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A Pragmatic Method to Estimate Plant Available Water Capacity (PAWC) of Rainfed Cracking Clay Soils (Vertisols) of Maharashtra, Central India

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Abstract *:* Three Vertisols from Nagpur, Amravati and Akola districts were studied in detail to understand the relation between moisture and soil properties. These soils are deep and during dry periods cracks cut through the slickensides in some soils with subsoil sodicity. A significant positive correlation between available water content (AWC) and smectite content, exchangeable sodium percentage (ESP) and exchangeable magnesium percentage (EMP) indicates the nature of clay and cations in exchange site plays an important role in retaining and releasing moisture. Studies on biophysical factors on water retention and release, and cotton yield in 32 Vertisols indicate that the determination of AWC and PAWC at 33 and 1500 kPa overestimates the soil moisture content because in field conditions soil water in the subsoil do not reach the saturation at 33kPa due to low to very low saturated hydraulic conductivity. A significant positive correlation between PAWC (estimated at 100-1500 kPa for non-sodic and 300-1500 kPa for sodic soils), and yield of cotton indicates that the PAWC estimated by this method can be considered as an important biophysical parameter for evaluation of rain fed Vertisols for growing deep rooted crops in Indian states in general and Vidarbha region of Maharashtra state in particular.

Key words : Plant available water capacity (PAWC), Available water content (AWC), Sodic and non-sodic Vertisols.

In India, cracking clay soils (Vertisols and their intergrades) are one of the major soils supporting agriculture. The revised estimates indicate Vertisols and the associated soils in India occupy 76.4 m ha and 35.5% of which is in the state of Maharashtra (Mandal *et al*., 2014). The majority of Vertisols distributed in the semiarid and arid part of central India, are rainfed. In many areas under Vertisols,

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cultural operations using handheld or animal-drawn implements are difficult. High ESP in the sub soils disperses the clay and restricts the water movement in the profile. Farmers faced with these difficulties often cultivate them only in the post-rainy season. Thus Vertisols (without soil modifiers, Pal *et al*., 2006) have limitations that restrict their full potential to grow both rainy season and winter crops (NBSS&LUP-ICRISAT, 1991) and this dismal agricultural situation is seen in Amravati and Akola districts of Maharashtra state of central India. Either rainy season or winter crop is grown in Vertisols of the western part of the Amravati district and the adjoining Akola district, whereas both rainy and winter crops are grown in those of Nagpur district with limited irrigation (NBSS&LUP-ICRISAT, 1991).

Vertisols vary in their morphology particularly cracking behaviour and cropping pattern from Nagpur to Akola district within a distance of about 100-200 km (NBSS & LUP-ICRISAT, 1991). Generally cracks are observed up to 40-60 cm depth (*ie*. upto the depth of initiation of slickenside) in Nagpur and eastern part of Amravati districts but in Akola cracks penetrates through the slickenside, thereby depleting the moisture from the subsoil. The diffential crack morphology is due to some intrinsic soil properties such as pH, hydraulic properties, ESP and presence of pedogenic $CaCO_3$, and the nature and content of clay minerals (Balpande *et al*., 1996; Vaidya and Pal, 2002).

The hydraulic properties of Vertisols are impaired due to the formation of pedogenic $CaCO_3$ and the concomitant development of subsoil sodicity even at a low ESP (≥5) (Kadu *et al*., 1993; Balpande *et al*., 1996; Pal *et al*., 2001; Vaidya and Pal, 2002) which affects the yield of crops (Kadu *et al*., 2003). With higher amount of sodium in the exchange complex (with a low electrolyte concentration), the interlayer is hydrated forming a diffuse double layer structure (Wilding and Tessier, 1988). Thus in sodic soils , the water is held at a higher tension and this water is rendered unavailable for plant and thus Kadu *et al*. (2003) suggested that the saturated hydraulic conductivity (sHC) is a more meaningful concept than AWC in Vertisols. This questions the validity of estimating the AWC in Vertisols on the basis of moisture held at 33 kPa and 1500 kPa tensions. Therefore, inclusion of AWC as one of the soil parameters for suitability of deep rooted crops like cotton (Sehgal, 1991; NBSS&LUP, 1994; Mandal *et al*., 2002) is inappropriate. This warrants a pragmatic method to estimate the actual antecedent soil water in terms of AWC and plant available water capacity (PAWC) just after the cessation of rains considering the amount of water that has actually percolated into the Vertisol profile under rainfed conditions. In reality, the yield of deep-rooted crops in Vertisols depends primarily on the amount of rain water stored at depth in the soil profile, and the extent to which this soil water is released during crop growth (Pal *et al*., 2012). In view of this predicament the present study was undertaken with two objectives, (i) to study the bio-physical factors that influence the soils' water retention and release characteristics which ultimately impairs the productivity and yield of crops, and (ii) to suggest a method to estimate the AWC and PAWC that relate significantly with cotton yield data collected from the farmers' field.

