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Pedogenic Processes Derived Plant Available Water Capacity (PAWC) for Rain-Fed Deep-Rooted Crops in Indian Vertisols: A Pragmatic Method

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Abstract: Global pedologists and edaphologists have created a huge database on the properties and management of smectitic Vertisols (cracking clay soils, CCS) but they are not adequate to optimize their use and management. This review is a synthesis of research done in the recent past at ICAR-NBSS, Nagpur, to search for real soil moisture status during crop growth. Despite the fact that the smectitic CCS do retain the highest amount of water both at 33 kPa and 1500 kPa, they have limitations to both rainy season and winter crops in the majority of CCS of central India under semi-arid tropical (SAT) environments due to lack of adequate moisture and poor porosity in their subsoils. Due to these predicaments, farmers of central India are unable to grow both rainy and winter crops in a year. Research indicated that the laboratory determined available water content (AWC) is not fully released during the crop growth period. Thus, the inclusion of AW capacity as one of the soil parameters for soil suitability analysis of cotton is inappropriate and inefficacious bio-physical parameter because soil moisture after cessation of rains remains at 100 kPa for non-sodic CCS and for sodic CCS (ESP > 5 but < 15), it remains at 300kPa. Inadequate soil moisture is due to the impairment of soil hydraulic properties caused by the dispersion of smectitic clays in the presence of both Mg and Na ions on the soil exchange complex. Recent research on depth-wise soil moisture characteristics curves indicates that the release of soil water beyond 800 kPa is negligible in Vertisols, indicating the failure in the release of soil water beyond 800 kPa is due to the dispersion of dominant nano-size smectite. The difficulties in releasing soil moisture at tension at or higher than 800 kPa suggest that moisture in micropores is held very tightly by Mg- and Na- smectite clays and thus, the release of soil moisture beyond 800 kPa is not significant throughout the depth of Vertisols. Therefore, the calculated PAWC considering the soil water held between 100-800 kPa for non-sodic CCS, and for sodic CCS, the soil water held between 300-800 kPa, showed a better significant positive correlation with cotton yields, in comparison to the correlation obtained between PAWC at 100-1500 kPa for non-sodic and 300-1500 kPa by the earlier method. The better correlation highlights how fundamentally pedogenetic processes driven by PAWC controls the movement of rainwater and its retention and release in SAT Vertisols. Therefore, PAWC is a unique bio-physical property, which can act as a guiding principle forthe growing of deep-rooted crops in abiotically stressed Vertisols of Indian SAT areas. In addition, PAWC could be applied as a useful parameter in further revision of agro-ecological sub-regions (AESRs) in black soils areas for better crop planning and ecosystem services of SAT Vertisols.

Key words: *Semi-arid climate, sodic and non-sodic cracking clay soils (Vertisols), pedogenic processs soil moisture, plant available water capacity- a pragmatic method*

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Introduction

Due to their unique morphology, cracking clay soils (CCS) (Vertisols and their intergrades) have attracted the attention of global pedologists and edaphologists. Although their research has created a large body of data on the properties and management of CCS, that are not adequate enough to optimize their use and management (Pal *et al*. 2012a). CCS occur in 80 countries, but more than 75% of the global Vertisol area is contained in India (25%), Australia (22%), Sudan (16%), the USA (6%), Chad (5%), and China (4%) (Wilding and Coulombe 1996).

