Role of soil physical properties in soil health management and crop productivity in rainfed systems-I: Soil physical constraints and scope

A. K. Indoria*, K. L. Sharma, K. Sammi Reddy and Ch. Srinivasa Rao

ICAR-Central Research Institute for Dryland Agriculture, Hyderabad 500 059, India

Soil physical degradation has become a serious problem in both rainfed and irrigated areas of India. According to an estimate, about 90 m ha area is experiencing soil physical constraint in the country. In rainfed regions, among several other constraints related to crop and climate, soil physical constraints are the key which severely limit crop productivity. The predominant soil constraints which are governed by the principles of soil physics include subsurface hard pan and compactness, crusting and hardening, slow and high permeability, non-optimal porosity, poor soil structure, poor water receptivity, retention and transmission, etc. It is now well-established 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 fulfiled. The optimum soil physical environment creates a suitable condition for better crop production both in irrigated and rainfed regions. Rainfed agriculture, often referred to as dryland agriculture, is practiced in areas that are relatively warmer (arid, semi-arid) and dry sub-humid regions of the country. These regions are highly diverse, ranging from resource-rich areas with good agricultural potential to resource-constrained areas with a much more restricted potential. These regions represent a wide variety of soil types, agro-climatic and rainfall conditions. This article discusses the soil physical constraints in rainfed regions of India.

Keywords: Rainfed agriculture, soil physical properties, soil physical constraints.

SOIL is a three-phase system consisting of solids, liquids and gaseous phase. Soil physics deals with the physical properties of the soil and their measurement, as well as the physical processes taking place in and through the soil. The importance of soil physical properties has been recognized since the early days of agriculture, as evidenced by the use of tillage tools for land preparation. Soil physics includes soil properties like soil texture, soil structure, bulk density, porosity, infiltration, water-holding capacity, soil temperature, erosion, compaction, drainage, water use efficiency, etc.

*For correspondence. (e-mail: akumar.indoria@crida.in)

The rainfed regions of India suffer from a number of biophysical and socio-economic constraints which affect productivity of crops and livestock. Major constraints in these areas are low and erratic rainfall, water scarcity, fragile environment, drought, land degradation due to soil erosion by wind and water, low rainwater use efficiency, poor productivity, low input use, poor technology adoption, low draft power availability, inadequate fodder availability, less productive livestock, inadequate credit availability and many more[1–4]. Thus, most of the soils in rainfed regions in India are on the verge of degradation having low cropping intensity, relatively low organic matter status, poor soil physical health, low fertility status, etc. Optimum soil physical health plays a central role in any agriculture production system. Once soil physical health is degraded, it takes a long time to be restored; it also affects the other soil properties and processes, and ultimately results in decline in crop productivity on a long-term basis. For optimum plant growth, it is important that the soil provides a favourable physical environment for root development that can exploit the soil adequately to support the water, nutrients and anchorage needs of plants. Therefore, it is necessary to maintain a good soil physical condition for sustainable food production and efficient use of natural resources. In this article, we discuss the important soil physical constraints that limit the crop production potential in rainfed soils of India.

Rainfed agriculture: national perspectives

Indian economy is primarily dependent on agriculture, which contributes 21% of the country's GDP and 60% of the employment. Rainfed agriculture occupies 60% of net sown area of the country and contributes 44% of food-grains[5]. It also supports 40% and 75% human and livestock populations respectively. At present, 95% of the area is under coarse cereals, 91% pulses, 80% oilseeds, 65% cotton and 53% rice under rainfed agriculture[6,7]. These areas are spread out throughout the length and breadth of the country with semi-arid to sub-humid environments, coarse-textured light soils to heavy-textured black and alluvial soils with effective crop growing

Table 1. Distribution of area (million ha) affected by various soil physical constraints in India[11]

Physical constraints	Area	Main states affected
Shallow depth	26.40	AP, Maharashtra, WB, Kerala and Gujarat
Soil hardening	21.57	AP, Maharashtra and Bihar
High permeability	13.75	Rajasthan, WB, Gujarat, Punjab and TN
Subsurface hard pan	11.31	Maharashtra, Punjab, Bihar, Rajasthan, WB and TN
Surface crusting	10.25	Haryana, Punjab, WB, Odisha and Gujarat
Temporary waterlogging	6.24	Madhya Pradesh, Maharashtra, Punjab, Gujarat, Kerala and Odisha

Table 2. Dominant cropping systems, crops, mean annual rainfall (MAR), length of growing season (LGP), available water holding capacity (AWC) and distribution of rainfed agriculture[12]

Production system	Dominant crops	Dominant soil order	MAR (mm)	LGP (days)	AWC (mm/m)	Distribution
Coarse cereal-based	Sorghum, pearl millet, maize, pigeon pea and other pulses, cotton and groundnut	Alfisols, Aridisols and Vertisols	648	50–150	50–200	It covers 34 districts located mostly in the western and central parts of the country and the semi-arid hot high-lands of the Deccan Plateau.
Groundnut-based	Groundnut, rice, cotton and pulses	Saline and alkaline Vertisols and Alfisols	684	90–150	50–150	Western plains, central highlands, semi-arid plateau and the Eastern Ghats. It covers 16 districts mainly in Gujarat, Karnataka, and AP (including Telangana).
Rice-based	Rice, sorghum, Pigeon pea and groundnut	Alfisols, Inceptisols, Entisols and related red soils	1166	120–210	50–200	Northern plains, Chhattisgarh, Mahanandi basin and sub-humid Eastern Plateau mainly in UP, Bihar, MP and Odisha. It covers a total of 34 districts.
Cotton-based	Cotton, wheat, chickpea, sorghum	Vertisols	795	120–150	100–250	Located mostly in the Deccan Plateau and hot, semi-arid peninsula.
Soybean-based	Soybean, wheat, chickpea and Sorghum	Vertisols and related Vertic soils	1058	120–180	120–250	MP and UP in the central highlands, Malwa, Gujarat Plains and Kathiawar peninsula. It covers 18 districts.