Materials and Methods

Representative Vertisols (without soil modifiers) from the districts of Nagpur (Linga series), Amravati (Asra) and Akola (Paral) of Maharashtra state were selected and studied in detail. All the soils were developed in basaltic alluvium and occur in alluvial plains of 1-2% slopes. The study area falls in a climosequence with the highest rain in Nagpur (1010mm), followed by decreased amount at Amravati (975mm) and Akola (793mm) representing a climosequence from dry sub-humid to semi arid climate. In order to accomplish the above objectives cotton yield data were collected from the farmers, and the soil properties data held by the Division of Soil Resource Studies were utilized supplemented by new data.

Methods

Morphological properties of pedons were studied as per Soil Survey Manual (Soil Survey Division Staff, 1995; Bhattacharyya *et al*., 2009) and horizon wise samples were collected for laboratory analysis. Both sphenoid and slickensides observed in the field confirm the presence of slickensided B horizon (Bss) and thus classified as Vertisols (Soil Survey Staff, 1999)

The bulk density of soil was determined using core samplers (Richards, 1954). The moisture retention and release behaviour within the available range of 33, 100, 300, 500, 800, 1000 and 1500 kPa were measured on less than 2 mm size sample using pressure plate membrane apparatus as per method outlined by Richards (1954). Plant available water capacity was determined by using the formula suggested by Gardner *et al*. (1984), modified by Coughlan *et al.* (1987).

The particle size distribution was determined as per the International Pipette method after the removal of calcium carbonate, organic matter and free iron oxides. Sand (2000-50µm), silt (50-2µm), total clay (<2µm) and fine clay (<0.2 µm) fractions were separated according to the size segregation procedure of Jackson (1979).The water dispersible clay was determined by the International Pipette method. Saturated hydraulic conductivity (sHC) was determined by constant head permeameter (Richards, 1954). Carbonate clay was estimated by rapid titration, (Piper, 1950) using fine earth sample of less than 2 mm drawn for water dispersible clay. The $CaCO_3$, pH, cation exchange capacity

(CEC), and exchangeable bases were determined following standard methods (Richards, 1954; Jackson, 1973). Extractable Ca and Mg were determined following the method of 1N Na Cl solution extraction (Piper, 1950)

Results and Discussion

Al though we have analytical data for many Vertisols of this area, for brevity one representative shrink-swell pedon from each district is presented below.

Morphological Properties of Soils

All the soils are very deep (>150 cm) and the colour varies from very dark grayish brown (10YR 3/2 M) to dark brown (10YR 3/3M) and structure is subangular blocky. The Vertisols generally had subangular to angular blocky structure. Intersecting slickensides forming parallelopipeds with their long axes tilted at $30\text{-}45^0$ from the horizontal were prominent in subsoils. All the pedons effervesced with HCl throughout the depth indicating presence of $CaCO_3$. The soils are Vertisols , but their cracks and $CaCO_3$ content differ. Cracks >0.5 cm wide extend down to the zones of sphenoids and wedge-shaped peds with smooth or slickensided surfaces in sub-humid soils, but cracks cut through these zones in semiarid soils. High $CaCO_3$ content indicate that a reduction in mean annual rainfall (MAR) leads to the formation of calcareous and alkaline soils in Akola. Thus, though the soils are Vertisols with comparable clay content, the differences in morphology are due to the modifications related to climatic variations (Pal *et al*., 2012).

Physical Properties of Soils

The total clay content varies from 59 to 69 per cent, and >50% of this is fine clay (Table 1). The fine clay content ranged from 33 to 65.6 per cent and it gradually increased with depth, indicating clay illuviation in Vertisols (Pal *et al*., 2006, 2012). Bulk density (dry) of the soils varies from 1.44 to 1.88 with a slight increasing trend with depth. Bulk density of $\geq$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 (Murthy *et al.,* 1982) and it increased in the soils of drier climates (Bhattacharyya *et al*., 2007).