Deccan basalt-derived CCS of India occupy 76.4 m ha (Mandal *et al*. 2014) and the majority of CCS occur in the semi-arid tropical (SAT) parts of central India and are mostly cultivated under rainfed conditions to support cropping sequences of sorghum/pigeon pea, cotton/pigeon-pea, and cotton/sorghum/soybean. Thus, Vertisols being a relatively homogeneous major soil group in India, support a variety of crops in subhumid moist (SHM), subhumid dry (SHD), semi-arid moist (SAM) and semi-arid dry (SAD) bio-climates, especially in central Indian states (Pal *et al*. 2012a, b). Smectitic Vertisols are well known to retain the highest amount of water both at 33 kPa and 1500 kPa, still, they have limitations to support both rainy season and winter crops under SAT environments. Lack of adequate moisture and poor porosity in their sub-soils, and occasional water-logging in the rainy season compel farmers of SAT Vertisols of India and elsewhere (Tamfuh *et al.* 2022) to grow crops in post rainy season. Moreover, the roots of annual crops cannot penetrate to the deeper depths (Pal *et al*. 2012 a, b) because of inadequate soil moisture in subsoils and thus, the farmers of Amravati and Akola districts of Vidarbha regions of central India grow only one season crop in SAT Vertisols. In contrast, both rainy and winter crops are grown with limited irrigation in SHD Vertisols of Vidarbha, namely Nagpur district (Pal *et al*. 2012a, b). A similar predicament in growing deep-rooted crops in Vertisols is also observed in the Marathwada region of central India (Zade *et al*. 2020).

Available soil moisture as biophysical factors influencing crop yields

In order to identify biophysical factors that cause a reduction in cotton yield, Kadu *et al*. (2003) indicated that the yield of rainfed cotton depends on the amount of rain water stored in the soil profile and the extent to which the soil water is released during crop growth between the rains. The available water capacity (AWC), calculated from moisture retained between field capacity (33kPa) and permanent wilting point (1500 kPa), indicated that sodic CCS as defined by Balpande *et al.* (1996) and Pal *et al*. (2006) with subsoil sodicity (exchangeable sodium percentages, ESP >5 but < 15, and saturated hydraulic conductivity, sHC < 10 mm hr^{-1}) can hold sufficient amounts of water as that of non-sodic CCS (ESP < 5 and sHC > 10 mm hr^{-1}). However, despite holding more or equal amounts of AWC, cotton yields are much less in sodic CCS than those in non-sodic soils and therefore, a non-significant negative correlation exists between cotton yield and AWC (Kadu *et al*. 2003; Pal *et al*. 2012 a, b). This is an intriguing situation especially when CCS is not sodic as per the definition of sodic soils in the US Soil Salinity Laboratory Handbook (Richards 1964). Nevertheless, the research findings of Kadu *et al.* (2003), Deshmukh *et al.* (2014) and Zade *et al*. (2020) reported a non-significant negative correlation, which clearly suggests that the laboratory-determined available water content is not fully released during the crop growth period. This fact suggests that the inclusion of AWC as one of the soil parameters for soil suitability analysis of cotton (Sehgal 1991; NBSS&LUP 1994; Mandal *et al*. 2002) is inappropriate and also proves to be an inefficacious biophysical parameter for evaluating Vertisols for cotton suitability (Kadu *et al*. 2003; Pal *et al*. 2012 a, b). Therefore, the CCS even with ESP> 5 but<15, causes an over estimation of AWC and does not reflect the real soil moisture status in the field (Pal *et al*. 2012b). Careful field estimations of soil moisture from June to September after the cessation of rains (Kadu 1997; Vaidya 2001) indicated that moisture remains at 100 kPa for non-sodic CCS (Typic Haplusterts and Aridic

Haplusterts). But for sodic CCS (Sodic Haplusterts, ESP > 5 but < 15) (Pal *et al*. 2012 a, b), moisture remains at 300 kPa because of the restriction in the free entry of rainwater down the soil profile. Poor drainage of CCS is reflected in the impairment of sHC in their subsoils. The sHC is affected by the dispersion of smectitic clay colloids in the presence of both Mg and Na ions on the soil exchange complex and decreases rapidly with depth. For sodic CCS (ESP > 5 and < 15) (Pal *et al*. 2012a, b), the decrease is sharper than in non-sodic CCS (Pal *et al*. 2009) (Fig. 1). The decreased sHC restricts the vertical and lateral movement of water in the subsoils. During the very hot summer months, lack of soil water in the subsoil of semi-arid dry CCS (Pal *et al*. 2001; Pal *et al*. 2012a), leads to the formation of deep cracks (> 0.5 cm) cutting through the Bss horizons in calcareous and sodic CCS (Fig. 2b). In contrast, cracks in non-sodic CCS extend down to the slickenside zones around 40-50 cm depth (Fig.2a), and show strong plasma separation when the exchange sites are relatively more enriched with Ca^{2+}

