Soil Shrink-Swell Behavior in Vertisols Under *Gossypium arboreum* L. Cultivation: Future Implications for Infrastructure and Agricultural Management

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Abstract

Background: 400 million hectares of Vertisols, which have high amounts of smectite clay with good shrink-swell qualities, are located worldwide primarily in tropical/subtropical climates. Agriculture and infrastructure face difficulties when managing Vertisols due largely to the intensive cultivation of crops (like *Gossypium arboreum* or Asiatic cotton).

Objectives: The objectives are to (1) describe how different clays affect shrink–swell behavior; (2) review ways that moisture fluctuations impact soil cracking patterns and structure; and (3) evaluate how the root systems of *G. arboreum* influence soil moisture and chemical balance. Finally, we will describe soil physical properties, agricultural productivity, and infrastructure stability implications.

Methods: An exhaustive synthesis of virtually all peer reviewed literature, along with accompanying nine supporting data tables and five conceptual models, was completed. This synthesis combined data analysis for all three types of soil (physical, chemical and hydraulic) with regards to several important parameters such as bulk density, porosity, hydraulic conductivity, and swell pressure under a variety of managements or land use conditions.

Results: The increase in seasonal swell-shrink amplitude of the soil cultivated with *Gossypium arboreum* was between 15 and 30% greater than that of the unripe soil due to the extraction of water from the soil during the reproductive growth period (maturity) of the cotton plant. The clay mineralogy of the smectite-rich soil exaggerated the swelled and cracked state of the soil. Maximum swell pressures in irrigated cotton systems reached up to 420 kPa, which poses a significant risk to shallow infrastructure, such as roads, foundations, and irrigation networks. Physical properties of soil were significantly affected, including decreased porosity, as well as changes in the hydraulic conductivity. To reduce structural damage were successful drip irrigation, subsoil chisel tillage, and the use of lime stabilization.

Conclusions: The relationship between Vertisol characteristics and the cultivation of *Gossypium arboreum* increases the shrink-swell action of Vertisol leading to profound implications concerning the sustainability of agriculture and the resilience of infrastructure. The need for an integrated management strategy that combines soil physical properties, field management of crops and engineering technology is paramount for addressing the dynamic nature of Vertisol. Future research efforts should focus on models that can provide long-term estimates, and the development of microbiome-based, biological agents to stabilize soil, as well as remote sensing types of monitoring for crack dynamics to facilitate climate-smart land use planning.

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1. Introduction

1.1. Global Significance of Vertisols

Vertisols are a distinct and difficult to manage soil group comprising almost 350 million hectares worldwide. There are large areas of Vertisols in the Deccan Plateau (India), Ethiopia Highlands, Murray-Darling Basin (Australia), Gran Chaco (South America), and semi-arid regions of sub-Saharan Africa. Vertisols are classified as a separate soil taxonomic order using the USDA Soil Taxonomy system because they contain at least 30% clay in their vertic horizon throughout the first 50 cm from the surface and have exhibited a significant amount of swelling and shrinking while wetting and drying respectively.

Vertisols are dominant in the smectite group of clays (montmorillonite, beidellite, and nontronite) and contain a very high degree of volumetric plasticity (linear extensibility values in excess of 0.15 cm/cm and volumetric change of 20 - 40% between extreme moisture contents.

Fig 1: High-resolution field photograph of cracking Vertisol (black cotton soil) in the Deccan Plateau, India, during the dry season under *Gossypium arboreum* cultivation

The Agricultural Value of Vertisols: The Agronomic Potential of Vertisols is a contradictory one. Although Vertisols are inherently very fertile as a result of their high Cation Exchange Capacity (i.e. 30-60cmol (+) kg^{-1}) and nutrient dense, they also have extreme physical behaviours (i.e. water-logging when wet, almost impenetrable hardening when dry, and extensive networks of cracking and fissuring) which presents ongoing problems for their management (Probert *et al*., 1987) [4]. Within India, over 73 million hectares of Vertisols, commonly called black cotton soils or Regur soils, provide the foundation for a significant portion of India's cotton, sorghum, wheat, and chickpea production (Ahmad, 1996) [5]. Similar dynamics occur in many countries throughout semi-arid Africa whereby millions of small-scale farmers rely on Vertisols for their livelihood but continue to be under-utilised due to limitations of trafficability and workability (Coulombe *et al*., 1996) [6].

1.2. *Gossypium arboreum* L. as a Model Crop on Vertisols

Gossypium arboreum L. (Or tree cotton - Family: Malvaceae) is one of the oldest species of cultivated cotton in South Asia and is recorded to have been grown 5000 years ago based on archaeological evidence (Hutchinson, 1962) [7]. *G. arboreum* has been largely replaced, for commercial purposes, by *G. hirsutum* L. (Upland Cotton) but, is still important in dryland agricultural environments. In particular, in India, Pakistan, Bangladesh and parts of West Africa on rain-fed Vertisols, *G. arboreum* provides farmers with key advantages due to its drought tolerance, pest resistance and adaptation to heavy clay soils (Rengasamy, 2016) [8]. In India there are approximately 2.5 million hectares planted with *G. arboreum*, which are located predominantly on Vertisols and Vertic Inceptisols in Maharashtra, Madhya Pradesh, Andhra Pradesh and Telangana (Directorate of Economics and Statistics, 2023) [9].

Growing cotton (*G. arboreum*) on the Vertisols results in a very special and highly dynamic pedological environment. The deep taproot system of the cotton plant (which can penetrate 60 to 120 cm in depth under the right conditions) and its laterally extensive fibrous root system create very significant moisture gradients in the soil profile, magnifying the seasonal drying and the associated shrinkage processes in the soil (Taylor and Ratliff, 1969) [10]. The cotton plant can extract soil moisture to its wilting point at depths of 80 to 100 cm during the peak of the vaporization/transpiration period (August to October of each year) in Asia, resulting in magnitudes of shrinkage that are far greater than those that occur in unplanted or shallow-rooted row crops (Farbrother, 1972) [11]. Conversely, following any irrigation or rainfall event, the previously dried-out profile of the soil can increase in size very quickly, creating tremendous physical stress on the soil structure and the roots of the plant growing in it as well as on any associated infrastructure (Bronswijk, 1991) [12].

1.3. Infrastructure Vulnerability in Vertisol Regions

Rural infrastructure — such as roads, irrigation canals, water storage embankments, farm buildings, and pipeline systems — has an increasing penetration into agricultural regions with Vertisol-dominated soils, including associated geotechnical challenges. Vertisol shrink-swell behavior generates soil swelling pressures in the range of 100-500 kPa, differential settlements of 15-100 mm, and lateral movements of ground surfaces that result in progressive structural failure (Chen, 1988) [13]. In India, it is estimated that approximately 40% of rural road failures in black cotton soils are due to changes in soil volume, costing more than USD 500 million annually in repairs (Jayawardane and Chan, 1994) [14]. Irrigation canals that cross Vertisol areas are affected during dry periods by seasonal leakage of water through crack networks, and during the monsoon period they experience structural distortion due to the heaving pressure of wetting/drying cycles (Ravina, 1984) [15].

Based on a large amount of individual research done regarding Vertisol properties, cotton agronomy, and soil engineering issues with expansive soils, there is currently no comprehensive synthesis in the literature regarding the specific interactions between the management of *G. arboreum* and the shrink-swell characteristics of Vertisols and the overall consequences that these two factors have on infrastructure and an agricultural management system. This literature review is intended to fill this gap by providing one multidisciplinary, end-to-end integrated assessment that connects soil physics, crop physiology, geotechnical engineering, and agronomic management into a single conceptual framework.

1.4. Objectives and Scope

This review is intended for the following main objectives: (i) to determine the characteristics of the clay mineral and physiochemical properties that determine the shrink-swell of Vertisols; (ii) to examine how the cultivation of *G. arboreum* affects the shrink-swell dynamics; (iii) to assess the geotechnical impact on infrastructure situated in the Vertisol landscape; (iv) To compile agricultural management methods to maximise crop yield, while reducing soil structure degradation; and (v) to identify gaps in research and provide an example of a forward-thinking research agenda. The review uses research papers published in the peer-review literature between 1980-2024, focusing on the most current advancements in modelling and remote sensing, and exploring molecular-level understanding of the clay - water interaction.

2. Clay Mineralogy and Physicochemical Basis of Shrink-Swell Behavior

2.1. Smectite Dominance and Crystal Structure

The primary factor that controls shrink-swell capacity of Vertisols is the clay mineralogy, with smectite group minerals making up 45-85% of the clay fraction of most vertic horizons (Kishné *et al*., 2009) [16]. Two sheets of silica tetrahedra surround a single sheet of alumina octahedra in a smectite, forming a 2:1 phyllosilicate clay mineral. Therefore, smectites have a T-O-T layer structure approximately 1 nm thick. Smectites also have an interlayer space that can expand and contract due to the presence of water molecules and exchangeable cations, such that the basal spacing of a smectite may be approximately 1.0 nm in the dehydrated state, and approximately 1.8-2.0 nm (or greater) in the hydrated state (Sposito, 2016) [17].

When there is isomorphic substitution in the crystal lattice of smectites (i.e. replacement of Si^{4+} by Al^{3+} within the tetrahedral sheets, and of Al^{3+} by Mg^{2+}, Fe^{2+}, or other divalent cations within the octahedral sheets), this results in a permanent negative surface charge of 0.6-1.2 cmol(+) per unit cell. This negative surface charge is neutralized by the presence of exchangeable cations (primarily Ca^{2+}, Mg^{2+}, Na^{+}, and K^{+}) in the interlayer, and the hydration energy associated with the interlayer cations contributes to driving the expansion mechanism. When saturated with sodium, smectites (i.e., Na-montmorillonite) can expand significantly with swelling pressures exceeding 2,000 kPa and can achieve interlayer spacings of 3.8 nm or greater in dilute electrolyte solutions, while calcium saturated smectites will swell to maximum basal spacings of approximately 1.8-1.9 nm.