The saturated hydraulic conductivity (sHC) is higher (13.9 to 23.2 mm hr^{-1}) in the soils of sub humid region (pedon 1) than that at semi arid climates (pedons 2 and 3). In soils of semi arid climate (Asra and Paral soils) sHC decreased slowly up to the slickenside layers and then rapidly down below (Table 1). Low sHC in subsurface soils indicate poor internal drainage in soils of semiarid area. A significant positive correlation between sHC and exchangeable Ca/Mg (r=0.619) and a significant negative correlation with ESP (r = - 0.870) and EMP (r= - 0.679) indicated that hydraulic properties are impaired initially by Mg^{+2} which is further aggravated by Na^{+} due to dispersion of clays (Pal *et al*., 2006). The dispersed clay blocks

Table 1. *Physical properties of the soils*

Horizon	Depth (cm)	BD (Mg m^{-3})	sHC (mm/hr)	COLE	Partical size distribution (%)				
					Sand (2.0-0.05 mm)	Silt (0.05-0.002)	Total Clay (<0.002) mm	Fine Clay (<0.0002) mm	FC/TC
Pedon 1 : Nagpur (Linga Series : Typic Haplusterts)									
Ap	0-13	1.44	13.9	0.26	1.4	34.5	64.1	48.1	0.75
Bw1	13-35	1.59	15.37	0.27	1.1	33	66	53.8	0.81
Bw2	35-56	1.57	20.76	0.28	1.1	32.5	66.4	56.1	0.84
Bss1	56-76	1.52	14.66	0.28	1	30.9	68.1	50.6	0.75
Bss2	76-106	1.56	14.72	0.29	2	28	70	62.2	0.88
Bss3	106-139	1.48	23.23	0.3	2	28.6	69.5	61.8	0.88
Bss4	139-152+	1.47	15.13	0.3	2.1	28.7	69.3	65.6	0.94
Pedon 2 : Amravathi (Asra Series: Sodic Haplusterts)									
Ap	0-12	1.46	20.84	0.24	1.2	35.3	63.5	33	0.51
Bw1	12—28	1.55	19.89	0.24	0.7	33.5	65.8	44.2	0.67
Bw2	28—54	1.76	16.66	0.25	1.1	36.4	62.5	42.1	0.67
Bss1	54-91	1.68	2.28	0.26	0.7	38.1	61.1	41.9	0.68
Bss2	91-136	1.72	1.31	0.27	0.5	34.7	64.8	44.8	0.72
BC	136-150+	1.88	0.37	0.31	0.5	38.6	60.9	49.5	0.81
Pedon 3 : Akola (Paral series : Sodic Haplusterts)									
Ap	0-16	1.47	24.84	0.27	1.2	33.8	65	33.4	0.51
Bw1	16-39	1.62	21.13	0.28	1	33.1	66	50.2	0.76
Bss	39-75	1.54	3.81	0.26	0.8	36.2	63	37.2	0.59
Bss1	75-118	1.65	0.44	0.29	1	33	66.1	37.3	0.56
Bss2	118-144	1.64	0.39	0.28	0.8	34	65.1	42.5	0.65
Bss3	144-150+	1.59	0.45	0.29	1.1	39.4	59.4	36.7	0.61

both macro and micro-pores of soils, resulting in poor drainage.

The moisture retention and release behaviour data at different tensions within the upper and lower limits of available water (Table 2) indicate that the increase in water content with depth at field capacity is nominal in Pedon 1. In other soils the difference in moisture stored at 1000 and 1500 kPa was very less, particularly in horizons where ESP is >5. Though there is a decrease in moisture retention at different tensions from 33 kPa to 1500 kPa the release of moisture after 800 kPa is not substantial particularly in soils with subsoil sodicity (pedons 2 and 3). The AWC of soils in different horizons varied from 19.0 to 23.6%, 15.2 to 23.8% and 19.0 to 26.3% in pedons 1, 2 and 3, respectively. PAWC (considering water content maximum at 33 kPa) of soils estimated at different horizons increased with depth and the values averaged for 100cm depth is almost comparable among non-sodic Linga soils (259.9 mm) and sodic Asra and Paral soils (Table 2), and it is in contrast to lesser