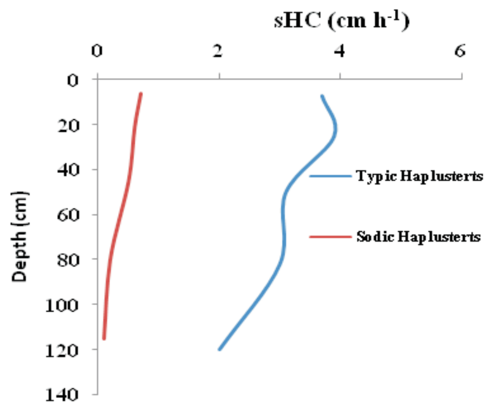


Fig.1 Saturated hydraulic conductivity (sHC hr^{-1}) of the representative non-sodic (Typic Haplusterts) and sodic (Sodic Haplusterts) Vertisols (Adapted from Pal *et al*. 2009).

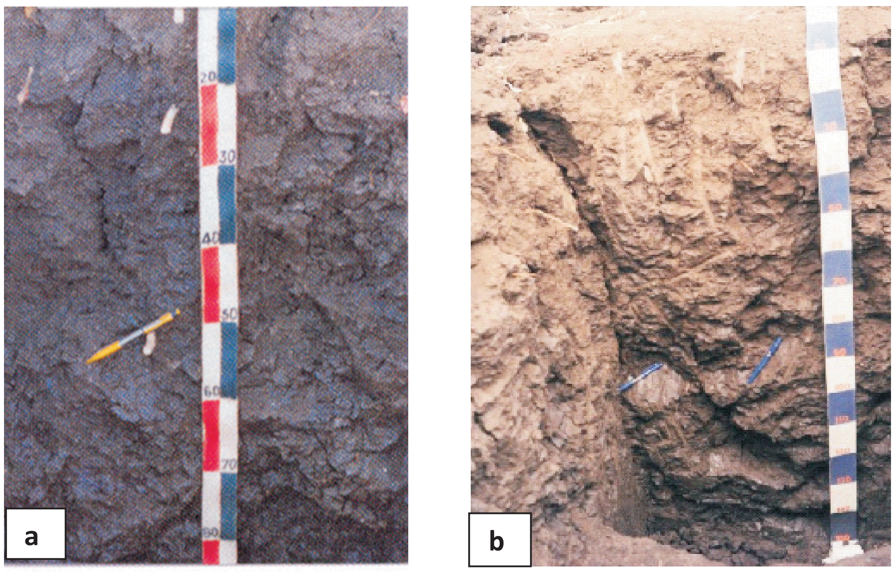


Fig.2. Cracks in non-sodic Vertisols (Typic Haplusterts) extend down to the slickenside zoneonly (a) but they puncture the whole slickensided horizons in Sodic Haplusterts/Calciusterts (b) (Photos, courtesy-DKP)

ions followed by Mg^{2+} (Fig.3a). In CCS with subsoil sodicity and moderate exchangeable magnesium, the less amount of soil water during the shrink-swell cycles restricts the swelling of smectite resulting in weaker plasma separation (Fig.3b) (Pal *et al*. 2001; Pal *et al*. 2012a). Therefore, the dominance of Ca^{2+} ions over the Mg and Na ions in the exchange sites of Vertisols is required to improve the sHC for favourable growth and yield of crops.