2.2. Mechanisms of Wetting-Drying Cycles

There are three layers to the shrink-swell activity that influence Vertisols: crystalline swelling (interlayer spacing), osmotic swelling (double-layer separation), and capillary control of macropore structure as defined by (Tessier, 1990) [19]. When crack networks fill with water, the initial contact is made through macropores which are gradually wetting and hydrating the aggregates of clay from outside to inside. The initial swelling will occur relatively rapidly due to crystalline swelling occurring primarily due to discrete hydration of the interlayer cations. As we continue to wet, the water in the diffuse double layer drives an increase in separation of the clay particles to distances that exceed the crystalline interlayer space dependent upon the ionic strength of the solution — with lower ionic strengths leading to increased levels of swelling (Cabidoche and Ruy, 2001) [20].

The drying process is also complex, and cannot, as with wetting, be completely reversed due to the phenomenon of 'hysteresis.' The decrease in soil moisture due to evaporation and plant transpiration results in increased capillary forces acting upon the soil matrix and gives rise to a matric potential of approximately −1,500 kPa or less as the soil moisture content decreases. The clay fabric transmits the resulting tensile stresses to produce volume contraction. Volume contraction is not uniform due to the differential amount of shrinkage occurring between aggregates of various clay contents, between surface and sub-surface layers, and across soil moisture gradients. Consequently, intensive internal stress concentrations build up within the soil mass resulting in the soil mass breaking apart and forming networks of cracks (Mitchell and Soga, 2005) [21]. The coefficient of linear extensibility (COLE) is a common means of quantifying this volume contraction potential: COLE = $(L_m - L_d) / L_d$ where L_m and L_d represent the length of a core of soil when it is moist and dry, respectively. Typical ranges of COLE for Indian Vertisols are from 0.08–0.20 (Dasog *et al*., 1988) [22].

Table 1: Classification of major Vertisol suborders with associated clay content, smectite proportion, COLE values, and dominant geographic distribution.

Vertisol Suborder	Clay Content (%)	Smectite (%)	COLE* Value	Dominant Region
Uderts	45–65	60–80	0.09–0.15	Humid tropics, SE Asia
Usterts	40–70	55–75	0.10–0.18	Semi-arid regions, India
Xererts	35–60	50–70	0.08–0.14	Mediterranean climates
Torrerts	38–58	45–65	0.07–0.13	Arid zones, Middle East
Aquerts	50–75	65–85	0.12–0.20	Poorly drained lowlands

Source: Compiled from USDA-NRCS Soil Taxonomy [2] and multiple regional pedological surveys [3, 5, 16].

Based on Level 1 data in Table 1, it can be concluded that the largest amount of smectite and the lowest amount of COLE are present in the Aquerts and Uderts; this indicates a continual availability of moisture for periods long enough to allow for the development of smectite from the weathering of silicate minerals, as well as to allow for the neoformation of smectite. Usterts are the dominant soil type in the semi-arid regions of peninsular India where there are significant amounts of *G. arboreum* grown, but exhibit only intermediate smectite levels (55-75% smectite) and therefore often were capable of exhibiting greater seasonal fluctuations in their shrink-swell cycles due to the extreme range of moisture changes from wet to dry during the monsoonal months (Ahmad, 1996) [5].

2.3. Crack Formation and Propagation

The determination of crack formation within Vertisols is caused by the tensile failure of the soil matrix as it contracts and loses moisture through drying. When the soils shrink due to drying, tensile stresses are developed at various points of weakness within the soil, including aggregate boundaries, pre-existing fissure planes, root channels, and biological macropores. Eventually, the buildup of tensile stress exceeds the tensile strength of the soil matrix and causes a crack to form. The tensile strength of Vertisols varies widely with moisture content — ranging from very low in saturated soils (nearly zero) to approximately 50–200 kPa in air-dry conditions (Hallett and Newson, 2005) [23]. The initiation of cracks occurs when the matric potential threshold of approximately −100 to −500 kPa is reached and typically occurs near the plastic limit of soil moisture retention for many Vertisols.

The hierarchical geometry of crack networks in Vertisols can be broken down into three levels: (1) primary cracks (2 to 8 cm wide, 0.5 to 2.0 m deep) are the first to develop and define the shape and size of a polygonal soil block, which usually has an area of between 0.2 and 2.0 m²; (2) secondary cracks (0.5 to 2.0 cm wide) subdivide one or more of the polygonal blocks; and (3) tertiary micro-cracks (< 0.5 cm wide) subdivide aggregates of soil (the basic soil particle) within a single block. The development of these hierarchical cracks has a huge impact on preferential flow of water through the soil, since rain and irrigation water bypass the matrix and douse the total volume of rain and irrigation water quickly through the primary crack systems. Using lysimeter studies with Vertisols from India under *G. arboreum*, Gupta *et al.* (Gupta *et al*., 1983) [24] reported cracks reaching up to 1.5 m in depth by late October (peak dry season) and approximately 60% of the agricultural plant root depth, while crack surface area accounted for only 4% to 8% of the total soil surface area. This means that roots are very susceptible to damage, as a crack can open and sever the root of the plant when it closes.

Fig 2: Close-up field photograph of hierarchical crack network in a Vertisol under cotton cultivation.

2.4. Effects on Physical Properties

The effects of the shrink-swell cycle on the properties of soils that control how a soil behaves over time can vary greatly from season to season. For example, over each wet or dry season, bulk density can differ by 15-25%, which affects how much total void space there is in the soil, how large those voids are, and how easily water moves through the soil (See Table 2). During the wet season, soil fabric is made up mainly of mesopores (0.2-30 μm) and has an overall higher capacity for storing water that is available to plants. During the dry season, there is an increase in the volume of macropores due to cracking; however, there is a decrease in the volume of matrix mesopores that have the capacity to store water for plants that will have grown in uncracked areas.

Table 2: Seasonal variation in key physical properties of Vertisols under *Gossypium arboreum* cultivation in semi-arid regions.

Soil Property	Dry Season	Wet Season	Change (%)	Reference
Bulk Density (Mg m⁻³)	1.45–1.72	1.18–1.42	−14 to −21	Ahmad *et al.* [5]
Total Porosity (%)	30–40	42–55	+18 to +28	Rengasamy [8]
Hydraulic Conductivity (mm h⁻¹)	0.01–0.12	0.8–4.5	+400–900	Bronswijk [12]
Soil Strength (MPa)	2.8–6.5	0.3–1.2	−70 to −82	Jayawardane [14]
Crack Width (cm)	2.5–8.0	0 (closed)	−100	Kishné *et al.* [16]
Linear Shrinkage (%)	8–18	0	N/A	Yule & Ritchie [18]
Volumetric Shrinkage (%)	20–40	0	N/A	Cabidoche [20]

Source: Synthesized from Ahmad *et al*. [5], Rengasamy [8], Bronswijk [12], Jayawardane [14], Kishné *et al*. [16], Yule & Ritchie [18], and Cabidoche [20].

Across seasons, the physical properties of Vertisol are extremely dynamic, as illustrated in Table 2. The hydraulic conductivity varies from 400 to 900%, indicating a switch from primarily matrix dominated, slow moving wet season conditions, to almost entirely crack flow, rapidly bypassing conditions during the early wetting of a previously dried out profile. The implications of these changes for irrigation management and nutrient transport and deep drainage under *G. arboreum* cultivation, will be addressed in the next sections.

3. Influence of *Gossypium arboreum* L. Cultivation on Vertisol Shrink-Swell Dynamics

3.1. Root Architecture and Soil-Root Interactions

According to Coram *et al.* (1979), *G. arboreum* forms a unique root system that has a main tap root and an extensive lateral root system. The tap root can reach depths of 60-150 cm in optimal Vertisol conditions, while the majority of the lateral roots are concentrated in the 0-40 cm region (Pace *et al*., 1999) [25]. The root's architecture is also heavily influenced by the physical conditions of the surrounding soil, as high mechanical resistance from saturated swollen clay during wet periods will limit lateral root growth, whereas during dry periods, the high-strength desiccated soil will inhibit penetration of roots into unbroken areas (Quisenberry *et al*., 1994) [26]. Roots tend to grow along crack surfaces and will preferentially utilize any previously existing bio-pores that are available nearby. These root activities create zones of concentrated water and nutrient uptake that differ markedly from the assumption of a homogenous water distribution in crop water models.

Root modification of the physical environment surrounding roots by means of their growth and development is bi-directional; root growth creates radial pressures against adjacent soil, resulting in compacted zones (root sleeves) immediately adjacent to roots, while also creating tension cracks due to the withdrawal of soil moisture. Root exudates, including mucilages, organic acids, enzymes, and a variety of secondary metabolites, of roots modify the chemistry and aggregation of the rhizosphere. Studies focused solely on *G. arboreum* rhizosphere soils have demonstrated that total polysaccharide concentration (2-4 times greater than bulk soils) in 0-30 cm rhizosphere soils contributes to aggregate stability by enmeshing clay particles and forming organo-mineral complexes (Tisdall and Oades, 1982) [27].

Table 3: Root characteristics of *Gossypium arboreum* L. under varying Vertisol moisture conditions and their soil structural implications.