periods varying from 50 to 210 days. These data emphasize that rainfed agriculture plays an important role in ensuring food for the ever-increasing population and for the overall agricultural growth. India ranks first among the rainfed crop growing countries in the world in terms of area, but ranks relatively low with respect to productivity of rainfed crops. In India, rainfed area covers about 220 districts in the states of Punjab, Haryana, Rajasthan, Uttar Pradesh (UP), Madhya Pradesh (MP), Chhattisgarh, Gujarat, Maharashtra, Andhra Pradesh (AP), Karnataka and Tamil Nadu (TN). Physiographically, the rainfed region encompasses the desert terrain of Rajasthan in the north-west, the plateau region of central India, the alluvial plains of the Ganga–Yamuna river basin, the central highlands of Gujarat, Maharashtra, MP and Chhattisgarh, the rain-shadow region of Deccan in Maharashtra, Deccan Plateau in AP and the TN highlands[8,9].

Soil physical constraints in rainfed regions

According to an estimate, about 90 m ha of the area in the country experiences soil physical constraints (Table 1). At present, nearly 70% of rainfed area is affected by wind erosion and sand deposition. Out of an estimated 142 m ha net cultivated area, about 83 m ha is rainfed and it is estimated that even after reaching the full irrigation potential, nearly 50% of the cultivated area will remain rainfed[10]. Shallow depth and soil hardening are the major soil physical constraints in rainfed regions, followed by highly permeable soil, subsurface hard pan, surface crusting and temporary waterlogging[11]. These soil physical constraints limit the crop production potential and severely affect the crop yield. Details of these soil physical constraints are described in the text.

Dominant cropping systems of rainfed regions

On the basis of crops, area-specific problems and potential, the rainfed areas of the country have been divided into five major production systems. These are: (i) coarse cereal-based, (ii) groundnut-based, (iii) rainfed rice-based, (iv) cotton-based and (v) soybean-based. It shows that the important crops, viz. rice, wheat, cotton, soybean, maize, sorghum, pearl millet, chick pea, pigeonpea and other pulses are predominantly grown in rainfed areas and a large variation exists in the cropping patterns. Similarly, the length of the growing period also shows a large variation; it varies from 50 to 210 days in rainfed regions. The soil available water-holding capacity of the rainfed regions also exhibits variation; it ranges from 50 to 250 mm m^{-1} (Table 2)[12]. The rainfed regions of the country predominantly represent the soil orders Vertisols, Alfisols, Entisols, Inceptisols and Aridisols. The soil orders terminology used here predominantly represents soil types as follows: Alfisols (red soils), Vertisols (black soil), Entisols (young alluvial soils), Inceptisols (alluvial soils) and Aridisols (desert soils).

Causes of soil physical degradation in rainfed regions

The various predominant causes of soil degradation include: (i) water erosion which sweeps away the topsoil along with organic matter and exposes the subsurface horizons; (ii) intensive deep tillage and inversion tillage with mouldboard and disc plough resulting in breaking of stable soil aggregates; (iii) repetitive cultivation, (iv) mono cropping without following any suitable rotation; (v) nutrient imbalance; (vi) low use of organic manure; (vii) removal of vegetation; (viii) uncontrolled and excessive grazing; (ix) unprotected fields, etc. These are known to cause soil physical deterioration by enhancing erosion in rainfed regions[13].

Distribution of soil orders in rainfed regions

Taxonomically, soils in India represent Entisols, Inceptisols, Vertisols, Aridisols, Mollisols, Ultisols, Alfisols, Oxisols and non-classified soils. Major soil orders which represent rainfed/dryland regions in India are Alfisols, Vertisols, Entisols and other associated soils (Figure 1). Soil orders such as Oxisols, Inceptisols and Aridisols also form a considerable part of the rainfed agriculture system. The total area under Alfisols in India is about $42,199 \times 10^3$ ha. The zone-wise distribution of Alfisol soils indicated that they occur mainly in the southern zone (42%), eastern zone (30%), central zone (19%), northern zone (5%), while a small part is present in the western zone, northeastern zone and island zone. About 94% of the Alfisol soils falls in eight states of India and the remaining is found in the other states (Table 3)[14]. In dryland regions, nearly 30% of soils is covered by Alfisols and associated soils. Vertisol is the other important soil order which constitutes a significant portion of the rainfed regions. The total area under Vertisols is about $26,616 \times 10^3$ ha in the country. This order is dominant in the central zone (61.4%), followed by the southern zone (22.4%), western zone (10.8%) and northern zone (1.6%). Table 3 gives state-wise distribution and area of this order. Out of the total Vertisols of India, more than 98% area falls in 10 states of the country[14]. In dryland regions, nearly 35% of soils is covered by Vertisols and associated soils (with vertic properties).

The total area under Entisols in the country is about $78,748 \times 10^3$ ha. The zone-wise distribution indicated that these soils occur mainly in the northern zone (25.4%), central zone (22.8%), western zone (20.8%), eastern zone (11.0%), northeastern zone (10.6%) and southern zone (9.0%); a very small part is also included in the island zone (0.4%)[14]. In dryland regions, nearly 10% of soils is covered by Entisols. About 85.1% of the total Entisol area falls in 11 states of the country and the remaining is found in other states (Table 3). The total area under Aridisols in the country is about $13,349 \times 10^3$ ha. The zone-wise distribution indicated that these soils occur mainly in the western zone (77.3%), sourthern zone (13.9%) and northern zone (8.8%). These soils contribute 4% area of the dryland regions of the country. The total area under Aridisols of the country falls under six states (Table 3)[14].