Initiatives to search for soil moisture during crop growth

In order to relate the actual soil moisture in field conditions, Deshmukh *et al*. (2014) calculated the PAWC at 100-1500 kPa for non-sodic and 300-1500 kPa for sodic CCS. They observed a significant positive correlation between PAWC with cotton yield data collected from the farmers' fields from 32 Vertisols of the Vidarbha region of central India. Therefore, this unique concept of PAWC would be favoured as an important biophysical parameter to evaluate rainfed Vertisols for deep-rooted crops. However, this study did not provide the depth-wise soil water release at higher tensions in the soil profile. Such a database appears to be necessary as sHC decreases with soil depth in SAT Vertisols associated with strong (for non-sodic, Fig 3a) and weak plasma separation (for sodic soils, Fig 3b) (Pal *et al*. 2001; Vaidya and Pal 2002; Pal *et al*. 2012a). Therefore, in recent research, it was envisaged (Zade *et al*. 2020) that moisture release behaviour in the subsoils at various tensions may provide further insight into the extent of soil moisture release at higher tensions (say at 800 kPa and beyond).

Recent research to a search of real soil moisture status

Due to a lack of depth-wise soil moisture data of SAT Vertisols at different tensions (100, 300, 500, 800, 1000 and 1500 kPa), research was conducted recently (Zade *et al*. 2020) to obtain the depth-wise soil moisture data of a large number of Vertisols (>50, Kadu 1997; Vaidya 2001; Zade 2007; Deshmukh *et al*. 2014) of Vidarbha and Marathwada regions in central India. The drainage favourable soil modifiers like Ca-zeolites are found in sodic soils (Pal 2013) whereas drainage impairing soil modifiers like Mg-rich palygorskite clay minerals in non-sodic soils (Kolhe *et al*. 2011; Zade *et al*. 2017; Bhattacharyya *et al.* 2018; Paul *et al*. 2021). Zade *et al*. (2020) determined the PAWC of each soil horizon for the entire soil depth instead of restricting to a depth where sHC falls less than < 10 mm hr^{-1} which was considered in calculating the length of growing period (LGP) for revised agro-ecological sub-regions (AESRs) in black soils regions (Mandal *et al*. 2014). The soil moisture characteristics curves indicate that the release of soil water beyond 800 kPa is negligible in Vertisols of