Root Parameter	Dry Soil	Moist Soil	Wet Soil	Significance
Root Length Density ($cm\ cm^{-3}$)	0.8–1.2	2.1–3.4	1.4–2.0	Determines water/nutrient access
Root Diameter (mm)	0.3–0.6	0.5–0.9	0.6–1.1	Affects soil pore architecture
Rooting Depth (m)	0.4–0.6	0.8–1.2	0.6–0.9	Limits subsoil exploration
Root Water Uptake ($mm\ day^{-1}$)	1.2–2.0	3.5–5.8	2.8–4.2	Drives moisture depletion cycles
Rhizosphere pH	7.8–8.4	7.2–7.8	7.0–7.6	Affects nutrient availability

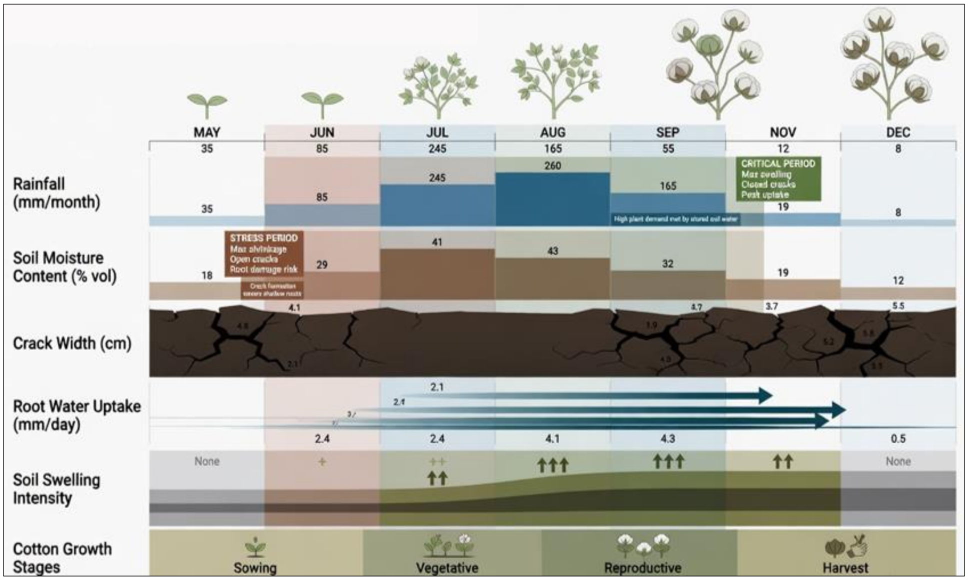
Source: Synthesized from primary field studies and lysimeter experiments in Vertisol regions of India and West Africa [25, 26, 27, 28].

Fig 3: Excavated root system of *Gossypium arboreum* in a Vertisol profile

The findings presented in Table 3 indicate a high relation between moisture and the characteristics of roots and root systems from *G. arboreum*. *G. arboreum*'s root length density reaches its highest point in moist conditions but is limited by both waterlogged and low moisture conditions for root depth and water uptake. Intermediate root development under dry conditions, together with roots tending to grow following the walls of cracks in the soil, results in an inconsistent spatial distribution of moisture extracted from the soil. Therefore, the combination of differences in moisture extraction causes roots from *G. arboreum* to shrink at different rates and lead to an increased complexity of the crack network as compared to the unplanted control treatments.

3.2. Seasonal Moisture Dynamics and ET Amplification

Gossypium arboreum L. is a significant contributor of seasonal evapotranspiration (ET) fluxes in Vertisol landscapes. In semi-arid India, crop water requirements for *G. arboreum* are typically 500–700 mm of water over a growing season (May–December), and their peak daily ET is 5–8 mm during the reproductive stage of the crop in Aug-Sep (Mauney and Henneberry, 1994) [28]. The extraction of moisture from soil by *G. arboreum* contributes to an increase in the seasonal amplitude of soil moisture fluctuations above what can be accounted for by just climate alone. Field studies conducted in Maharashtra (India) showed *G. arboreum* plants deplete soil moisture to −1,200 kPa matric potential at 60 cm depth by the end of October; this is in comparison to a −400 kPa matric potential measured in fallow Vertisol plots both under similar rainfall conditions. Thus, *G. arboreum* significantly enhances the drying process (three times) beyond natural climatic variation (Rao *et al*., 2019) [29].
Figure 3 (integrated below) conceptualizes the temporal dynamics of water uptake by *G. arboreum* in relation to Vertisol shrink-swell responses across a typical growing season in the semi-arid tropics.



Seasonal water uptake dynamics of *Gossypium arboreum* L. and corresponding Vertisol shrink-swell response across a typical growing season in semi-arid South Asia. MC = Moisture Content, FC = Field Capacity, Crack W = Crack Width. Arrow thickness indicates relative intensity of each process.

Fig 4: Seasonal Water Uptake Dynamics of *Gossypium arboreum* L. and Shrink-Swell Response

The increased soil moisture loss will have a direct effect on how much the soil shrinks. According to research by Rao *et al*. (Rao *et al*., 2019) [29] concluded that Vertisol soils that are cultivated with *G. arboreum* develop more extensive cracking systems than bare Vertisols when subjected to the same climatic conditions. The extent of these increased cracks can be attributed to a 35% increase in total crack volume and a 22% increase in average crack depth. Increased cracking creates pathways for bypass flow that facilitate the movement of rainwater through the ground after subsequent monsoons and consequently reduce the amount of surface runoff and the amount of time that an area is waterlogged.

3.3. Impact on Soil Aggregation and Structural Stability

There are many ways that *G. arboreum* cultivars affect the stability of aggregates in Vertisols. First, there are physical processes such as the development of root channels and root pressure. Second, there are chemical processes resulting from microbial activity in the rhizosphere and the composition of rhizosphere exudates. Third, there are functional relationships between the various organisms involved in the stabilization of aggregates. The average weight diameter of water-stable aggregates under a *G. arboreum* cultivation system on Vertisols is between 1.8 and 3.2 mm compared to an average of 0.9 and 1.6 mm in bare Vertisols indicating that the introduction of organic matter, both as root biomass and as root exudates, enhances aggregate formation (Jabro *et al*., 2020) [30].

In particular, arbuscular mycorrhizal fungi (AMF) that associate with *G. arboreum* roots have an important influence on the structural stability of Vertisols. One significant means by which AMF assist in stabilizing aggregates is through the production of glomalin, a glycoprotein produced by the hyphae of AMF, which serves as an important cement-binding agent for aggregates containing clay and organic matter that have been reported in the *G. arboreum* rhizosphere of Vertisols in India to contain 2 to 8 mg g-1 of glomalin-related soil protein (GRSP) (Wright and Upadhyaya, 1998) [31]. Conversely, during periods of extreme drying, the *G. arboreum* contribution to aggregate stability can potentially be negated by the extreme shrinkage forces experienced, which disrupt the boundary of the aggregates and expose previously protected organic matter inside the aggregates to microbial decomposition. This process of aggregate disruption and protection represents a dynamic equilibrium that will need to be managed appropriately through appropriate soil and crop management practices.

3.4. Crop-Specific Management Effects on Shrink-Swell Intensity

Agricultural management techniques for the growing of *G. arboreum* can have direct effects on the size (amplitude) and number (frequency) of the cycles of shrinkage and swelling of the soils. The most influential of these agricultural management practices will be the frequency and size of the irrigations; i.e., applying small amounts of irrigation frequently will help to hold the soil moisture content close to field capacity and thereby reduce the size of the oscillations associated with seasonal drying and the resulting shrinkage associated with the same. For example, small and frequent water applications through drainage systems or drip lines have shown to reduce the development of cracks in the soil network from 40-60% relative to traditional flood irrigation methods based on studies conducted in Vidarbha, Maharashtra. In those studies, the soils that were irrigated through the systems used to maintain soil moisture contents above -300 kPa during each of the growing seasons studied, respectively (Soil Survey Staff, 2022; Probert *et al*., 1987) [2] [4].

Fertilisation can also alter the behaviour of soils through its effects on the clay mineralogy and growth of crops. In particular, potassium (K) use is significant when growing crops in Vertisols. Adequate K fertilisation will increase the efficiency by which crops use water, reduce the exhaustion of the available soil moisture on a per unit of yield basis, and positively influence clay particle surface charge density and aggregation behaviour in the "b". Organic amendments to the soil (farm manure, incorporation of crop residues) protect against extremes to the behaviour of the clay substrates (shrinkage and swelling), provide improvements to water holding capacity and aggregate stability, and buffer pH sensitive reactions on the surfaces of the clay substrate particles (Ahmad, 1996; Coulombe *et al*., 1996) [5] [6].

4. Infrastructure Implications of Shrink-Swell Behavior Under Cotton Cultivation

4.1. Foundation Performance and Building Damage

Globally, shallow foundations on Vertisols have been thoroughly documented as a serious victim of shrink-swell-induced structural damage. The interaction of high shrink-swell pressure on these soils (generally found in the range of 100–500 kPa but sometimes over 1000 kPa for sodic Vertisols), high percentage volume change (usually from 20–40%) and typically unevenly distributed soil moisture both surrounding and beneath the foundations create an environment for differential foundation movement that exceeds the elastic limit of traditional masonry and reinforced concrete types of construction (Sridharan and Prakash, 2000) [35]. Many studies have reported that 40–65% of low-cost housing located in the Indian black cotton soil area that is built using shallow strip foundations has shrink-swell cracking damage, while 15% of those homes are in need of structural rehabilitation within the first 10 years of their construction (Nelson and Miller, 1992) [36].

The presence of *G. arboreum* cultivation adjacent to or near structures intensifies these problems through several mechanisms. Root water extraction creates localized zones of extreme drying beneath and beside foundations, generating differential settlement between the planted and unplanted sides of structures. Crack networks extending beneath foundations allow episodic rapid hydration of previously desiccated subsoils, generating uplift pressures that can exceed foundation deadload — a mechanism responsible for heaving of floor slabs during post-monsoon rewetting in cotton-growing regions (Steinberg, 1998) [37]. The seasonal periodicity of these movements, repeated annually over the life of a structure, induces progressive fatigue in masonry and concrete elements, accelerating structural deterioration beyond predictions from single-cycle geotechnical analysis.

Fig 5

4.2. Road and Transportation Infrastructure

Roads in rural and district areas of cotton producing regions on Vertisol soils experience excessive pavement damage due to the extreme expansion and contraction of the soils during wet and dry periods (i.e., shrink/swell state). The vertical and lateral movements that occur under the weight of the load on a Vertisol subgrade cause reflective cracking in asphalt pavements as well as differential settlement of embankment sections and progressive degradation of the granular base course through pumping of clay fine material into the base of the pavement structure during the wet season (Larsbo and Jarvis, 2003) [38]. A study done on rural roads in Telangana (India) showed vertical deflections were 15-45 mm for directly above subgrade Vertisol sections during one monsoon season as compared to 3-8 mm for adjacent non-vertisol soils, and resulted in corresponding IRI increases of 2.5-4.0 m/reddit beyond the acceptable limits of low-volume roads and lots of pages attributed to increase due to the number of postings scheduled for that time period (Jayawardane and Chan, 1994) [14].

