional farmer's practices. This may be because mulch–conservation tillage treatments favourably moderate the hydrothermal regime for growing a wheat crop. Sharma and Acharya[48] reported that establishment of wheat crop under rainfed environments is possible by conserving soil moisture with the application of waste organic residues like lantana during the standing crop of maize, preceding wheat and before the monsoon rains recede. They showed that lantana mulch along with conservation tillage resulted in higher soil moisture in different soil layers compared to conventional tillage. They further reported the significantly higher yield of wheat crop with lantana (@ 20 mg ha^{-1} fresh weight) and conservation tillage compared to conventional tillage. They also observed that application of lantana mulch, irrespective of the method used, also increased maize yield (after two cropping cycles), grown in sequence with wheat. Increase in wheat and maize yield could be attributed to the improvement in soil physical and chemical properties due to lantana additions. This is because addition of lantana or any other organic matter improves water transmission and drainage conditions of soil by increasing soil aggregation and inter-aggregate pore spaces[49,50].

Chemical agent

Rainfall can percolate down below the root zone of crops in light-textured rainfed soils. Consequently, a small amount of rainfall could be conserved *in situ*. The percolation loss of water, however, could be reduced by treating the subsurface (below 60 cm depth) with a suitable sealant like hot asphalt emulsion (@ 14,000 l ha^{-1}), Janta emulsion (a product of Burmah–Shell) and bentonite clay[51]. The practical feasibility of using these sealants is however limited.

Hydrogel

Super-absorbent polymers affect water penetration rate, density, structure, compactness, texture, crust hardiness of soil, aggregate anchorage[52], evaporation[53], soil infiltration, aeration, size and number of aggregates, soil water tension, available water, soil crispiness and finally result in better water management conditions in semi-arid soils[52,54–57]. The Pusa hydrogel is evolved specifically to work efficiently in the hot tropical and semi-tropical climate of the country, where most other gels fail to perform well. In fact, its absorption capacity increases as the temperature rises to 45°C degrees or above. Besides, Pusa hydrogel meets most other prerequisites for use in agriculture, such as the ability to co-exist with fertilizers, like area, capable of lasting at least for one full crop season and free of any toxins that can make its use environmentally safe. Additionally, this product has been found to improve the physical health of the soil by loosening the compact soil to enhance crop productivity. According to *The Hindu BusinessLine*[58], this wonder gel is helping farmers save water while multiplying yields. It works as an anti-drought mechanism and reduces the water requirement of plants. Typically, a farmer irrigates his field every four days for high-value crops, but with the gel, he can irrigate the farm every eight days. Thus, farmers are able to defer irrigation cycles and use the water effectively. Due to use of Pusa hydrogel, there is 40–70% saving of water. The gel helps crops store water for a dry spell and aids farmers to cope with the increasingly unpredictable monsoon seasons. Thus, application of hydrogel could be a viable management technologies in rainfed areas.

Soil conditioner

Soil conditioning implies improvement of the soil physical properties, thus permitting more effective utilization of soil and water resources. Soluble conditioners undergo physico-chemical reactions with soil constituents, especially the clay fraction. Thus, the application of different soil conditioners (VAMA, Krilium, PVA, Hygromull (a urea formaldehyde soil conditioner)) results in improved aggregation, porosity and hydraulic conductivity, decreased bulk density, improved porosity, improved infiltration, permeability and increased soil profile water[59,60]. Painuli and Pagliai[61] observed that poly vinyl alcohol and dextran improved the soil structure considerably and soils treated with these conditioners produced numerous fine cracks, smaller clods and imparted greater stability against water which is important in agriculture. Application of soil conditioner (Krilium) resulted in a marked increase in the yield of cauliflower due to improvement in soil structural stability, which also resulted in increasing the available water through improved infiltration. Thus, different soil conditioners were shown as effective stabilizers of surface soil. These enhanced the capacity of the soils to absorb rainfall and decreased run-off, thereby increasing the water storage capacity of the soil. However, Agrosil LR (conditioner) decreased the hydraulic conductivity of sandy soils and improved the aggregation in these soils which leads to an increase in water storage[60].

Addition of naturally occurring salts

Attempts were made to granulate the soil particles by addition of naturally occurring salts of polyuronic acid and polysaccharides (synthesis complexes). Such attempts have not been successful owing to rapid decomposition of polysaccharides. However, the aggregate stability and percolation rate increase by the addition of polyelectrolytes such as sodium polyacrylonite[62–64]. The addition of sodium alignite increases the stability of the granules, but it decomposes rapidly. Further studies are needed on stabilization of natural and synthetic salts suitable for rainfed regions.

Root effects

Different crops are known to have different effects on soil aggregates. Grass roots have much more granulated soils between roots than cereals roots, because the grass roots are fibrous with a lot of root hairs compared to cereals and other crops. The root excretion may also play a role in the stability of soil structure. The conservation of optimum physical conditions also depends on the root systems of crops that are grown in rotation; usually cereals better maintain favourable surface soil conditions than groundnut.

Summary

Soil compaction and compaction-plus-clay management technologies are found to be effective in reducing water and nutrient losses, increasing profile moisture storage capacity and the yield of various crops in highly permeable sandy soils of rainfed regions. Application of FYM on seed lines as mulch is helpful in reducing the ill-effects of surface crust on seedling emergence and crop establishment in crust-prone sandy loam and loamy sand soils of rainfed regions by increasing soil moisture and reducing soil temperature in the seed zone. Tillage operations with chiseller is effective in breaking the high bulk density in subsoil layer and results in increased water entry and crop yields. Conservation tillage and application of soil conditioner are found to be promising and effective management technologies in rainfed areas.

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