Table 2. *Water retention of soils at different tensions*

Horizon	33 kPa(%)	100 kPa (%)	300 kPa (%)	500 kPa (%)	800 kPa (%)	1000 kPa (%)	1500 kPa (%)	AWC (%)	PAWC* (mm)
Pedon 1: Nagpur (Typic Haplusterts)									
Ap	42.0	28.8	28.4	28.2	25.6	22.5	22.4	19.6	
Bw1	41.1	29.1	29.3	28.0	25.9	22.5	22.1	19.0	
Bw2	44.3	29.4	29.6	28.7	26.5	23.6	21.4	22.9	259.9[a]
Bss1	45.3	29.9	28.9	28.5	27.0	23.3	22.4	23.0	122.9[b]
Bss2	47.6	33.9	31.5	30.2	29.4	24.8	23.9	23.7	
Bss3	47.7	33.8	34.0	32.0	29.3	25.2	24.8	22.9	
Bss4	47.8	33.0	32.5	31.8	30.3	27.0	26.1	21.7	
Pedon 2 : Amravati (Sodic Haplusterts)									
Ap	34.1	22.5	22.4	22.3	21.3	19.2	18.4	15.8	
Bw1	34.3	23.7	23.1	22.9	21.2	19.7	19.0	15.3	
Bw2	37.9	25.3	24.8	24.7	23.6	20.4	19.2	18.7	217.5[a]
Bss1	41.8	27.9	26.8	26.5	24.7	21.5	21.4	20.4	102.6[b]
Bss2	45.6	31.4	30.8	28.5	26.0	22.7	21.8	23.8	90.6[c]
BC	46.7	31.3	30.8	28.8	26.4	23.6	22.2	24.5	
Pedon 3 : Akola (Sodic Haplusterts)									
Ap	41.4	27.7	26.8	26.5	24.7	23.6	21.2	20.3	
Bw1	41.4	27.8	27.2	27.7	25.9	24.4	22.4	19.1	
Bw2	45.8	32.4	31.6	30.3	27.8	25.1	22.3	23.5	218.7[a]
Bss1	48.4	34.5	33.6	31.5	28.5	26.1	26.0	22.3	126.9[b]
Bss2	52.1	36.4	34.8	32.5	29.3	26.5	26.3	25.8	113.8[c]
Bss3	51.9	35.6	33.0	31.5	28.8	25.5	25.4	26.3	

*PAWC mm= [a] (33-1500kPa), [b] =nonsodic (100-1500kPa), [c] =sodic (300-1500kPa)

yield of cotton in sodic soils (Kadu *et al*, 2003). Thus Kadu *et al.* (2003) observed that though the Vertisols can hold sufficient water for optimum crop growth, the AWC has no significant correlation with cotton yield due to poor internal drainage in the subsoils.

Chemical Properties of Soils

Soils are moderately to strongly alkaline in reaction. The higher pH (>8.0) in soils of semiarid climate is probably due to higher ESP (Table 3). A positive and significant correlation between pH and ESP (r=0.852 at 1% level) is an indication of this relationship. Organic carbon (OC) content of these soils are low to moderate due to higher rate of decomposition in semi-arid environment (Velayutham *et al*., 2000). Both free carbonates and $CaCO_3$ equivalent on fine earth basis increased with decrease in rainfall was evident from this study (Table 3). Calcareousness in Vertisols is due to the presence of both pedogenic and non-pedogenic $CaCO_3$ (Pal *et al*., 2000a). Since both the forms react with HCl, it is difficult to distinguish one from the other. The CEC of these soils are high and among the extractable cations, Ca^{2+} is dominant followed by Mg^{2+}, Na^{+} and K^{+} except in Pedon 1 (Table 3). Extractable Ca^{2+} decreases with depth whereas Mg^{+2} increased from subhumid to semi-arid climate. This is due to precipitation of carbonates caused by decrease in rainfall and high evapotranspiration demand (Table 3). A significant positive correlation between sHC and Ca/Mg ratio (r = 0.619) indicate the positive role of Ca^{+2} ion in improving drainage of Vertisols. A significant negative correlation between extractable Mg^{+2} and sHC (r=-0.705) indicates the deterioration of hydraulic properties due to clay dispersion caused by Mg^{+2} ions. ESP increased with depth in semiarid soils but this trend is not observed in soils of the subhumid region. ESP (>5) impairs the hydraulic properties of soils due to deterioration of physical properties of soil (Kadu *et al*., 1993; Balpande *et al*., 1996). A significant positive correlation observed between ESP and water retention at 33 kPa (r = 0.563) and at other tension indicates the capacity of these soils to retain more moisture at high level of ESP.