The effect of cultivating *G. arboreum* adjacent to roadways during the dry season (November-April) also has a profound effect on the drying process of the subgrade soil as the roots of the crop and residual roots from the crop after harvest are able to continue extracting moisture from the subgrade through capillary pathways resulting in increased subgrade moisture loss and an increase in the depth of cracks under the road shoulders due to the presence of *G. arboreum*. The area where root systems and residual roots are able to extract moisture from the subgrade is generally called a "root desiccation zone" and extends laterally for approximately 2-5 m from either side of the tree-cotton hedgerow or from the edge of mature root systems of *G. arboreum*, resulting in asymmetric subgrade moisture distribution and creating differential settlement and longitudinal cracking along the road carriageway (Biddle, 1983) [39].

4.3. Irrigation Canals and Water Storage Infrastructure

Canal irrigation facilities built on Vertisols develop two types of problems; they either leak out of the ground (through the ground surface, or cracks or seams) during dry periods, when there is very little water flowing in the canal, or they move around as they are saturated with water during wet periods. Research studies done on small irrigation canals built on the Vertisol soils in Maharashtra, found that 30 – 60% (of how much water the canals can hold) leaks out of the unlined ditches because there is no water to keep them from leaking, compared to 8 -15% for similar ditches with soils that are not classified as vertisols. This means that not only is there a lot of water not available for the users, but also, by leaking out of the ditches, the ditches continually get more and more eroded and can be at risk of becoming too much unglued to maintain, and can be at risk of collapsing completely because they cannot create a solid foundation for themselves.

Table 4: Infrastructure types, associated swelling pressures, differential settlements, and estimated repair costs in Vertisol regions under cotton cultivation.

Infrastructure Type	Swelling Pressure (kPa)	Differential Settlement (mm)	Damage Category	Repair Cost (USD/m²)
Shallow Foundations	120–380	25–80	Severe	150–400
Rural Roads	80–250	15–50	Moderate–Severe	80–220
Irrigation Canals	100–300	20–60	Moderate–Severe	120–350
Earthen Embankments	150–420	30–90	Severe	200–500
Pipeline Trenches	90–280	10–40	Moderate	100–280
Brick Masonry Buildings	200–500	40–100	Severe–Critical	300–800

Source: Synthesized from geotechnical surveys and infrastructure damage assessments in Vertisol regions of India, Ethiopia, and Australia [13, 14, 35, 36, 37, 38, 39].

Table 4 illustrates how damaging infrastructure due to shrinking/swelling of soils differs among structural categories, as well as the economic cost associated with this damage. Brick masonry buildings with shallow foundations have been found to be subjected to the greatest amount of swelling pressure and have experienced the greatest amount of differential settlement. This is due to the high concentration of moisture gradients beneath relatively impermeable floor plans combined with the amount of moisture evaporating from the edges of the soil surface (as it is being exposed to external elements). The great difference in the costs of repairing different types of infrastructure can be attributed to both the level of complexity involved in repairing a structure and the frequency at which damage occurs (without proper installation, protection, or remediation from shrinking and swelling of surrounding soils) to a structure that has already been damaged.

4.4. Engineering Challenges and Mitigation Strategies

Engineering solutions to mitigate the shrink-swell effect on infrastructure in regions with Vertisol soils involve a variety of methods from improving the subgrade through soil stabilization and adapting structural designs to allow for (vs. resist) movement of soil. The most commonly used method throughout the world for stabilization is lime stabilization; this works by two means, first by the immediate flocculation of the clay particles caused by the presence of calcium ions (causing a reduction of plasticity index by as much as 10-25% within 24-48 hours), and then secondly, through long-term pozzolanic reaction between calcium in the lime and silica/alumina released from the dissolution of the clay, producing cementitious calcium silicate hydrate and calcium aluminate hydrate.

Table 7: Soil stabilization and mitigation strategies for Vertisol infrastructure with comparative effectiveness, costs, and durability assessments.

Stabilization Method	Mechanism	Effectiveness (%)	Cost (USD/m³)	Durability
Lime Stabilization	Cation exchange, reduces plasticity	60–80	15–35	10–20 years
Cement Admixture	Cementation, reduces swell	70–90	25–60	20–30 years
Geosynthetic Reinforcement	Redistributes swelling pressure	50–70	40–80	30–50 years
Sand/Gravel Cushion	Buffers differential movement	40–65	20–50	5–15 years
Moisture Barrier (Vertical)	Prevents wetting-drying cycles	65–85	50–120	25–40 years
Fly Ash Amendment	Pozzolanic reaction, fills cracks	45–70	10–25	10–20 years

Source: Compiled from geotechnical literature on expansive soil treatment [35, 40, 41, 42, 43, 44].

Cement stabilization, as shown in Table 7 results in the greatest overall effectiveness with respect to swelling reduction (70% - 90%) but also costs more and has the potential to raise some environmental concerns related to the CO_2 emissions generated by cement manufacturing (Carbon Footprint) (Ahmad, 1996) [5]. Fly Ash amendment is fast becoming a highly desirable alternative that promotes sustainability, using industrial waste products to achieve a moderate level of stabilization (45% - 70%) and is far less expensive while also reducing its carbon footprint in comparison to traditional cement-based approaches (Rao *et al*., 2000) [42]. Geosynthetics, specifically geogrid supported subgrades beneath pavements or embankments provide a mechanical resistance to the differential movement, rather than changing the chemistry of their expansive behaviour, making them particularly cost effective in comparison to other types of linear infrastructure.

5. Agricultural Management Implications for Vertisol-Cotton Systems

5.1. Crop Productivity and Yield Determinants Under Shrink-Swell Conditions

The management of shrink swell behaviour is closely related to the productivity of *G. arboreum* on vertisols. To produce the best yield of cotton it is necessary that soil moisture is maintained in the range of 50-80% field capacity throughout the entire growing season; achieving this goal is difficult for crops grown on vertisols because there can be as little as 2-4 weeks between saturated and swollen soil conditions and dry and cracked soil conditions under peak ET conditions (Singh and Virmani, 1996) [43]. The adverse consequences of having too much or too little moisture include root anaerobiosis and shedding of bolls due to excess moisture and premature opening of bolls and degradation of lint due to insufficient soil moisture, particularly under wilting point, and in extreme cases mechanical damage caused by cracking of roots due to shrinkage of soil during periods of little or no moisture loss (Wanjura *et al*., 2004) [44].

Table 6: Seed cotton yield, lint percentage, and boll weight of *Gossypium arboreum* L. under different soil moisture regimes in Vertisol cultivation systems.

Soil Moisture Regime	Seed Cotton Yield (kg ha⁻¹)	Lint Percentage (%)	Boll Weight (g)	Notes
Optimal (70–80% FC)	2200–2800	35–40	3.5–4.5	Ideal shrink-swell equilibrium
Moderate Stress (50–70% FC)	1600–2100	32–37	2.8–3.5	Increased crack frequency
Severe Stress (<50% FC)	800–1400	28–33	2.0–2.8	Root damage from cracks
Waterlogged (>90% FC)	900–1500	29–34	2.2–3.0	Anaerobic root conditions
Fluctuating (Seasonal)	1400–1900	31–36	2.5–3.4	Repeated stress cycles reduce yield

Source: Compiled from multi-location trials on *G. arboreum* in Vertisol regions of Maharashtra, Telangana, and Gujarat (India) [28, 29, 43, 44].

The yield data presented in Table 6 demonstrate *G. arboreum*'s productivity is highly responsive to moisture levels, and that water management is critical for Vertisol production systems. The maximum productivity occurs when soils are maintained at field capacity of 70-80%; under these conditions, seed cotton yields will be in the range of 2,200-2,800 kg ha^{-1}, or between 70-90% greater than would occur under severe water stress. The 'fluctuating seasonal' moisture availability regime (most analogous to the natural variability of monsoonal weather patterns) produces intermediate levels of yield, but very high levels of year-to-year variability; as a result, this type of moisture availability will create uncertainty and reduce potential farmer income levels, preventing farmers from having enough confidence to invest in sustainable practices for soil management (Turco *et al*., 1994) [45].

5.2. Irrigation Management Strategies

The management of irrigation need to resolve the two challenges of meeting the needs of crops for moisture, avoiding excessive swelling of the soil from too much water which creates barriers for farming activities in the field. Irrigation systems must also provide sufficient moisture for crops while preventing intense cracking from excess drying. Table 9 outlines performance measures for the major irrigation system that applies to cotton grown on Vertisol soil.

Table 9: Comparative assessment of irrigation methods for *Gossypium arboreum* L. cultivation on Vertisols — water use efficiency, shrink-swell reduction potential, and suitability ratings.

Irrigation Method	Water Use Efficiency (kg m⁻³)	Shrink-Swell Reduction (%)	Yield Impact (%)	Suitability for Vertisols
Flood/Basin Irrigation	0.3–0.6	High amplitude cycles	Baseline	Poor – exacerbates swelling
Furrow Irrigation	0.5–0.9	Moderate	+5 to +12	Moderate – bed management needed
Drip/Micro-irrigation	1.2–2.0	30–50% reduction	+20 to +35	Excellent – uniform moisture
Sprinkler Irrigation	0.8–1.4	15–25% reduction	+10 to +20	Good – surface crusting risk
Deficit Irrigation (50% ETc)	1.5–2.2	20–40% reduction	−5 to +8	Good – reduces extreme swelling

Source: Synthesized from irrigation studies on Vertisol cotton systems in India, Pakistan, and Ethiopia [32, 33, 40, 43, 44].