Soil physical constraints in rainfed regions affecting plant growth and yield

Soil textural constraints

Alfisols: These soils are agriculturally important and predominantly found in rainfed regions. Alfisols of the rainfed regions are generally characterized by light texture (due to the leaching of clay in lower soil horizons) and shallow depth. Fine clay (<0.0002 mm) is considered as the most reactive part of the soil in terms of the actual seat of reactions due to its small size and high surface area. For rainfed Alfisol soils, clay content in the profile ranges between 30% and 40%, but in surface horizons it

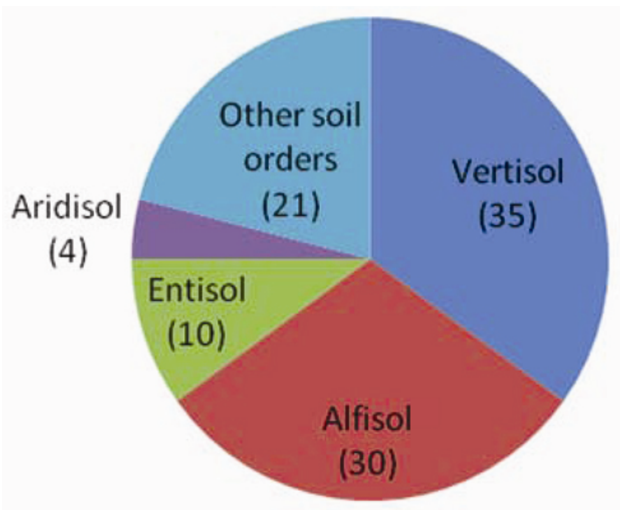

Figure 1. Percentage share of different soil orders in dryland regions.

Table 3. Area under major soil orders in different states (in 000 ha)[14]

Soil order	Statewise area (>400 × 10^3 ha)
Alfisol (red soil)	AP (8347), MP (7394), Bihar (5507), Karnataka (5454), Odisha (4949), TN (3973), WB (2221), UP (1793), Assam (762), Maharashtra (559)
Vertisol (black soil)	MP (10751), Maharashtra (5603), Karnataka (2802), AP (2238), Gujarat (1877), Rajasthan (989), TN (911), Odisha (908), UP (415)
Entisol (young alluvial soil)	Rajasthan (13,799), Jammu & Kashmir (9917), Maharashtra (9818), MP (8130), UP (4813), Bihar (4723), Arunachal Pradesh (3900), Karnataka (3162), AP (2981), Assam (2900), Himachal Pradesh (2895), Gujarat (2529), WB (2061), Odisha (1620), Harayana (1189), Punjab (1175), TN (720), Mizoram (589), Manipur (428)
Aridisol (desert soil)	Rajasthan (8287), Gujarat (2027), Karnataka (1046), AP (810), Punjab (770), Haryana (409)

Table 4. Total clay and fine clay percentage of rainfed Alfisol soils (red soils) of Hyderabad and Vertisol soils (black soils) of Amravati (Maharashtra) in semi-arid, rainfed regions[15,17]

Alfisols				Vertisols			
Depth	Total clay (TC)*	Fine clay (FC)**	FC/TC (%)	Depth (cm)	Total clay*	Fine clay**	FC/TC (%)
0–16	17.4	16.0	92.0	0–12	63.5	33.0	51
16–41	28.7	23.4	81.5	12–28	65.8	44.2	67
41–62	35.6	27.9	78.2	28–54	62.5	42.1	67
62–89	22.9	17.9	78.2	54–91	61.1	41.9	68
89–115	21.2	17.5	82.5	91–136	64.8	44.8	72

*Diameter of total clay particles is <0.002 mm. **Diameter of fine clay particles is <0.0002 mm.

varies from 15% to 20% (refs 15, 16). The soil texture of rainfed Alfisols showed that the fine clay percentage increased with increase in soil depth (Table 4). As a result, the ratio of fine clay to total clay decreased with increase in soil depth. In these soils, the weathering of minerals in the A and E horizons yields clay minerals that are carried downwards in percolating water and accumulate to form clay skins on the surface of angular and sub-angular blocky peds and root channels. The clay skins are not only enriched in clay, but also contain more organic carbon, iron and other elements compared to the composition of the total horizon. High clay content below the root zone in Alfisols is not desirable for shallow-depth root crops. Due to less clay content and organic matter in surface horizons, lack of aggregation or presence of unstable aggregation is the tendency of the soils to reduce surface roughness, rapidly seal the surface after rainfall and produce crusting with subsequent drying cycles. Another reason for the formation of shallow and gravelly soils is erosion.

Vertisols: This is another important soil order which constitutes a significant portion of the rainfed regions. The fine clay percentage is more in Vertisol soils compared to the other soils present in rainfed areas. The clay content of Vertisols remains uniformly high (>35%), throughout the profile to a depth of at least 50 cm or more[15,17,18]. However, the total clay content in the soil profile varied in different places; for example, it was 23.2% at Arjia, Rajasthan (maize-based production system) to as high as 74.9% at Solapur (rabi–sorghum-based production system), Maharashtra, in rainfed regions[16]. In most of the rainfed regions of India, clay content was higher than 50%. Table 4 shows a typical Vertisol soil order representing rainfed region in Maharashtra.

Entisols and aridisols: Another important soil order in rainfed areas is Entisols. In general, these soils have little profile development and are commonly found with Aridisols, which also contribute to rainfed areas. Many different parent materials contribute to varied soil properties of this order. The clay content of the rainfed Entisols widely varies and ranges between 16.8% at Hoshiarpur, Punjab (maize-based production system) to 14.0% at Rakh Dhiansar, Jammu & Kashmir (maize-based production system)[16].