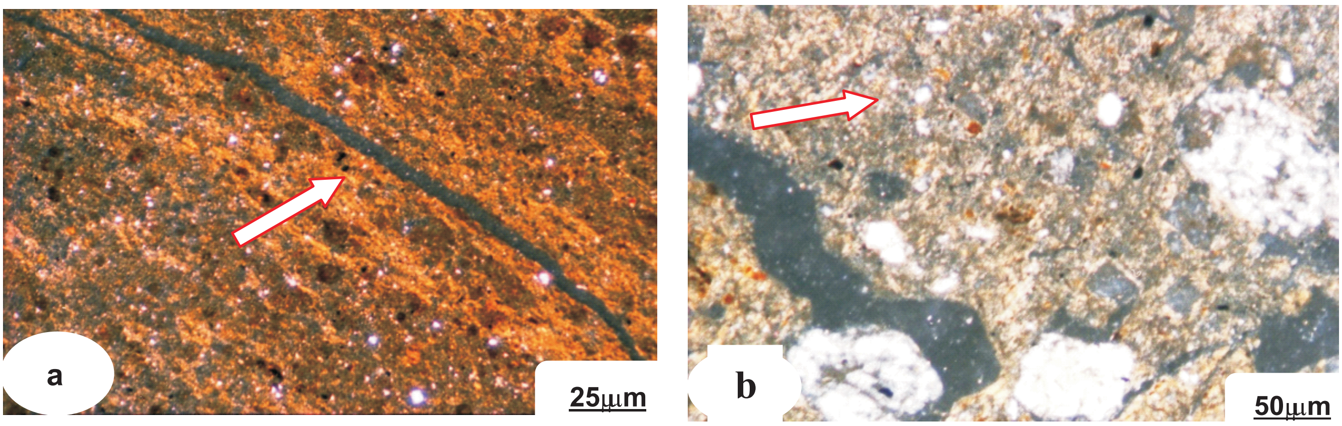
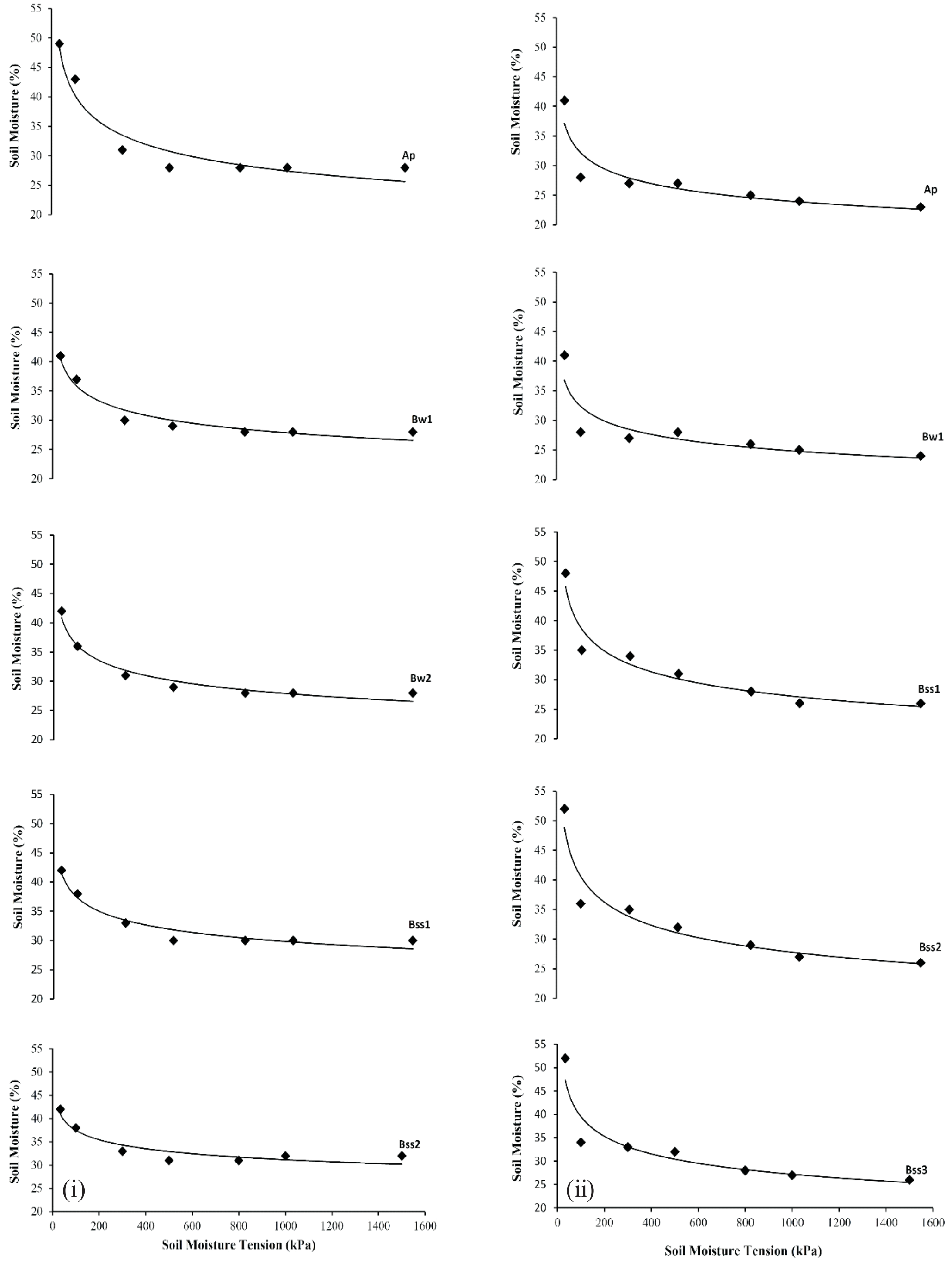