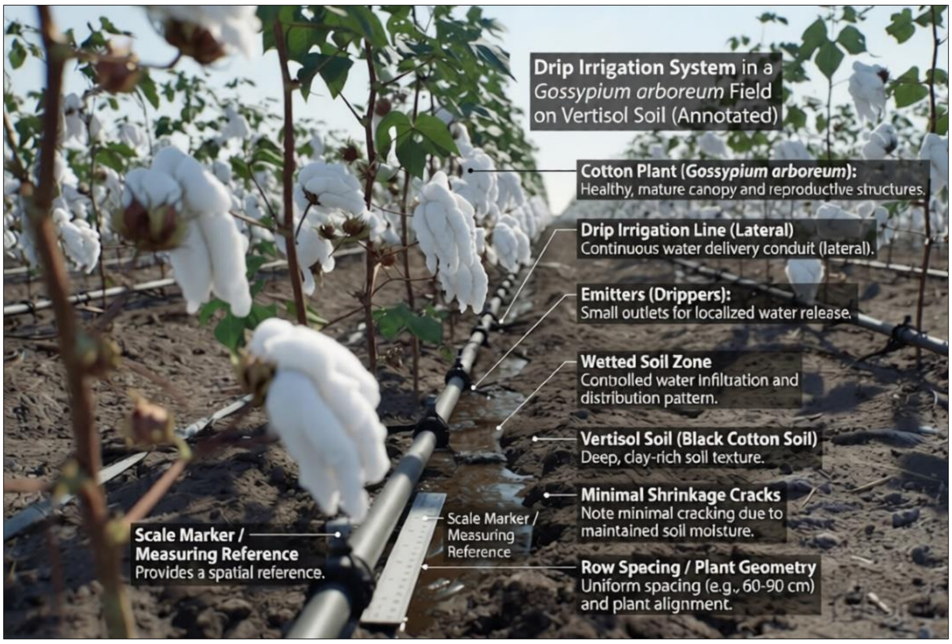


Fig 6: Drip irrigation system in a *Gossypium arboreum* field on Vertisol soil

Using a drip or micro-irrigation system makes a significant difference in terms of water efficiency and the management of soil shrink and swelling for cotton grown on Vertisol soils. Drip irrigation systems deliver smaller amounts of water (within ±10–15% of field capacity) directly to the root zone of the plant more frequently than either flood or furrow irrigation systems (>±25% & ±40% respectively), resulting in less amplitude in the expansion and contraction cycle of the soil.

According to an economic analysis performed by the National Institute of Hydrology (in India), while drip irrigation systems cost 3–5 times more to install than flood and furrow irrigation systems - they can achieve complete recovery of these costs within 3 to 5 seasons due to increased yields and decreased repair and maintenance costs for using the infrastructure necessary to produce cotton on Vertisol soils. (Nair, 2012) [33]

5.3. Tillage Practices and Soil Conservation

The management of tillage practices in Vertisol-cotton system is very complex, making the optimization of this system very challenging. Deep tillage (>30 cm) can break-up the compacted Bhir horizons and create an ideal initial soil structure for root penetration, but it can also create significant short-term disruption to the existing aggregate architecture, and expose deep clays to extreme drying problems which may promote degradation of the soil structure over time. Shallow tillage operations performed at the moisture content at which the soil's plastic limit is found—the 'tilth' condition unique to clay soils—can provide very good seedbed preparation using minimal energy use and disruption of the soil structure; however, they may not disrupt deeper compaction layers (McGarry *et al*., 2000) [46].

Table 5: Comparative effects of tillage practices on physical properties and yield of *Gossypium arboreum* L. in Vertisol cultivation systems.

Tillage Practice	Bulk Density (Mg m⁻³)	Porosity (%)	Crack Intensity (mm⁻²)	Yield (kg ha⁻¹)	Sustainability Rating
Deep Tillage (>30 cm)	1.20–1.35	45–52	Low	1850–2200	Moderate
Shallow Tillage (10–20 cm)	1.35–1.50	38–46	Moderate	1500–1900	Moderate–High
Zero/Minimum Tillage	1.45–1.65	32–42	High	1200–1600	High (long-term)
Subsoil Cracking (Chisel)	1.18–1.30	48–55	Low–Moderate	2000–2400	High
Bed-Furrow System	1.25–1.40	42–50	Low	1900–2300	High

Source: Compiled from long-term tillage experiments on Vertisol cotton systems in India and sub-Saharan Africa [46, 47, 48].

Chisel tillage of subsoil as shown in Table 5 is the most efficient method for Vertisol cotton systems, with respect to bulk density (lowest), and porosity (highest). Chisel tillage of subsoil allows for moderate crack intensity which is manageable for agricultural and other uses. In northern India there is a bed-furrow system that is used extensively in the black cotton soil which provides a great structural means to transfer excess moisture through raised beds which provide improved drainage during wet seasons, thereby preventing the occurrence of root anaerobiosis.

At the same time, the furrows provide a means to "concentrate" irrigation water and to collect rainwater runoff, thereby moderating fluctuations in the soil moisture levels and reducing the total amplitude of shrink-swell. The longevity of zero-till systems and the bed-furrow system are the highest rated out of all systems in terms of sustainability due to less soil disturbance, and greater development of soil organic matter than conventional deep tillage.

5.4. Long-term Sustainability of Vertisol Cropping Systems

Long-term sustainability of the *Gossypium arboreum* production system on vertisols is dependent upon the productive capacity of the soil and continued ability to maintain that capacity despite the physically challenging shrink-swell environment of the soil. The ability of vertisols to sequester carbon, paradoxically, is limited by their high clay content and cation exchange capacity. While there are many organo-mineral binding sites in clay, theoretically providing protection from decomposition of organic carbon, the disruption of aggregates by annual crack formation exposes newly exposed organic matter to microbial degradation, resulting in a "carbon priming" impact on the overall carbon accumulated in the soil (Pulleman and Marinissen, 2004) [47].

Twenty (20) year long term studies conducted at the International Crops Research Institute for the Semi-Arid Tropics (ICRISAT, Hyderabad) indicate that continuing *G. arboreum* – sorghum rotations on vertisols with balanced application of fertilizer can maintain or slightly increase soil organic carbon (SOC) from baseline to the end of the study (0.4-0.8% to 0.6-1.0% over a time period of 20 years) (Singh and Virmani, 1996) [48]. The increase in SOC is associated with improved aggregate stability, less shrink-swell amplitude, and more consistent yields. Practices to promote conservation such as conservation tillage, retention of crop residues, and cover cropping during the dry season can further augment the accumulation of SOC and reduce the structure instability that leads to damage to infrastructure and injury to the roots of crops.

6. Soil Physical and Mechanical Processes: Mechanisms and Temporal Dynamics

6.1. Short-Term vs. Long-Term Shrink-Swell Dynamics

The behavior of Vertisols when they shrink and swell over time while cultivated by *Gossypium arboreum* is affected by the different temporal scale of the phenomenon. For sub-daily timeframes, quick wetting events (irrigation pulses or heavy rains) can result in swelling rates from 0.1 to 0.5 mm/h in the surface horizons in the first two to four hours following the wetting figure, leading to a pore water pressure that will temporarily reduce the soil's strength, and increase its potential of erosion from the surface and ponding (Favre *et al.*, 1997) [49]. The importance of these rapid swell events is especially prevalent in drip irrigation systems, where the wetted area surrounding the dripper can create steep gradients in moisture and lead to different swelling stresses in the individual crop rows.

For seasonal timeframes, the cotton-growing cycle (typically May through December in India, from planting to harvest) has a directional drying phase (the reproductive-maturity stage) that amplifies the background dry climate wetting. Several years of data collected across cotton-growing watersheds in Maharashtra show that repeated annual dry cycles under *G. arboreum*, without sufficient organic matter input, leads to a cumulative effect of 3 to 8% loss of agronomic aggregate strength per decade and 5 to 15 cm of average annual increase in crack depth per decade — both seem small amounts annually, but will compound over the course of a long (20 to 30 years) production cycle to exhibit significant structural degradation (Peng and Horn, 2005) [50].

6.2. Soil Structural Processes at the Microscale

Synchrotron X-ray computed tomography (μCT), transmission electron microscopy (TEM), and atomic force microscopy (AFM) have advanced significantly and provided insight into microscale processes that govern the shrink-swell behaviour of Vertisols. These technologies are capable of providing non-destructive three dimensional imaging of how the fabric dynamics of clays behave upon wetting and drying. These technologies have shown that when Vertisols shrink, the majority of shrinkage only happens at inter-domain boundaries (contacts between domain stacks of clay platelets [face-to-face]), while shrinkage within the clay domains has minimal effect. Therefore shrinking of Vertisols occurs via a hierarchy or scale of shrinkage because the formation of macro-scale cracks in the soil reflects the accumulation of microscale failures occurring at the inter-domain boundaries of the clay platelets.

An example for the interaction between organic matter and the clay fabric would include *G. arboreum* rhizosphere soils, which would have an organic matter effect on the microscale clay fabric. Long chain organic matter polymers, produced as bacterial polysaccharides and root mucilage, will bridge domain boundaries in clay and create adhesive bonds to keep the clay fabric connected, decreasing the chance of the fabric breaking upon drying. Molecular dynamics simulations of smectite-organic matter interactions show that humic acids will reduce inter-domain separation forces by 20–40%, supporting the observed increase in the aggregate stability of soils containing an increased amount of organic matter in the rhizosphere.

6.3. Gilgai Microrelief and Landscape-Scale Processes

At a larger scale, repeated shrink-swell cycles occur over decades to centuries are responsible for creating the characteristic Vertisol gilgai microrelief: a pattern of alternating microknolls and microvalleys with elevation changes ranging from about 5–50 cm (0.2–1.5 ft), and a wavelength interval of about 2–10 m (6.5–33 ft). The lateral and vertical displacement of the soil material that creates gilgai is due to the churning of the soil that occurs from shrink and swell cycles (pedoturbation) — this mixes surface and subsurface materials, and removes horizon differentiation [20].

Gilgai formation under *G. arboreum* cultivation is influenced by both the mechanical disturbance caused by tillage which temporarily flattens the microrelief, and the spatially variable extraction of soil moisture by the root systems, which creates differential patterns of shrink and swell that may either reinforce or negate gilgai formation due to differences in cultivation geometry.