Aridisol soil order also plays an important role in rainfed agriculture. The clay content in these soils ranges between 26.6% at Hisar, Haryana (pearl millet-based production system) to 11.7% at S. K. Nagar, Gujarat (pearl millet-based production system). These data indicate a large variation in clay percentage and less amount of the profile clay in Entisols and Aridisols compared to other soil orders present in rainfed regions. Due to less clay content and associated constraints, these soils (Entisols and Aridisols) support only limited crops.

Soil structural constraints

Development and stabilization of soil structure help in understanding the other soil physical properties, i.e. soil water, aeration, soil pores, temperature, mechanical properties, susceptibility to crust development, erosion, etc. Therefore, soil structure is important for all aspects of soil use and management. In India, soil structure problems in different regions are associated with texture, topography and rainfall. The predominant soil structural associated problems include crusting and hardening with sandy loam texture of alluvial (Inceptisols and Entisols), red (Alfisols) and laterite (Ultisols and Oxisols) soils, slow pearmeability with clay and silty clay loam textutre of black soils (Vertisols), and high pearmeability with sand and loamy sand texture of desert soils (Aridisols). Rainfall and temperature are two important factors influencing soil aggregation. In arid agroclimatic regions, chemical weathering does not proceed rapidly; consequently, a small amount of clay is formed from the clay-forming minerals. Evaporation causes the formation of intra-granular braces by the organic materials accumulated between particles. When the moisture content is gradually reduced, it forms uniform coating over the particles as the soil dries up[19]. The common causes for soil structure degradation in rainfed regions include poor tillage operations, rapid decomposition of organic matter, compaction by machinery tyres and exposure of bare soil surface to falling raindrop energy. Crop cultivation too frequently results in degradation of soil structure to some degree. The structureless nature of Alfisols is due to the low content of fine particles of clay in the surface horizon, predominance of 1 : 1 type minerals and cropping systems which add only small amounts of decomposed organic matter[19].

The aggregate stability depends upon the resistance of soil particles to the disintegrating influence of water and mechanical manipulation. The poorly aggregated soil particles in rainfed regions disintegrate easily under the impact of raindrops. In rainfed areas, generally, the soil surface is not covered by any mulch materials because mostly monocropping is followed in them. Hence, after the harvesting of one crop, no crop residue is left on the surface. This in turn results in surface sealing and crusting due to the impact of raindrops leading to structural instability. Moreover, the cultivation process loosens the surface soil, thereby disintegrates the water-stable aggregates (WSP) and also dispersion by exposing the soil to the action of raindrops and by decreasing organic matter through rapid oxidation. The mechanical manipulation of soil at improper soil moisture status also leads to crushing of soil aggregation.

Crusting and hardening

Surface crusting and hardening are the most frequently reported physical problems in rainfed areas because these are predominantly light-textured soils, particularly in surface horizons due to less clay percentage, except Vertisols. Due to the impact of raindrops, the fine fraction goes into suspension, which either enters the soil and clogs the macro pore or is carried away with the run-off. This results in the loss of topsoil and nutrients; or it resettles on the surface to form a crust depending upon the intensity of rainfall, capacity of the soil and topography of the area[19]. The soils in rainfed regions in AP, Haryana, Rajasthan, UP, Bihar and West Bengal form a crust on the soil surface which interferes with germination and growth of the crops. The red sandy loam soils, 'Çhalkas' which cover a large area in AP become very hard on drying, with the result that the crop growth is adversely affected. The optimum proportion of coarse and fine fractions in the surface layer along with less than 1% organic matter provides conditions conducive for hardening of these soils. The red sandy loam soil (Alfisols) is soft when wet, but becomes very hard on drying due to presence of sesquioxides. In these soils, the packing of clay particles to form a more extensive interleaving domain produces a massive and hard structure with minimum porosity[19]. The growth of the continuous matrix of iron-oxide crystals within which other materials are enclosed also causes hardening in Alfisols[20]. Crusting and hardening are directly related to the soil aggregate stability, rainfall characteristics and its mineral and chemical composition. In case of rainfed soils, especially in Alfisols, Entisols and Aridisols, the aggregate formation is a problem due to less clay content and poor organic matter of soils. Thus, the surface layer of these soils dries up very quickly owing to shallow depth and poor water-retention capacity, and becomes very hard. Since the maximum root growth of most of the crops is confined to the surface layers, unless this layer remains moist, the crop growth suffers. The yields of gram, maize, castor and sorghum grown on these soils are relatively low and especially in case of groundnut, the crop yield is reduced due to reduced size of pods caused by hardening of the soils[21].

The crust formed on the surface in the rainfed soil offers mechanical impedance during the early stages of crop growth to the emerging plumes of the seedlings and consequently some seedlings get injured at their tips and fail to emerge. The emergence of pearl millet, cotton, fingemillet, raya and Indian colza seedlings is adversely affected. In these soils, crust is formed on soil surface by the occurrence of rainfall within 48 h of sowing, specially when the moisture content of the soil is less than 10% (refs 21, 22), and 20–40% clay is present in the surface soil[23–25].

As most of the soils in rainfed areas are not covered by any mulch or crop residue materials, they are more prone to soil crusting and hardening. In India, soils of the rainfed regions mostly support single-cropping systems. Thus most of the year, they remain without any crop, so these are called naked soils and the impact of the beating action of raindrops is more pronounced in these areas, resulting in the formation of a hard crust. The fine particles which settle on top of the coarse particles during the process of drainage and evaporation also form a crust on drying. Thus, in rainfed soils, due to sealing, water that would normally infiltrate into the soil will be lost to run-off during rainstorm because the direct impact of raindrops can break down aggregates which block the pores that would normally conduct water. The overall effect of sealing is reduction in porosity and permeability of the soil surface.