Relation between water retention and soil parameters with yield of cotton

In rainfed Vertisols, the available water (AWC and PAWC) required for better yield depends on the rain water stored in the profile and the capacity of the soil to release the same during crop growth .This depends on many biophysical properties and among them, sHC, ESP and pedogenic carbonates plays an important role. Kadu *et al*., (2003) observed that in Vertisols with high amount smectite clay along with subsoil sodicity (ESP>5), the water held at 33kPa may not be available to plants, and the AWC estimated on this basis amounts to overestimation. Thus we estimated the AWC and PAWC at different tensions for 32 Vertisols at sites (Table 4) of the three districts and correlated with yield and other soil properties.

The AWC of Vertisols (Table 4) indicates that the soils can hold sufficient water for optimum growth, but correlation between yield of cotton and AWC was poor and non-significant. This indicates that, after the cessation of rain, the water is held at higher tensions in Vertisols. This prompted us to try the PAWC at a combination of different tensions. A significant positive correlation between yield of cotton and PAWC (estimated at 100-1500 kPa for non-sodic and 300-1500 kPa for sodic soils) (Table 5 and Fig. 1) was obtained. This suggests that during the crop growth, estimated amount of water (AWC and PAWC) estimated on the basis of 33 kPa and 1500 kPa, is not released because of prevalence of Na^{+} ions on exchange sites in soils of semi arid region (Amaravati and Akola). This is supported

Table 3. *Chemical properties of soils*

Horizon	pH (1:2)	Org.C	$CaCO_3$	$ClayCO_3$	CEC	Exchangeable Cations					Base saturation (%)	Exch. Na (%)	Exch. Mg (%)	Exch. Ca/Mg
						Ca^{2+}	Mg^{2+}	Na^{+}	K^{+}	Σ of cations				
		(%)			*Cmol(p+)kg^{-1}*									
Pedon 1 : Nagpur (Typic Haplusterts)														
Ap	7.8	0.82	4.67	1.04	60.4	50.57	3.3	0.19	1.02	55.07	91.2	0.31	5.45	15.32
Bw1	7.8	0.67	4.34	1.08	64	50.89	3.08	0.22	0.78	54.96	85.8	0.34	4.8	16.52
Bw2	7.9	0.52	4.66	1.08	64.5	50.43	2.91	0.19	0.67	54.2	84.1	0.3	4.51	17.32
Bss1	7.9	0.54	7.99	1.08	64.5	49.25	3.01	0.22	0.75	53.22	91.3	0.37	4.66	16.36
Bss2	7.9	0.44	5.53	1.09	65.9	49.41	6.27	0.17	0.72	56.57	85.9	0.25	9.52	7.88
Bss3	7.8	0.59	5.55	1.02	64.6	50.88	3.28	0.24	0.79	55.18	85.4	0.37	5.07	15.51
Bss4	7.9	0.59	4.62	1.1	64.1	49.68	5.02	0.22	0.71	55.63	86.7	0.34	7.83	9.9
Pedon 2 :Amravati (Sodic Haplusterts)														
Ap	8.1	0.8	14.24	1.84	52.1	43.82	3.74	0.14	1.04	48.74	93.5	0.27	7.17	11.71
Bw1	8.2	0.65	14.97	1.74	50.9	41.27	7.61	0.62	0.56	50.06	98.4	1.21	14.96	5.42
Bw2	8.4	0.56	14.02	1.89	51.9	39.92	6.5	1.79	0.51	48.73	93.8	3.44	12.51	6.14
Bss1	8.6	0.52	13.12	1.84	53.5	35.66	8.74	3.95	0.51	48.34	91.2	7.37	16.32	4.08
Bss2	8.7	0.48	12.93	1.88	52.6	30.93	9.37	6.77	0.46	47.53	90.4	12.88	17.82	3.3
BC	8.6	0.3	18.13	1.73	52.1	27.98	10.9	8.41	0.49	47.74	91.6	16.15	20.84	2.57
Pedon 3 : Akola (Sodic Haplusterts)														
Ap	8.1	0.94	8.7	1.77	60.5	41.47	6.15	0.26	1.76	49.64	82.7	0.43	10.16	6.74
Bw1	8.4	0.75	10.01	1.75	59.9	39.07	11.5	1.44	0.69	52.73	88	2.4	19.23	3.38
Bw2	8.6	0.68	8.36	1.72	63.4	35.23	10.8	3.48	0.93	50.47	86	5.93	17.1	3.25
Bss1	8.7	0.61	9.65	1.67	70.3	36.09	10.3	5.43	0.89	52.75	82.2	7.72	14.7	3.49
Bss2	8.6	0.56	9.99	1.94	64.2	30.03	14.8	7.21	0.92	52.95	84.1	11.45	23.05	2.02
Bss3	8.7	0.41	14.87	1.94	48.5	22.61	15.7	6.9	0.69	45.89	94.7	14.24	32.38	1.44