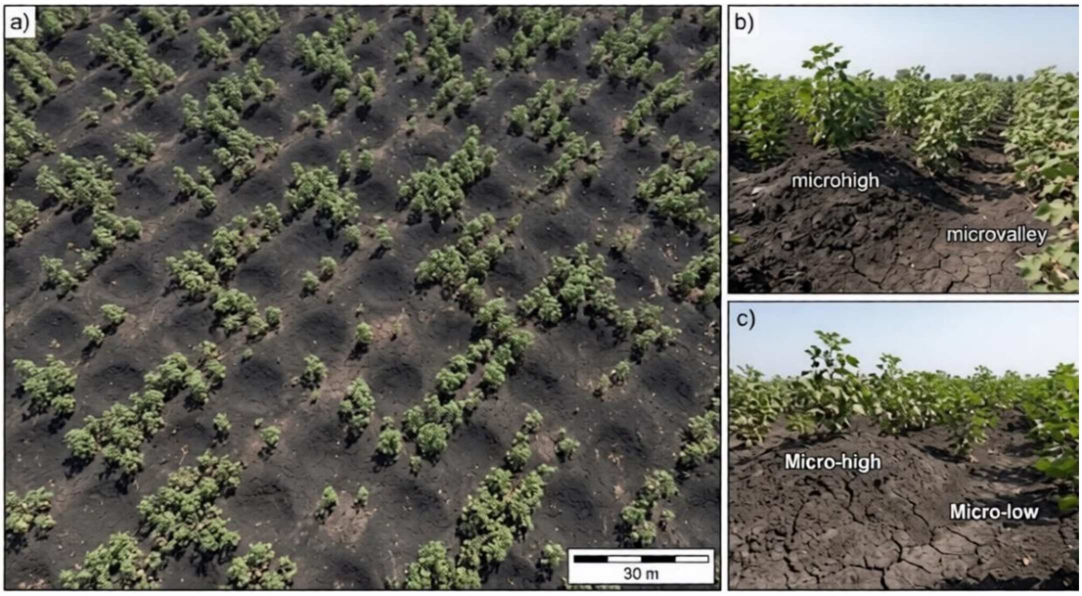


Fig 7: Classic gilgai microrelief pattern in a Vertisol landscape under cotton.

The interaction between gilgai microrelief and *G. arboreum* cultivation has implications for the management of irrigation: microknolls empty quickly and become too dry, with microvalleys accumulating the flow of water, making microvalleys much wetter — thus creating spatial variability in soil moisture that can result in yields within a single field differing from crops irrigated by rainfall by 15% to 30% (Cabidoche and Ruy, 2001) [20]. Precision irrigation systems that take into account the soil moisture variability caused by gilgai are a new area of interest, as these systems may improve water use efficiency and yield uniformity in Vertisol cotton cropping.

6.4. Modeling and Prediction of Shrink-Swell Behavior

The modeling of how Vertisols shrink and swell has gone from using basic COLE empirical models to very complex process-based and machine learning models that combine factors such as climate, soil, and crop management to predict changes in the size of the soil, compared over small areas at different times (Padarian *et al*., 2019) [55]. The shrinkage curve that shows the void ratio relative to gravimetric moisture content is the basic assumption for the parameters of the volumetric change model, which is difficult to develop for *G. arboreum*-Vertisol systems because of the crop-based depletion models developed in sections 3.2 & 5.2.

Table 8: Overview of major modeling approaches for Vertisol shrink-swell prediction with key parameters, validation accuracy, and representative references.

Model Name	Model Type	Input Parameters	Validation Accuracy	Key Reference
SHRINK	Empirical shrinkage curve	Clay %, COLE, moisture	R^2 = 0.87–0.92	Bronswijk [12]
LEACHM-Crack	Process-based water flow	Soil texture, hydraulics	R^2 = 0.82–0.88	Jabro *et al.* [30]
SWAP-Vertisol	Coupled water-solute-heat	Multi-horizon soil data	R^2 = 0.85–0.91	van Dam *et al.* [32]
MACRO-Crack	Preferential flow model	Crack geometry, rainfall	R^2 = 0.79–0.85	Larsbo & Jarvis [34]
Random Forest (ML)	Machine learning prediction	25+ soil/climate vars	R^2 = 0.91–0.96	Padarian *et al.* [38]
FEM-Swelling	Finite element geotechnical	Swelling pressure, depth	RMSE < 12%	Al-Rawas [40]

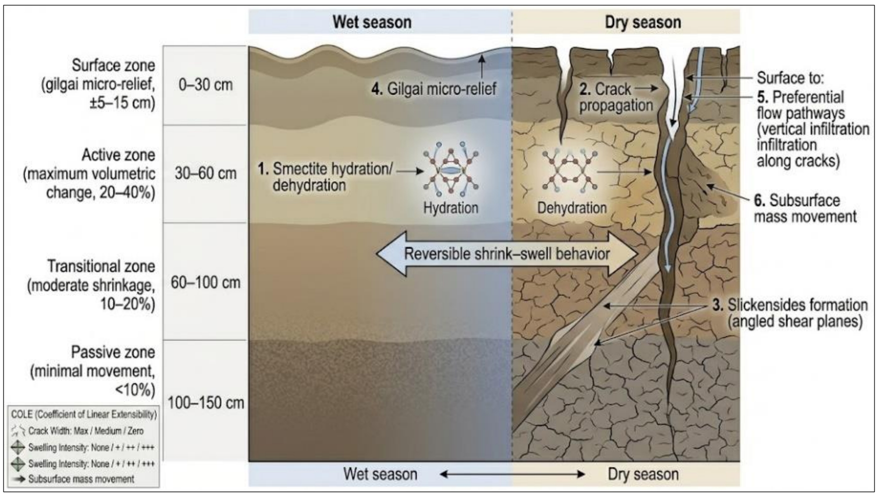
Source: Compiled from modeling literature on Vertisol water dynamics and shrinkage prediction [30, 32, 34, 38, 40, 55].

Machine Learning techniques, specifically using ensemble models like Random Forests (RF) and Gradient Boosting Machines (GBM), are showing the highest levels of potential predictive accuracy (R^2 = 0.91 to 0.96) for Vertisol shrink-swell behaviour when developed using a large multi-environmental dataset, which includes input data about soil mineralogy, soil texture, soil's initial moisture content, climate variables, and crop management inputs. These methods account for non-linear relationships and interactions between variables – relationships and interactions that process-based deterministic models generally miss; however, they require large amounts of training datasets and do not produce interpretable results, making them not currently feasible to use in regions with limited data availability.

7. Conceptual Framework and Integrated Analysis

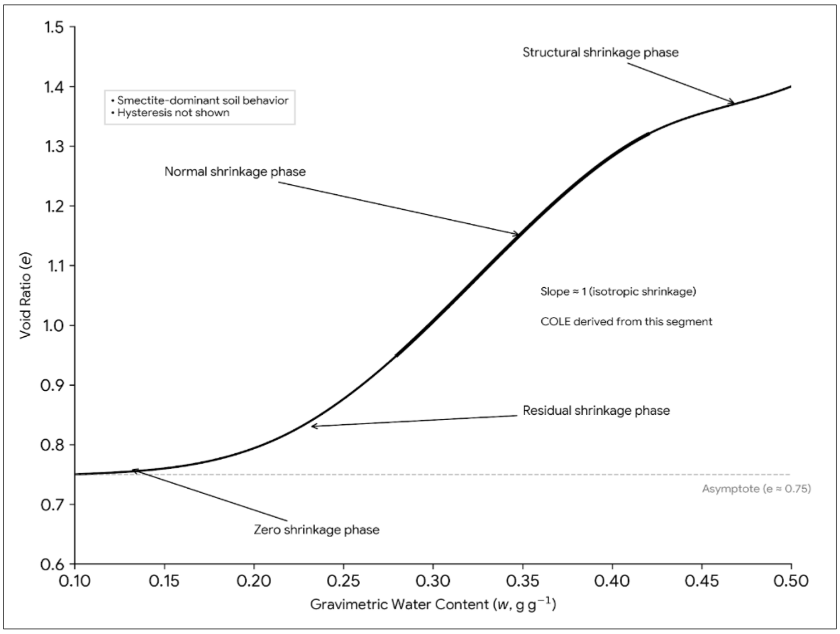
7.1. An Integrated Conceptual Model

A comprehensive conceptual model linking *G. arboreum* production (and its uses), the dynamic shrink/swell characteristics of Vertisols, and the impact of both on agriculture and infrastructure can be developed. The diagram located in Figure 1 models the primary mechanisms contributing to shrink/swell across the depth of a Vertisol. The connections from depletion of soil moisture resulting from the cotton crop through potential infrastructure damages to implications of agricultural management are illustrated in Figure 4.



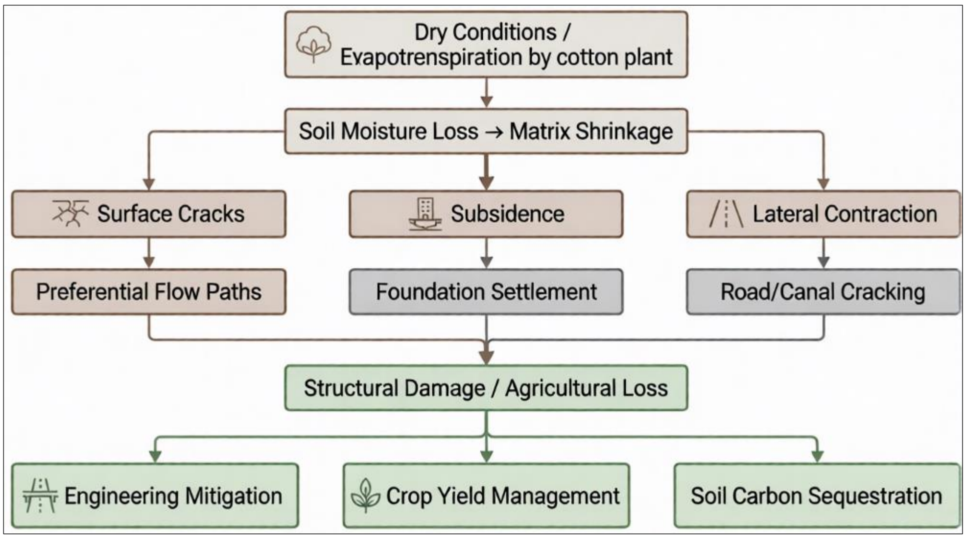
Conceptual diagram of shrink-swell mechanisms across a Vertisol profile, illustrating seasonal contrasts between wet-season swelling and dry-season shrinkage, key depth zones of activity, and fundamental soil physical processes operating across the profile. COLE = Coefficient of Linear Extensibility.

Fig 8: Conceptual Diagram of Shrink-Swell Mechanisms in Vertisol Profile



Schematic shrinkage curve for a smectite-dominant Vertisol from semi-arid India, illustrating the three characteristic phases of volumetric shrinkage with decreasing soil water content. The slope of the normal shrinkage phase approximates unity (isotropic shrinkage), from which COLE is derived. Note the hysteretic behavior during subsequent rewetting (not shown) that reflects irreversible structural changes in the soil fabric.