Subsurface hard pan and compactness

This problem is more severe in areas where dryness is most pronounced and in soils that contain a large amount of very fine sand and coarse silt (Alfisols, Aridisols, Entisols) in surface horizons. The subsoil hard pan in red soil is due to the illuviation of clay to the subsoil horizons coupled with cementing action of oxide of iron, aluminium and calcium carbonate, which increase the soil bulk density to more than 1.8 Mg m^{-3}. Further, the hard pan can also develop due to continuous cultivation of crops using heavy implements up to certain depths. The higher bulk density, particularly in red Alfisols, does not permit proper root development. Alfisols also contain distinct layers of gravel and weathered rock fragments at lower depths, often called 'murram'. The rooting depth of crops is limited by the presence of such layers or by compact argillic horizon. The increase in bulk density decreases the hydraulic conductivity and water diffusivity in black silty clay and infiltration rate in rainfed alluvial loam soils (Entisols, Aridisols and Inceptisols). The higher bulk density in these soils results in reduction in the infiltration rate due to less porosity and compaction which restricts the entry of water; hence more water remains on the soil surface. The irrigation and rainwater are lost by evaporation, because high-temperature conditions prevail in these areas and the soil has poor vegetative cover. The reasons for higher bulk density in these areas are excessive tillage and improper tillage time (at excessive or deficit soil moisture condition). To some extent, heavy tillage implements are also responsible for increasing the bulk density in these soils. These high mechanical impedance layers are relatively impervious resulting in water stagnation on the soil surface after heavy rainfall or irrigation and the crops turn yellow due to oxygen stress[19]. In rainfed soils, the primary particles disintegrated from aggregates in the loose upper soil move into the pores of the subsoils along with rainwater or irrigation water, thereby reducing the non-capillary pore space and increasing the bulk density. Bulk density (dry) of Vertisols varies from 1.44 to 1.88 Mg m^{-3}, with a slight increasing trend with depth[26]. Bulk density of >1.4 Mg m^{-3} may pose problem of root penetration. But roots are observed penetrating deep in soils. Higher bulk density was reported for black soils of India[26] and it increased in the soils of drier climates[15]. The increase in bulk density of soil decreases the percentage of pores greater than 0.5 mm diameter, without affecting the capillary pore space; this decrease is more drastic in heavy-textured soils (Vertisols) than light-texture soils (Alfisols, Aridisols)[19].

High bulk density in soil layers does not allow the roots to penetrate and thus reduces the rate of root elongation; the shallow root system makes the plant drought-prone during dry spells and promotes lodging during unusually wet conditions. In rainfed areas, higher bulk density results in poor seed germination and poor root development. Thus, a weak root system is developed and plants are not able to extract nutrients from the soil; most of the applied nutrients are leached out from the root zone. Higher bulk density also restricts the proper soil aeration that restricts root respiration as well as aerobic microbes that help in the transformation of different nutrients.

High permeability

High permeability and poor nutrient retention capacity are associated with sand and loamy sand texture of rainfed soils (Entisols, Aridisols and Inceptisols). These soils cover large areas of the country. Due to high permeability, most of the rainwater is lost in deeper soil layers and the availability of water in the upper soil profile is only for a short period. The high permeability and poor nutrient retention capacity of soils reduce the water and fertilizer use efficiency and cause waterlogging in areas having impervious layer at shallow depths. The low fertilizer use efficiency and high nutrient loss discourage farmers from using high levels of inputs, resulting in low yields of pearl millet, maize, wheat and barley in western India, and sorghum, maize, finger millet and sugarcane in southern India.

Slow permeability and extremes of consistence

Slow permeability is associated with black Vertisol soils of rainfed regions. The problems of these soils are linked with topography and annual rainfall of the regions. Due to slow permeability, water stagnates in the field during heavy rainfall; paddy crops fail in lowland areas and most of the upland crops like sorghum and maize produce low yields. Further, the prevailing anaerobic condition causes the accumulation of carbon dioxide and other toxic by-products in this zone, which restrict root growth. In the rainfed areas, where natural slope is less than 1.5%, crop growth suffers due to temporary waterlogging of soil which develops oxygen stress in the root zone, if rainfall exceeds 1000 mm. In some areas, water may accumulate on the soil surface from a few centimetres to more than 100 cm (ref. 19). Vertisols exhibit extremes in their consistence property. They are very hard when dry

Table 5. Correlation coefficients between soil properties and water retention characteristics of soils in different rainfed regions[16]

		Water retained at		
Soil type/group	Soil properties	1/3 bar	15 bar	Available water
Vertisols/Vertic sub-groups (*n* = 63)	Sand	–0.79**	–0.77**	–0.63**
	Silt	0.04^{ns}	-0.07^{ns}	0.22^{ns}
	Clay	0.87**	0.90**	0.60**
Alfisols/oxisols (*n* = 28)	Sand	–0.49**	–0.89**	0.25^{ns}
	Silt	0.16^{ns}	0.36^{ns}	-0.16^{ns}
	Clay	0.48**	0.82**	-0.20^{ns}
Inceptisols/Entisols (*n* = 42)	Sand	–0.96**	–0.73**	–0.87**
	Silt	0.78**	0.72**	0.62**
	Clay	0.89**	0.61**	0.84**
Aridisols (*n* = 12)	Sand	–0.99**	–0.96**	–0.98**
	Silt	0.98**	0.94**	0.97**
	Clay	0.99**	0.96**	0.98**

**Significant at 1% level of significance; ns, Nonsignificant; *n*, Number of observations.

and very sticky and plastic when wet[27]. These permit tillage and seedbed preparation only within a narrow range of moisture content. The cultivation of Vertisols when too dry or too wet may therefore result in poor tilth due to cloddy or puddled structure respectively[28].