Table 4. *Some soil properties and yield of cotton of 32 Vertisols.*

District	Pedon No.	Soil classification	AWC (%)[a]	sHC (mm/hr)[a]	ESP Max [b]	Cotton yield (q/ha) [c]	PAWC (33-1500kPa) (mm m^{-1}) [a]	PAWC (100-1500kPa) (mm m^{-1}) [a]	PAWC (300-1500kPa) (mm m^{-1})[a]	PAWC 100-1500[a] &300-1500[d] kPa(mm m^{-1})
Nagpur	1	Typic Haplustert	20	17.7	1.2	13	257.0	123.5	35.8	123.5
	2	Typic Haplustert	18	7.7	4.7	17	221.3	110.9	26.5	110.9
	3	Typic Haplustert	16	17.8	2.6	13	195.3	86.0	33.1	86.0
	4	Typic Haplustert	20	4.2	11.2	9.5	234.5	115.0	26.6	115.0
	5	Typic Haplustert	20	10.6	3.6	18	234.9	109.3	30.5	109.3
	6	Typic Haplustert	18	14.0	0.5	14	213.3	108.6	33.0	108.6
	7	Typic Calciustert	15	6.2	2.5	9.5	175.5	82.4	25.9	82.4
	8	Typic Haplustert	19	13.5	2.3	10	231.9	107.1	31.1	107.1
	9	Typic Haplustert	22	16.0	0.4	17	259.9	122.9	111.7	122.9
Amravati	10	Sodic Haplustert	18	8.8	15.7	7.5	270.3	198.7	80.4	80.4[d]
	11	Aridic Haplustert	19	18.7	4.3	15	213.7	139.6	70.0	139.6
	12	Aridic Haplustert	13	15.7	0.8	16.6	144.4	89.8	23.2	89.8
	13	Aridic Haplustert	10	9.8	1.3	6.6	130.9	57.6	20.2	57.6
	14	Aridic Haplustert	13	15.5	1.1	15	156.9	100.7	29.4	100.7
	15	Sodic Haplustert	18	7.4	16.8	7.9	284.9	134.5	56.7	56.7[d]
	16	Aridic Haplustert	15	7.8	14.5	6.8	208.8	94.4	46.1	94.4
	17	Aridic Haplustert	15	10.7	2.3	12.5	185.1	95.8	53.7	95.8
	18	Sodic Haplustert	19	1.6	44.1	2.5	271.9	233.1	49.8	49.8[d]
	19	Aridic Haplustert	15	9.9	2.2	12	212.0	169.2	32.5	169.2
	20	Sodic Haplustert	17	0.6	28.7	3.5	268.5	140.1	62.6	62.6 [d]
	21	Sodic Haplustert	18	4.2	16	6.5	249.9	109.1	36.0	36.0 [d]
	22	Aridic Haplustert	20	7.5	10.6	6	296.3	248.7	123.3	248.7
	23	Aridic Haplustert	19	2.5	1.3	10	223.8	122.7	31.6	122.7
	24	Aridic Haplustert	18	3.4	1.1	11	221.4	120.1	39.8	120.1
	25	Aridic Haplustert	26	2.4	1.4	9.5	273.8	199.2	82.0	199.2
	26	Sodic Haplustert	15	0.9	15.8	6.5	179.4	156.4	5.9	5.9 [d]
	27	Sodic Haplustert	8	3.7	23.3	7.5	111.3	95.5	13.1	13.1 [d]
	28	Sodic Haplustert	20	2.4	26.2	6	230.9	102.1	42.1	42.1 [d]
	29	Sodic Haplustert	19	11.0	12.8	7.5	217.5	102.6	90.5	90.5 [d]
Akola	30	Aridic Haplustert	17	3.5	4.2	10	215.9	107.3	39.2	107.3
	31	Sodic Haplustert	18	1.1	19.9	6.4	218.6	115.4	43.5	43.5 [d]
	32	Sodic Haplustert	22	10.3	7.7	9.5	218.7	126.9	113.8	113.8 [d]