Fig. 3. Representative photographs of plasmic fabric in cross-polarized light. (a) strong plasma separation as parallel-oriented plasmic fabric in Typic Haplusterts and (b) weak plasma separation as mosaic/stippled-speckled plasmic fabric in *Sodic* Haplusterts/Calciusterts of dry climates (Adapted from Pal *et al*. 2009)

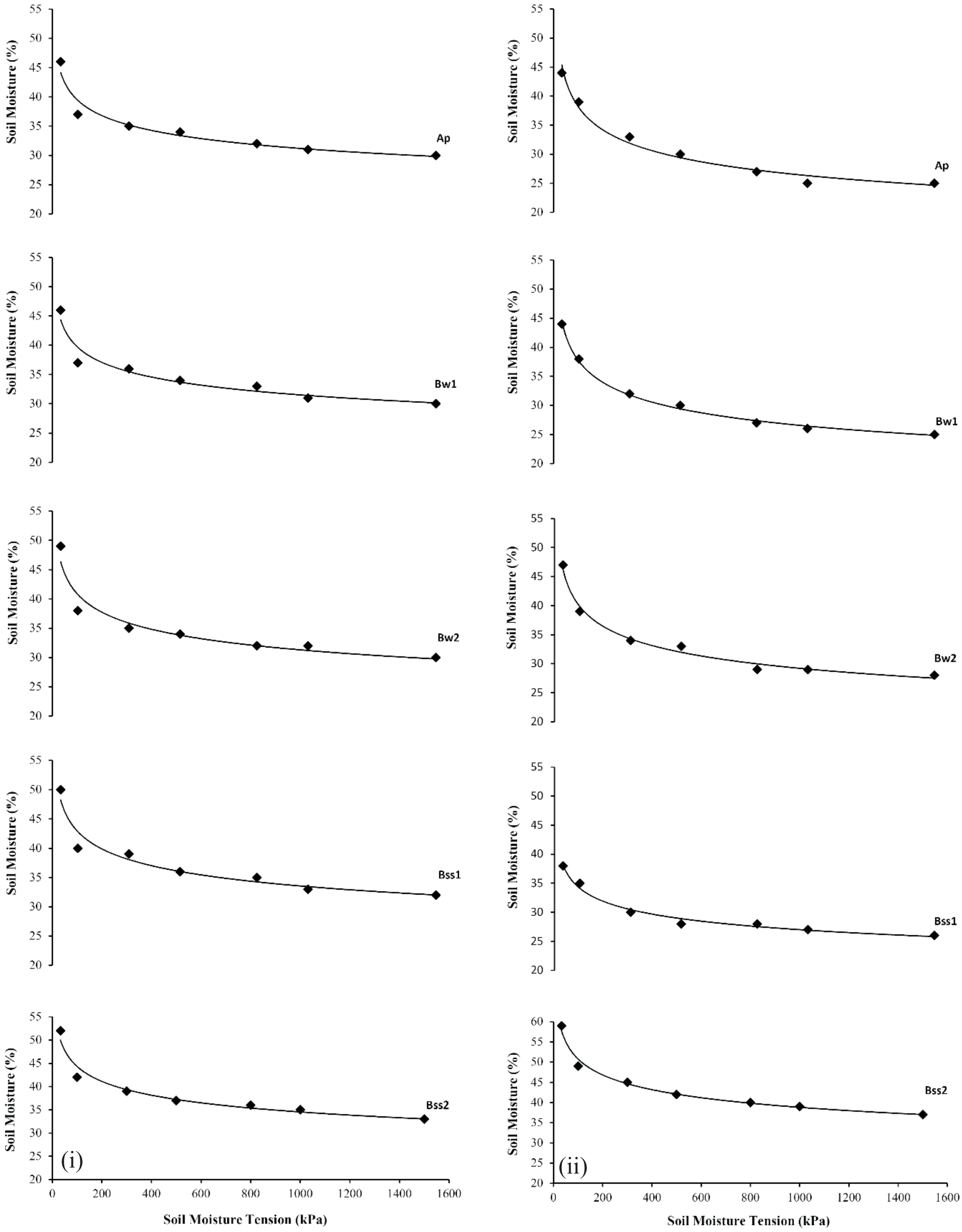
Vidarbha and Marathwada regions (Fig.4 a, b). It appears that failure in the release of soil water beyond 800 kPa is due to the dispersion of dominant nano-size smectite (< 100 nm) in the fine clay size smectite (< 200