Soil water retention characteristics

A study conducted by Rao *et al.*[16] in different soils of rainfed regions revealed that water retention at 0.33 and 15 bar of various soil types was positively correlated with clay content. Thus, clay content showed highly significant positive correlation with water retention parameters in all the soil types of rainfed soils (Table 5). In Vertisols and associated soils with high clay content, higher water retention at both the tension levels (at 0.33 bar and 15 bar) was observed. Sand content showed a negative correlation with water retention in most of the soil types. The data further revealed that in Inceptisols, Entisols and Aridisols, silt fraction also played a significant role in water retention at both the suction levels (0.33 and 15 bar; Table 5). In rainfed Vertisols, there was a significant positive correlation between exchangeable sodium percentage (ESP) and water retention at 33 kPa and higher tension levels up to 1500 kPa. Kadu *et al.*[29] revealed that in Vertisols with high exchangeable Na^+, water was held at higher tension and unavailable to plants. Thus in case of the Alfisols, Aridisols and Entisols, the water retention is poor due to low clay content, while in the case of Vertisols, the high Na^+ ion disturbed water retention.

Available water content

Figure 2 provides the information on available water content of different soil orders in rainfed agriculture. The available water content was higher in rainfed Vertisols followed by Inceptisol/Entisols, Alfisols and was least in Aridisols. The available water storage capacity of red Alfisols was poor, resulting in quick drying of the soils.

Rao *et al.*[16] reported that the available water content of some rainfed Vertisols present in India ranged from 4% at Arija (maize-based production system) to 21% at Bijapur, Karnataka (rabi–sorghum based production system). When averaged over different rainfed Vertisol locations, available water content ranged between 11% and 14%. Similarly, Alfisols/Oxisols at Ranchi, Jharkhand (rice-based production system) showed a range 4–5%, while at Anantapur, AP (groundnut-based production system) ranged from 9% to 12% available water content. Inceptisols/Entisols at Rakh-Dhiansar (maize-based production system) showed available water content in the range 1% to 4%, while at Faizabad, UP (rice-based production system) it varied from 11% to 20% available water content. In Aridisols at SK Nagar (pearl millet-based production system), available water content ranged from 1% to 3%, while it ranged from 7% to 13% at Hisar (pearl millet-based production system).

Deshmukh *et al.*[17] showed that the available water content of rainfed Vertisols varied from 19.0% to 23.6%, 15.2% to 23.8%, and 19.0% to 26.3% in Nagpur (Typic Haplusterts), Amravati (Sodic Haplusterts) and Akola (Sodic Haplusterts), Maharashtra respectively, in different horizons. Data clearly indicated that there were large variations in the available water content in the rainfed soils even within the same soil order. The low available water content of these soils limits crop choice and badly affects plant growth, resulting in poor productivity in rainfed areas.

It has been reported that a deep rainfed Vertisol at Hyderabad is able to hold about 250 mm m^{-1} of available water for crop production, once the profile is fully saturated. This is in contrast to the much lower capacity to hold water from nearby related shallow soils (Vertic Inceptisols and Inceptisols) and nearby deep Alfisols, which can rarely store more than 150 mm m^{-1} water[28]. The soil water storage capacity is particularly important in rainfed regions with uncertain rainfall distribution. Based on the estimates of week-to-week changes in available moisture in relation to potential evaporative demands, Krantz *et al.*[28] concluded that the growing season on a deep Vertisol at ICRISAT, Hyderabad centre was 21–33 weeks, whereas it was only 14–21 weeks on a nearby Alfisol. Kadu *et al.*[30] observed that though the Vertisols can hold sufficient water for optimum crop growth, the available water content had no significant correlation with cotton yield due to poor internal drainage in the subsoil. In rainfed Vertisols, the available water (available water content and plant available water content) required for better yield depends on rainwater stored in the profile and the capacity of the soil to release the same during crop growth period. This implies that, after the cessation of rainfall, the water held at higher tension in Vertisols is not available to the plant. Deshmukh *et al.*[17] found a significant positive correlation between yield of cotton and plant available water content (estimated at 100–1500 kPa for non-sodic and 300–1500 kPa for sodic soils; Figure 3). This suggests that during crop growth, estimated amount of water (available water content and plant available water content) is not released because of prevalence of Mg^{2+} and Na^{+} ions on exchange sites in soils of semi-arid region of Maharashtra. According to these authors, plant available water content is an important biophysical parameter in evaluating rainfed Vertisols for deep-rooted crops.

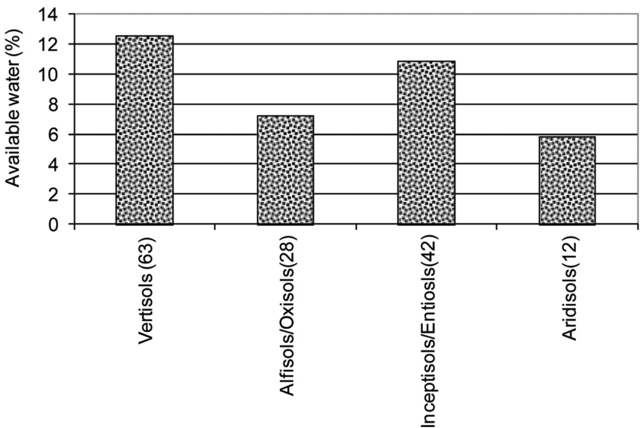

Figure 2. Available water content in soil profile in different soil orders under rainfed production systems[16]. Values in brackets indicate number of observations.

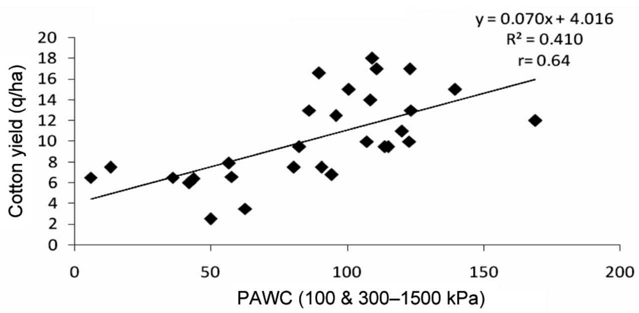

Figure 3. Relationship between plant available water content (PAWC) and cotton yield[17].