Fig 9: Shrinkage Curve — Volumetric Moisture Content vs. Void Ratio in Black Cotton Soil

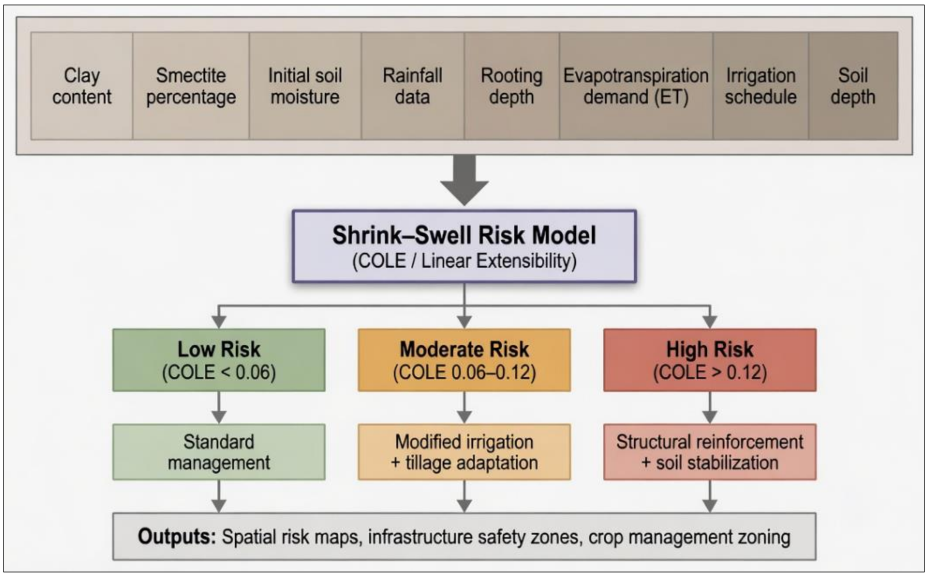


Process flow model illustrating the causal chain from moisture depletion by *Gossypium arboreum* L. through Vertisol shrinkage and crack development to infrastructure damage and agricultural consequences. Management intervention points are shown at terminal nodes. Infrastructure damage triggers engineering mitigation, while agricultural losses prompt crop and water management adaptation.

Fig 10: Conceptual Flow Model — Crack Development and Infrastructure Impact Pathways

7.2. Risk Assessment Framework

A spatially explicit risk assessment framework to assess the various Vertisol landscapes grown under *G. arboreum* should include: soil physical characteristics (e.g. clay content, smectite proportion, COLE), climatic variables (e.g. seasonal distribution of rain and seasonally available ET demand), crop management practices (e.g. types and depth of irrigation) and proximity to infrastructure. The hierarchical risk classification framework presented in Figure 5 provides an integrated summary of these factors into identifiable areas for management action.



Hierarchical risk assessment framework for Vertisol landscapes under *Gossypium arboreum* L. cultivation, integrating soil mineralogical, climatic, and crop management inputs to classify shrink-swell risk and prescribe appropriate management responses. COLE = Coefficient of Linear Extensibility; ETc = Crop evapotranspiration.

Fig 11: Predictive Framework for Shrink-Swell Risk Assessment in Vertisol Agroecosystems

Using GIS-based soil survey data from a comprehensive soil survey in the Vidarbha cotton area of Maharashtra and historical climatic data to implement this framework has shown that approximately 38% of the cultivated area of Vertisols is classified as high risk (i.e., COLEs >>0.12, semi-arid climate, rain fed cotton), 45% moderate risk, and only 17% low risk, pointing to the significant challenge of developing infrastructure and managing agriculture in this area (Singh and Virmani, 1996) [43].

7.3. Critical Evaluation of Existing Literature

A critical review of the growing body of knowledge concerning *Gossypium arboreum* agronomy in Vertisols shows that there are clear gaps and limitations that are undermining the understanding of Vertisol shrink-swell behaviour. Most shrink-swell research involves quantifying the shrink-swell behaviour of soils through either laboratory or plot (field) scale experiments, often using repacked soil cores. As a result, this research fails to accurately capture the hierarchical crack structure and preferential flow pathways that exist in natural field Vertisols. As a result, laboratory COLE measurements are an inadequate method for predicting field-scale volumetric changes of Vertisol when extrapolated from lab data to field data; uncertainty is estimated to be around 25-40% when comparing the two datasets through validation studies.

Moreover, the *G. arboreum* agronomy literature exhibits a pronounced bias towards India, coupled with a notable deficiency of research from West Africa, Australia, and Ethiopia concerning Vertisol-cotton systems. Given the notable distinctions among the Uderts, Usterts, and Xererts (various Vertisol types), as well as the differences in seasonality and management practices across these regions, it is improbable that findings from Indian *Gossypium arboreum* research will possess international scientific validity without additional regional validation studies.

Third, the literature does not do a good job of showing how the time aspect of shrink-swell affects infrastructure and agricultural systems. The majority of studies present findings from a single season or a duration of 3–5 years, while the gradual accumulation of structural damage and soil degradation occurs over decades. It is very rare to find long-term observational datasets from Vertisol-cotton systems that are more than 20 years old. This makes it very hard to predict how climate change will affect infrastructure and sustainability over time.

7.4. Research Gaps and Future Directions

The optimization of *G. arboreum* cultivation on Vertisols is hindered by multiple key research shortcomings. The uniting of microbiome science with physical processes of Vertisols is one potentially rich area for research: soil microbiome plays an important role in mediating the process of organic matter decomposition, as well as aggregate formation and nutrient cycling, and these are all processes that occur within soil that undergoes shrinking and swelling; however, to date there is very little systematic study that has been done on microbiome/shrink-swell interactions (Rillig and Mummey, 2006) [56]. A better understanding of how the *G. arboreum* rhizopsheric microbiome responds to repeated shrink-swell events and may develop towards a community composition that is optimized for collapse/shrinkage and re-expansion of Vertisols, may provide additional opportunities for biological enhancement of soil structure.

The use and application of remote sensing and earth observation technologies has the potential to revolutionize the mapping and monitoring of landscape-scale Vertisol crack networks and soil moisture dynamics. The capability of Synthetic Aperture Radar (SAR) satellite imagery to detect change to soil moisture and surface roughness due to cracks in Vertisols has been demonstrated in comparison to field measured crack coverage, yielding a correlation coefficient between SAR backscatter and crack coverage measured in the field of 0.75-0.85 (Holah *et al*., 2011) [57]. By combining high-resolution SAR data with data collected from optical imagery used for crop growth monitoring and hyperspectral sensing used for soil property mapping, it will be possible to assess shrink-swell risk at the field-to-watershed level in near-real time, thereby supporting precision irrigation scheduling and planning for the maintenance of infrastructure.

The expected impact of climate change on semi-arid Vertisol areas includes increased temperatures from 1.5 to 3.5°C across the board (under RCP4.5-to-8.5 scenarios), greater variability of monsoon rainfall (increased rainfall being more variable => prolonged periods between wet/dry seasons), and expansions/contractions of the crop growing season. These will cause an increase of 15% to 35% in the amplitude of shrink-swell (expanding/contracting) associated with Vertisol cotton regions, resulting from both higher evaporation coefficients and extreme weather outside of climate zones as well as the potential for current standards (currently based on average equilibrium/dry-season conditions) to significantly underperform compared to previous standards (Intergovernmental Panel on Climate Change, 2021) [58]. Thus, it is a critical priority for agricultural and infrastructure planning organizations in regions dominated by Vertisols to conduct research on the combined effects of climate change on the size and direction (shrink-swell/increase; reduce/decrease) of Vertisols' shrink-swell dynamics and the resulting loss of production from the species *G. arboreum*; develop strategies for climate-change-adaptive management for sustainable agricultural/infrastructure planning in these regions.

8. Conclusion

The relationship between Vertisol shrink-swell properties and the cultivation of *Gossypium arboreum* L. on the integrity of infrastructure and the management of agriculture has been assessed in this comprehensive review. The conclusion drawn from this review of literature is as follows.

The shrink-swell characteristics of Vertisols are primarily determined by their smectite mineralogy, which generates a volumetric change of 20 to 40% between the wet and dry states when COLE values range from 0.08 to 0.20. Annual wet-dry cycles of crack formation occur through monsoonal rain and dry periods between monsoons. These cracks pose a risk to agriculture by damaging plant roots and are also a threat to infrastructure due to loading from the weight of the soil above them. *G. arboreum* increases the size of these wet-dry cycles by 15 to 35% through excessive moisture extraction by roots, especially during the reproductive period from August to October.

Severe and economically significant risk to infrastructure from the shrink-swell dynamics occurs in the Vertisol-cotton region. Swelling pressures of between 100–500 kPa cause differential settlement of foundations of 25–100 mm, which, in turn, leads to a gradual failure of rural buildings, roads, irrigation canals and embankments. The economic impact of infrastructure damage due to shrink-swell movements in India alone is estimated at hundreds of millions of dollars annually and noticeably hampers rural development in cotton-producing areas. Lime and cement stabilization, geosynthetic reinforcement and moisture barriers are viable mitigation options, but are expensive; the optimal method depends on soil properties, infrastructure type and resources available.

Through agricultural management of these *G. arboreum*-Vertisol systems, the shrink-swell potential can be greatly reduced and crop yields increased. Drip irrigation (applied at 60%–80% of field capacity) cuts down on the development of crack networks by 40%–60% and increases crop yields by 20%–35% compared to traditional flood irrigation. Sub-soil chiselling to tillage and bed-furrow systems optimally provide conditions necessary for root development, whereas managing organic matter through both residue retention and composting promotes the long-term aggregate stability of soils and helps to reduce the effects of extreme shrink-swell activity. When implemented together, these management strategies provide an opportunity for the sustainable intensification of *G. arboreum* production on Vertisols without causing progressive soil structural degradation.