Pedon 3 (Pusada, Amravati): Very fine, smectitic, hyperthermic family of Aridic Haplusterts

Pedon 4 (Paral, Akola): Very fine, smectitic, hyperthermic family of Sodic Haplusterts

Fig.4a. Release of soil moisture at different tensions of representative Vertisols of Vidarbha region (i) non-sodic soils and (ii) sodic soils (Adapted from Vaidya 2001)



Pedon 5 (Chandaj, Parbhani): Very fine , smectitic, hyperthermic family of Typic

Pedon 4 (Kalegaon, Jalna): F ine, smectitic, hyperthermic family of Sodic Haplusterts

Fig.4b. Release of soil moisture at different tensions of representative Vertisols of Marathwada region (i) non-sodic soils and f) sodic soils (Adapted from Zade 2007) nm) (Paul *et al*. 2021) in presence of Mg^{2+} and Na^{+} ions in slight to high alkaline pH conditions of calcareous Vertisols (Balpande *et al.* 1996)**.** Calcification is one of the major pedogenic processes in SAT Vertisols (Pal *et al*. 2000; Srivastava *et al.* 2002), which causesa rise in soil pH by precipitation of Ca ions as pedogenic $CaCO_3$ (PC). The PC induces dispersion of nano-clay smectite and illuviation of Mg- and Na-clays. These pedogenic processes help in the enrichment of Mg- and Na- ions on soil exchange complex in the subsoils (Fig.5 a, b, c), leading to an increase in water dispersible clay with soil depth (Balpande *et al.* 1996; Vaidya and Pal 2002; Kadu *et al*. 2003; Pal *et al*. 2006). Even in non-sodic soils with ESP < 5, increasing depth distribution of exchangeable Mg (Exch. Mg) (Fig.5 b) blocks the macropores, causing a reduction in sHC (Fig. 1) and an increase in micropores with a concomitant rise in COLE (co-efficient of linear extensibility) (>> 0.06 < 0.30), and BD (bulk density) (= 1.4 =1.9) (Vaidya and Pal 2002; Pal *et al*. 2006). In sodic soils, ESP with >5 but < 15, s HC values further decreases with a simultaneous increase in micropores. The difficulties in releasing soil moisture at tension at or higher than 800 kPa suggest that moisture in micropores is held very tightly (Zade *et al*. 2020) by Mg- and Na-