Water transmission characteristics

A good distribution of pores throughout a soil profile is vitally important for crop growth, which is necessary for water, air and nutrients to circulate in the soil. The soils in rainfed regions, particularly Entisols and Aridisols, contain good hydraulic conductivity. In case of Alfisols, lack of fine clay particles and low amount of organic matter within the soil matrix limit the water transmission characteristics. Alfisols in these areas are mostly structureless or massive, and hence have low hydraulic conductivity. ESP is an important factor which positively contributes to water retention, but negatively to water movement (saturated hydraulic conductivity) and yield of crop in Vertisols. The subsoil sodicity impairs the hydraulic properties, as evident from the significant negative correlation between ESP and saturated hydraulic conductivity in Vertisols[17]. It has been reported that significant negative correlation between extractable Mg and saturated hydraulic conductivity ($r = 0.705$) indicates the deterioration of hydraulic properties due to clay dispersion caused by Mg^{+2} ions. ESP increases with depth in semi-arid soils, but this trend is not observed in soils of the sub-humid region. The ESP value more than 5 impairs the hydraulic properties of soils due to deterioration in their physical properties[30,31].

Infiltration characteristics

Infiltration through the soil surface depends on soil surface features and hydraulic conductivity in the underlying soil mass. It is a soil surface phenomenon and important in rainfed areas. If the soil has high infiltration rate (as in the case of Entisols and Aridisols), water applied through irrigation and received through rainfall enters into the soil as early as possible, which in turn reduces the evaporation and run-off losses. Infiltration is a consequence of porosity and it also influences porosity by detaching, transporting and relocating soil particles through its mechanical action. Change in porosity leads to change in water movement through the soil profile. The water supply of soils is also reduced by impaired infiltration due to lower conductivity of the pores wherever vegetative cover is not available to dissipate the energy of falling raindrops. Cultivation increases infiltration initially but in the long run, porosity and infiltration rates are usually lower than those in untilled soil under mulch cover. Further, these soils are denuded and/or cultivated, high rainfall intensities cause particle detachment and degeneration of infiltration capacity. This results in high run-off and soil loss. Low water-holding capacity of the semi-arid tropical Alfisols can be attributed to the fact that little water is transmitted to deeper layers of the profile due to poor porosity as a result of seal formation. Organic carbon content of Vertisols is low to moderate due to higher rate of decomposition in semi-arid environment[32]. Besides the higher exchangeable sodium content of clay complexes in black soils, these soils also suffer from compactness of the subsoil layer. Thus, these soils have low infiltration and percolation rates, less movement of nutrients and free air transport within the soil profile. In sandy soils, the decrease in porosity is less; it is higher in soils having higher clay content (Vertisols). This invariably leads to decrease in water movement through soil profile and deep percolation[33]. Thus, infiltration of rainwater into the soil is a basic and important process directly controlling surface run-off, soil erosion, soil water storage and deep percolation.

Summary

In rainfed regions there are several constraints related to soil, crop, topography and climate, which determine crop productivity. Among these, soil physical constraints are predominant, which severely limit the crop production potential. Among the physical constraints, soil structural constraints which include surface crusting and hardening are prominent. This occurs because in these soils surface horizons are characterized by less clay content and low organic matter. Another important soil physical constraint is the subsurface hardpan and compactness which also adversely hampers the crop growth in these soils. Most of the soils of rainfed regions have undesirable water retention and transmission characteristics that again pose a serious threat to crop cultivation. In Vertisols, extreme consistency poses the problem of narrow workability of soils. Thus, soils of rainfed regions suffer on account of several physical constraints which make these soils less productive.