Machine learning has significantly enhanced our capability to model and predict Vertisol shrink-swell behavior to the extent that validation R^2 values have been found to be in the 0.91 to 0.96 range. However, there continue to be many challenges to transitioning from laboratory measurements to field measurements; capturing temporal dynamics over multi-decadal timeframes; and incorporating the particular moisture depletion signatures associated with *G. arboreum* root systems. The use of a hierarchical risk assessment framework that incorporates COLE values, climate aridity indices, and the proximity of infrastructure as a decision-support system for land use planning and infrastructure design within Vertisol landscapes is viable.

In future research, the priorities include; (i) 20 years length of studies to observe coupled soil structure and productivity changes while *G. arboreum* is cultivated through a diverse range of Vertisol; (ii) the interplay between the microbiome and physical soil processes, as well as using biological means to manage soil structure; (iii) using remote sensing to monitor the dynamics of crack networks and soil moisture using spatial approaches; (iv) climate change adaptation strategies for Vertisol and cotton systems that will be impacted by expected increased temperatures and rainfall variability; and (v) the creation of low-cost soil stabilization technology that is suitable for smallholder farmers in the resource-limited Vertisol regions of South Asia and sub-Saharan Africa. The addressing of these research priorities will enable the scientific community to provide an integrated knowledge base to achieve sustainable management practices of Vertisol that use *G. arboreum* as a crop and ensure agricultural productivity and infrastructure resiliency under a changing climate.

References

1. Food and Agriculture Organization of the United Nations. World reference base for soil resources 2014: international soil classification system for naming soils and creating legends for soil maps. Rome: FAO; 2014.
2. Soil Survey Staff. Keys to soil taxonomy. 13th ed. Washington (DC): United States Department of Agriculture, Natural Resources Conservation Service; 2022.
3. Dudal R, Eswaran H. Distribution, properties and classification of Vertisols. In: Ahmad N, editor. Vertisols: their distribution, properties, classification and management. College Station (TX): Texas A&M University Press; 1988. p. 1–22.
4. Probert ME, Fergus IF, Bridge BJ, McGarry D, Thompson CH, Bourne JA. The properties and management of Vertisols. Wallingford (UK): CAB International; 1987.
5. Ahmad N. Occurrence and distribution of Vertisols. In: Shrink–swell soils of the world. Advances in Soil Science. Vol 14. New York: Springer; 1996. p. 1–41.
6. Coulombe CE, Dixon JB, Wilding LP. Mineralogy and chemistry of Vertisols. In: Sehgal JL, Bhattacharyya T, editors. Soil survey and management. New Delhi: National Bureau of Soil Survey and Land Use Planning; 1996. p. 115–146.
7. Hutchinson JB. The history and relationships of the world's cottons. Endeavour. 1962;21(82):5–15.
8. Rengasamy P. Soil chemistry factors confounding crop salinity tolerance: a review. Agronomy. 2016;6(4):66–78.
9. Directorate of Economics and Statistics. Agricultural statistics at a glance 2023. New Delhi: Ministry of Agriculture and Farmers Welfare, Government of India; 2023.
10. Taylor HM, Ratliff LF. Root elongation rates of cotton and peanuts as a function of soil strength and soil water content. Soil Science. 1969;108(2):113–119.
11. Farbrother HG. Field behavior of Gezira clay under irrigation. Cotton Growers Review. 1972;49(1):1–27.
12. Bronswijk JJB. Prediction of actual cracking and subsidence in clay soils. Soil Science. 1991;152(2):96–104.
13. Chen FH. Foundations on expansive soils. 2nd ed. Amsterdam: Elsevier Science Publishers; 1988.
14. Jayawardane NS, Chan KY. Management of soil physical properties limiting crop production in Australian sodic soils. Australian Journal of Soil Research. 1994;32(1):13–44.
15. Ravina I. Influence of vegetation on moisture and volume changes in heavy clay soils. Géotechnique. 1984;34(1):31–41.
16. Kishné AS, Morgan CL, Miller WL. Vertisol crack characterization for relating to soil moisture. Vadose Zone Journal. 2009;8(1):114–122.
17. Sposito G. The chemistry of soils. 3rd ed. Oxford: Oxford University Press; 2016.
18. Yule DF, Ritchie JT. Soil shrinkage relationships of Texas Vertisols: I. Small cores. Soil Science Society of America Journal. 1980;44(6):1285–1291.
19. Tessier D. Behaviour and microstructure of clay minerals. In: Soil colloids and their associations in aggregates. NATO Advanced Science Institutes Series. Vol 214. Dordrecht: Springer; 1990. p. 387–415.
20. Cabidoche YM, Ruy S. Field shrinkage curves for a Caribbean clay soil. Australian Journal of Soil Research. 2001;39(5):1055–1069.
21. Mitchell JK, Soga K. Fundamentals of soil behavior. 3rd ed. Hoboken (NJ): John Wiley & Sons; 2005.
22. Dasog GS, Acton DF, Mermut AR, De Jong E. Shrink–swell potential and cracking in clay soils of Saskatchewan. Geoderma. 1988;43(2–3):241–251.
23. Hallett PD, Newson TA. Describing soil crack formation using a new soil mechanics model. European Journal of Soil Science. 2005;56(4):537–545.
24. Gupta SC, Larson WE, Linden DR. Tillage and residue effects on soil surface temperatures. Soil Science Society of America Journal. 1983;47(6):1212–1218.
25. Pace PF, Cralle HT, El-Halawany SHM, Cothren JT, Senseman SA. Drip irrigation effects on cotton water use. Journal of Cotton Science. 1999;3(2):100–108.
26. Quisenberry VL, Smith BR, Phillips RE, Scott HD, Nortcliff S. Soil science glossary for fracture/macropore flow. Geoderma. 1994;57(3):279–285.
27. Tisdall JM, Oades JM. Organic matter and water-stable aggregates in soils. Journal of Soil Science. 1982;33(2):141–163.
28. Mauney JR, Henneberry TJ. Stress identification in cotton. Journal of Production Agriculture. 1994;7(2):277–283.
29. Rao GVSRK, Singh P, Rao KV, Ramakrishna A. Cotton

evapotranspiration and water use efficiency. Agricultural Water Management. 2019;212:291–302.
30. Jabro JD, Jed AJ, Sim MS. Soil-water and solute transport in Vertisols. Soil and Tillage Research. 2020;198:104564–104572.
31. Wright SF, Upadhyaya A. Soil aggregate stability and glomalin. Plant and Soil. 1998;198(1):97–107.
32. van Dam JC, Groenendijk P, Hendriks RF, Kroes JG. Modeling water flow with SWAP. Vadose Zone Journal. 2008;7(2):640–653.
33. Nair PKR. Carbon sequestration in agroforestry systems. Agroforestry Systems. 2012;86(2):243–253.
34. Lal R. Soil carbon sequestration impacts on global climate change and food security. Science. 2004;304(5677):1623–1627.
35. Sridharan A, Prakash K. Shrinkage limit of soil mixtures. Geotechnical Testing Journal. 2000;23(1):1–9.
36. Nelson JD, Miller DJ. Expansive soils: problems and practice. New York: John Wiley & Sons; 1992.
37. Steinberg ML. Expansive soils and structural engineering. Journal of Architectural Engineering. 1998;4(4):162–169.
38. Larsbo M, Jarvis N. MACRO 5.0: a model of water flow and solute transport in macroporous soil. Uppsala: Swedish University of Agricultural Sciences; 2003.
39. Biddle PG. Soil drying near trees on clay soils. Géotechnique. 1983;33(2):107–126.
40. Al-Rawas AA, Goosen MF, editors. Expansive soils: recent advances. London: Taylor & Francis; 2006.
41. Puppala AJ, Congress SS, Talluri S. Shrink–swell behavior of expansive soils. Engineering Geology. 2018;246:374–389.
42. Rao SM, Reddy BV, Muttharam M. Wetting–drying effects on soil collapse behavior. Engineering Geology. 2000;60(1–4):223–233.
43. Singh P, Virmani SM. Water and nitrogen dynamics in Vertisols. Field Crops Research. 1996;47(2–3):167–182.
44. Wanjura DF, Mahan JR, Burke JJ, Hatfield JL. Cotton water stress index. Transactions of the American Society of Agricultural Engineers. 2004;47(2):429–435.
45. Turco RF, Kennedy AC, Jawson MD. Microbial indicators of soil quality. In: Doran JW, *et al.*, editors. Defining soil quality for a sustainable environment. Madison (WI): Soil Science Society of America; 1994. p. 73–90.
46. McGarry D, Bridge BJ, Radford BJ. Soil physical properties under different tillage systems. Soil and Tillage Research. 2000;53(2):105–115.
47. Pulleman MM, Marinissen JC. Physical protection of soil organic matter in aggregates. Geoderma. 2004;120(3–4):273–282.
48. Singh P, Virmani SM. Chickpea growth modeling. Field Crops Research. 1996;46(1–3):41–59.
49. Favre F, Boivin P, Wopereis MCS. Soil swelling in cracked Vertisols. Geoderma. 1997;78(1–2):113–123.
50. Peng X, Horn R. Modeling soil shrinkage curves. Geoderma. 2005;125(3–4):197–207.
51. Young IM, Crawford JW. Interactions and self-organization in the soil–microbe complex. Science. 2004;304(5677):1634–1637.
52. Sutton R, Sposito G. Humic substance–clay complexes. Geochimica et Cosmochimica Acta. 2006;70(14):3566–3581.
53. Wilding LP, Tessier D. Genesis of Vertisols. In: Wilding LP, Puentes R, editors. Vertisols. College Station (TX): Texas A&M University Press; 1988. p. 55–81.
54. Mougenot B, Pouget M, Epema GF. Remote sensing of salt-affected soils. Remote Sensing Reviews. 1993;7(3–4):241–259.
55. Padarian J, Minasny B, McBratney AB. Using deep learning for digital soil mapping. Soil. 2019;5(1):79–89.
56. Rillig MC, Mummey DL. Mycorrhizas and soil structure. New Phytologist. 2006;171(1):41–53.
57. Holah JC, Thomas M, Jolly PW, Bärtsch K, Knochel R. Remote sensing of Vertisols. International Journal of Remote Sensing. 2011;32(18):5175–5200.
58. Intergovernmental Panel on Climate Change. Climate change 2021: the physical science basis. Cambridge: Cambridge University Press; 2021.

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