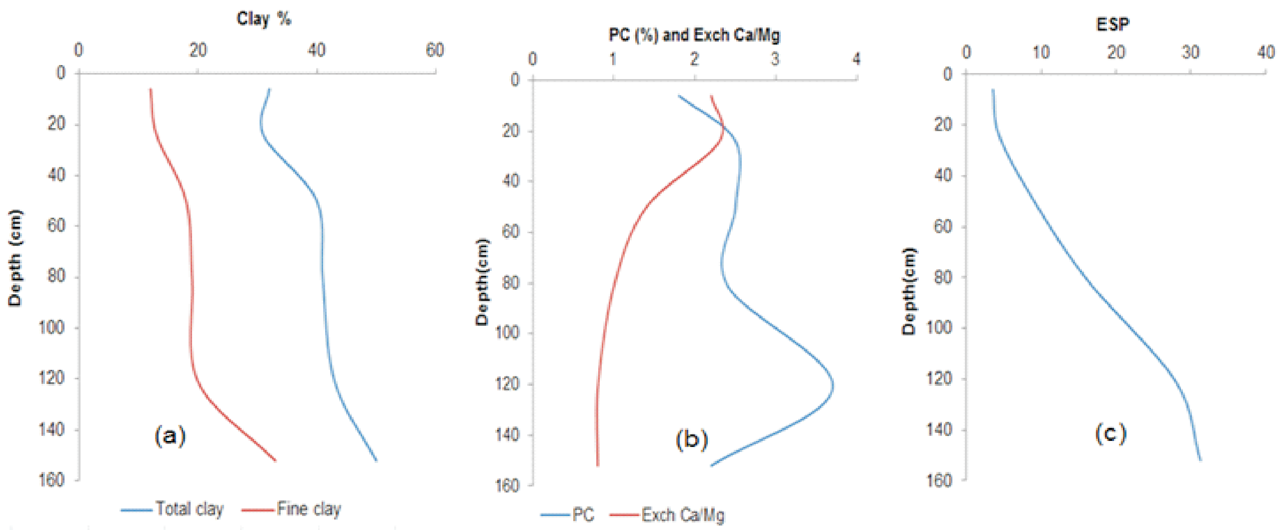


Fig.5. Depth distribution of clays (a), PC and Exch. Ca/Mg (b) and ESP (c) in a Sodic Calciusterts (Adapted from Pal *et al*.2009)

smectite clays (Pal *et al.* 2012a; Paul *et al.* 2021) and thus, the release of soil moisture beyond 800 kPa is not significant throughout the depth of Vertisols. Therefore, Zade *et al.* (2020) calculated PAWC considering the soil water held between 100-800 kPa for non-sodic CCS, and for sodic CCS, the soil water held between 300-800 kPa. The PAWC showed a better significant positive correlation with cotton yields (r = 0.605), in comparison to the correlation obtained between PAWC at 100-1500 kPa for non-sodic and 300-1500 kPa (the method used by Deshmukh *et al*. 2014) and crop yields (r = 0.407). This higher correlation highlights how the PAWC (Zade *et al*. 2020) emerges as a pragmatic method with unique bio-physical property, which is fundamentally pedogenetic processes driven, controlling the movement of rainwater and its retention and release in SAT Vertisols. The PAWC has uniqueness for being a robust bio-physical property signifying the abiotic stress in SAT Vertisols.

Conclusion

Earlier research carried out on the proposal of considering soil moisture held between 33 kPa and 1500 kPa, as an important biophysical parameter in terms of AWC for evaluating the suitability of cotton crop in SAT Vertisols was not infallible and needed some new insights as evidenced by the non-significant correlation between crop yields and AWC (Kadu *et al*. 2003; Pal *et al*. 2012a). Deshmukh *et al.* (2014) established a positive correlation between cotton yields and PAWC by considering the soil moisture held between 100-1500 kPa for non-sodic and 300-1500 kPa for sodic soils, in view of antecedent soil moisture held in the field after the cessation of rains. Recent research studies by Zade *et al.* (2020) emphasized the pedogenic processes in SAT Vertisols (calcification, clay illuviation and concomitant development of exchangeable Mg percentage and ESP, which cause rapid reduction in sHC in the subsoils) that actually control the downward movement of rain-water in the soil profile, retention of rain water and release of water between the rains. These processes cause the non-significant amount of water released beyond 800 kPa. Pedogenic processes driven pragmatic PAWC shows a better correlation with crop yields than earlier research efforts. Therefore, pragmatic PAWC (Zade *et al.* 2020) emerges as a novel index parameter of soil abiotic stress in SAT environment, which may also act as a guiding principle for the growing of deep-rooted crops in Indian Vertisols under SAT environments and also in similar soils of tropical parts of the world. In view of its uniqueness, as discussed above, PAWC could be applied as a useful parameter in further revision of AESRs in black soils regions (Mandal *et al*. 2014) for better crop planning and ecosystem services of SAT Vertisols.

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