1. Abrol, I. P. and Katyal, J. C., Sealing, crusting and hardening soils in Indian agriculture. In Paper presented at the Second International Symposium on Sealing, Crusting and Hardening soils: Productivity and Constraints, Queensland, Australia, 7–11 February 1994.
2. Mayande, V. M. and Katyal, J. C., Low cost improved seeding implements for rainfed agriculture, Technical Bulletin 3, Central Research Institute for Dryland Agriculture, Hyderabad, 1996, p. 26.
3. Singh, R. P., Dryland agriculture research in India. In *40 years of Agricultural Research and Education in India*, Krishi Anusandhan Bhavan, New Delhi,1989, pp. 136–164.
4. Singh, H. P., Sharma, K. L., Venkateswarlu, B. and Neelaveni, K., Prospects of Indian agriculture with special reference to nutrient management under rainfed ecosystems. In National Workshop on Long-term Soil Fertility Management through Integrated Plant Nutrient Supply System, Indian Institute of Soil Science, Bhopal, 2–4 April 1998.
5. Venkteswarlu, B. and Rama Rao, C. A., Rainfed agriculture: challenges of climate change. In Agriculture Year Book 2010, Agriculture Today, 2011, pp. 43–45.
6. Government of India, Agricultural statistics at a glance. Ministry of Agriculture, Government of India, 1994, p. 140.
7. CRIDA, Vision 2025: CRIDA perspective plan. Central Research Institute for Dryland Agriculture, Hyderabad, 2007, pp. 1–52.
8. Singh, H. P., Venkateswarlu, B., Vittal, K. P. R. and Ramachandran, K., Management of rainfed agro-ecosystem. In *Natural Resource Management for Agriculture Production in India* (eds Yadav, J. S. P. and Singh, G. B.), Indian Society of Soil Science, New Delhi, 2000, pp. 669–774.
9. Rama Rao, C. A. *et al.*, Climate change projections – a district-wise analysis for rainfed regions in India. *J. Agrometeorol.*, 2013, **15** (Spec. Issue I), pp. 13–19.
10. Katyal, J. C. and John, F., *Research for Rainfed Farming*, Central Research Institute for Dryland Agriculture, Hyderabad, 1997.
11. Painuli, D. K. and Yadav, R. P., Tillage requirements of Indian soils. In *50 Years of Natural Resource Management Research* (eds Singh, G. B. and Sharma, B. R.), Division of Natural Resource Management, Indian Council of Agricultural Research, New Delhi, 1998, pp. 245–262.
12. Singh, H. P., Management of the rainfed areas. In *50 years of Natural Resource Management Research* (eds Singh, G. B. and Sharma, B. R.), Division of Natural Resource Management, Indian Council of Agricultural Research, New Delhi, 1998, pp. 537–578.
13. Sharma, K. L., Mandal, B. and Venkateswarlu, B., Soil quality and productivity improvement under rainfed conditions – Indian perspectives. In *Resource Management for Sustainable Agriculture* (eds Abrol, V. and Sharma, P.), In European Union, Tech, Rijeka, Croatia, 2012, pp. 203–230; doi:10.5772/45870.
14. Bhattacharyya, T. *et al.*, Soils of India: historical perspective, classification, and recent advances. *Curr. Sci.*, 2013, **104**, 1308–1323.
15. Bhattacharyya, T. *et al.*, Physical and chemical properties of red and black soils of selected benchmark spots for carbon sequestration studies in semi-arid tropics of India. In Global Theme on Agroecosystems, Report No. 35, International Crops Research Institute for Semiarid Tropics, Patancheru and Indian Council of Agricultural Research, New Delhi, 2007, pp. 1–232.
16. Rao, C. S., Rao, K. V., Chary, G. R., Vittal, K. P. R., Sahrawat, K. L. and Sumanta, K., Water retention characteristics of various soil types under diverse rainfed production systems of India. *Indian J. Dryland Agric. Res. Dev.*, 2009, **24**, 1–7.
17. Deshmukh, H. V., Chandran, P., Pal, D. K., Ray, S. K., Bhattacharyya, T. and Potdar, S. S., A pragmatic method to estimate plant available water capacity (PAWC) of rainfed cracking clay soils (Vertisols) of Maharashtra, Central India. *Clay Res.*, 2014, **33**, 1–14.
18. Raychaudhuri, S. P., Roy, B. B., Gupta, S. P. and Dewan, M. L., Black soils of India. National Institute of Science of India, 1963.
19. Ghildyal, B. P. and Gupta, R. P., Soil structure problem and management. Division of Soil Physics, Indian Agricultural Research Institute, New Delhi, 1991, p. 58.
20. Sivarajasingham, S., Alexander, L. T., Cady, J. G. and Cline, M. G., Laterite. *Adv. Agron.*, 1962, **14**, 1–60.

21. Agrawal, R. P. and Batra, M. L., Soil moisture and seedling emergence under surface crusting. *J. Indian Soc. Soil Sci.*, 1977, **25**, 77–80.
22. Sharma, D. P. and Agrawal, R. P., Seedling emergence behavior of bajra, cotton, and guar as affected by surface crust strength. *Mysore J. Agric. Sci.*, 1979, **13**, 400–404.
23. Ranganatha, B. R. and Satyanarayana, T., Soil crust and its effect on seedling emergence. *J. Indian Soc. Soil Sci.*, 1979, **27**, 369–374.
24. Singh, B. and Chowdhary, M. R., Effect of intensity, duration and time of rain and soil type on soil crusting and seedling emergence in pearl millet. *J. Indian Soc. Soil Sci.*, 1985, **33**,145–148.
25. Sinha, A. K. and Ghildyal, B. P., Emergence force of crop seedlings. *Plant Soil*, 1979, **51**, 153–156.
26. Murthy, R. S., Bhattacharjee, J. C., Landey, R. J. and Pofali, R. M., Distribution, characteristics and classification of Vertisols. In *Vertisols and Rice Soils of the Tropics*, Twelfth International Congress of Soil Science, New Delhi, India, 8–16 February 1982, pp. 3–22.
27. Jewitt, T. N., Law, R. D. and Virgo, K. J., Vertisol soils of the tropics and subtropics: Their management and use. *Outlook Agric.*, 1979, **10**, 33–40.
28. Krantz, B. A., Kampen, J. and Virmani, S. M., Soil and water conservation and utilization for increased food production in the semi-arid tropics. International Crops Research Institute for the Semi-Arid Tropics, Hyderabad, 1979.
29. Kadu, P. R., Vaidya, P. H., Balpande, S. S., Satyavathi, P. L. A. and Pal, D. K., Use of hydraulic conductivity to evaluate the suitability of Vertisols for deep-rooted crops in semi-arid parts of central India. *Soil Use Manage.*, 2003, **13**, 208–216.
30. Kadu, P. R., Pal, D. K. and Deshpande, S. B., Effect of low exchangeable sodium on hydraulic conductivity and drainage in shrink–swell soils of Purna Valley, Maharashtra. *Clay Res.*, 1993, **12**, 65–70.
31. Balpande, S. S., Deshpande, S. B. and Pal, D. K., Factors and processes of soil degradation in Vertisols of the Purna Valley, Maharahstra, India. *Land Degrad. Dev.*, 1996, **7**, 313–324.
32. Velayutham, M., Pal, D. K. and Bhattacharyya, T., Organic carbon stock in Indian soil. In *Global Climate Change and Tropical Ecosystems – Advances in Soil Science* (eds Lal, R., Kimble, J. M. and Stewart, B. A.), CRC Press, Boca Raton, FL, USA 2000, pp. 71–95.
33. Painuli, D. K. and Pagliai, M., Changes in porosity of three different soils induced by water infiltration. *J. Indian Soc. Soil Sci.*, 1996, **44**, 361–364.

Received 12 May 2015; revised accepted 28 February 2017

doi: 10.18520/cs/v112/i12/2405-2414