[a]Weighted mean in 0-100 cm depth of soil; [b] maximum value in 0-100 cm depth of soil; [c] seed + lint.; AWC, available water content; [d] PAWC at 300-1500 kPa for sodic soils, ESP:exchangeable sodium percentage; sHC: saturated hydraulic conductivity. Source : Balpande, 1993; Kadu, 1997, Vaidya, 2001.

by a significant negative correlation between yield and ESP (r= - 0.75, significant at 1% level). A significant positive correlation between yield and sHC (r= 0.694 significant at 1% level) indicates that a better hydraulic properties favour the yield of cotton (Table 5).

The subsoil sodicity impaired the hydraulic properties as evident from the significant negative correlation value between ESP and sHC (Table 5). ESP is an important factor which positively contributes to water retention but negatively to water movement (sHC) and yield of crop. In soils with high exchangeable Na^+, the water is held at higher tension and thus is unavailable to plants (Kadu *et al*., 2003) Thus the method to estimate PAWC at different tensions for non-sodic and sodic soils is justified and this way a positive correlation between PAWC and cotton yield could be obtained (Fig.1). This suggests that PAWC (determined as shown in this communication) needs to be favoured as an important biophysical parameter in evaluating rainfed Vertisols (without soil modifiers) for deep rooted crops.

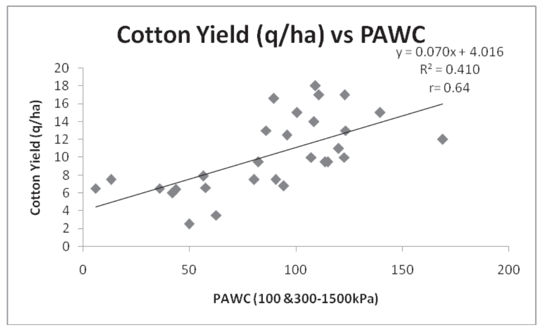

Fig 1. *Relation between yield of cotton and PAWC in Vertisols*

Conclusion

In deep cracking clay soils (Vertisols) hydraulic properties govern the movement

Table 5. Correlation between soil attributes and the yield of cotton

Sl. No.	Parameter A	Parameter B	'r' values
		Based on 32 Vertisols.	
1.	Yield of cotton (q ha^{-1})	AWC [a]	0.05
2	Yield of cotton (q ha^{-1})	PAWC[a] (33-1500 kPa)	-0.21
3	Yield of cotton (q ha^{-1})	PAWC[a] (100-1500 kPa)	-0.33
4	Yield of cotton	PAWC[c]	0.653*
5.	Yield of cotton (q ha^{-1})	ESP^{a}_{max}	-0.75*
6.	Yield of cotton (q ha^{-1})	sHC [b]	0.694*
7.	ESP	sHC	-0.584*
8.	ESP	AWC	0.21

[a] Weighted mean in 0-100 cm depth of soil; [b] maximum value in 0-100 cm depth of soil; [c] PAWC estimated at 100-1500 kPa and 300-1500 kPa for non-sodic and sodic soils, respectively. *Significant at 1% level.

of water in soil profile, and the exchangeable Mg^{+2} and Na^{+} ions restrict the release of water. These two factors, especially the ESP, influence the PAWC. Therefore, determination of AWC and PAWC considering moisture at 33 kPa. needs a relook. Instead, a pragmatic approach to estimate these two parameters would be to consider soil water held at 100 kPa for non-sodic soils and at 300 kPa for sodic cracking clay soils that contain no soil modifiers. PAWC estimated this way emerges out as one of the yield influencing parameters for evaluating Vertisols for the suitability of deep rooted crops.

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