



RESEARCH ARTICLE

Deep sub-soiling improves soil-water conductance, root architecture and cotton yield in semi-arid systems

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Abstract

Cotton productivity in the Indo-Gangetic loamy sands has remained stagnant, largely due to subsoil compaction, which restricts water infiltration and root elongation. This study quantified the effects of one-time sub-soiling, applied as single or cross passes at different spacings, on soil hydraulics, root and fruit development and seed cotton yield (SCY) using analytical approaches beyond conventional mean comparisons. Five tillage treatments, including conventional tillage (CT) and 4 subsoiling configurations, were evaluated across 3 site-years on fixed plots in Punjab, India. Treatment responses were assessed using effect size estimates (Hedges *g*) for key traits, while a piecewise structural equation model traced the causal pathways linking tillage intensity (TI) to infiltration rate (IR), root length (RL), fruiting capacity and yield. A quadratic response surface regression was used to identify the joint optimum of the IR and RL. Cross sub-soiling at 1 × 1 m spacing increased infiltration by 10–13 mm h⁻¹, enhanced rooting depth by 31–33 % and improved SCY by approximately 33 % relative to CT. Structural equation modelling indicated that 57 % of the total tillage effect on yield was mediated through improved soil hydraulics, with an additional 34 % being mediated through enhanced fruiting capacity. The response surface explained 80 % of the yield variability and identified an optimum near a 40 mm h⁻¹ IR and 110 cm RL, with small deviations causing substantial yield losses. Overall, deep, closely spaced cross sub-soiling improved soil-root functioning and translated these gains into higher fruit retention and yield, providing a robust framework for optimising sub-soiling strategies in semi-arid cotton systems.

Keywords: deep tillage; effect-size analysis; infiltration rate; response-surface methodology; root architecture; seed-cotton yield; structural-equation modelling

Introduction

With nearly 30 million hectares under production, cotton delivers approximately 25 million tonnes of lint annually and supplies only one-fifth of the fibre demanded by the global apparel industry (1, 2). Global lint yields have stagnated at approximately 0.8–0.9 t ha⁻¹ for nearly 2 decades despite notable genetic and agronomic advances, with the Organisation for Economic Co-operation and Development-Food and Agriculture Organization Agricultural Outlook (OECD-FAO) reporting stagnation since 2004 (2). India, which accounts for roughly one-third of the world's harvested area, illustrates this ceiling: the average productivity in 2023–24 was just 446 kg ha⁻¹, barely 60 % of the global mean and down from its 2013 peak (3). Among the biophysical factors implicated in this yield plateau, subsoil compaction has emerged as a silent but critical constraint in mechanised cotton fields (4).

Heavy machinery, frequent traffic and repeated shallow tillage often compress the 15–40 cm horizon, routinely pushing cone index values above the 2 MPa threshold at which cotton roots cease to elongate axially (5, 6). These high-strength zones reduce macroporosity and can depress steady-state infiltration by 22–40 %, shrinking the soil-water reservoir available during the crop's long

reproductive phase (7, 8). Field spectroscopy and penetrometer surveys have confirmed that compacted zones restrict canopy development and reduce yield potential across soil textures, from Arkansas silt loams to Indo-Gangetic sandy loams (9). In northwestern India, where intense monsoon events must be stored for later crop stages, hardpans increasingly channel rainfall into runoff, compounding the risk of mid-season drought stress (10).

Subsoiling or deep ripping to depths of 35–50 cm offers a targeted remedy: shanks fracture compacted zones, reduce bulk density in the 20–60 cm layer and have been shown to double infiltration for up to 2 seasons on several soil types (10–12). Yield responses often mirror these hydraulic gains. Long-term experiments in Georgia, Alabama, Louisiana, Pakistan and the North China Plain have reported seed-cotton increases of 10–40 % following a single subsoiling pass compared with conventional tillage (CT) (13–15). However, adoption remains tempered by high energy costs: draft and fuel demands increase with depth, although variable-rate and site-specific guidance technologies can reduce fuel use by 27–43 % without compromising yield (12, 16). In addition to energy demand, deep tillage may involve agronomic trade-offs. Excessive soil disturbance can disrupt soil structure, increase susceptibility to erosion in light-textured soils and accelerate moisture loss in arid environments, while operational

constraints such as fuel cost and machinery availability may further limit adoption. Regional studies from Punjab indicate that cross-subsoiling once every 3 years reduces bulk density, increases infiltration rate (IR) and boosts cotton yields by 13–34 %. However, responses to deep tillage are often site-specific and may vary depending on soil texture, antecedent compaction intensity and seasonal rainfall conditions. In some environments yield responses are small or inconsistent, particularly when compaction layers are weak or where rapid re-compaction occurs following traffic and irrigation. Consequently, understanding the mechanisms linking soil loosening, water movement, root growth and yield remain important for identifying situations where subsoiling provides durable agronomic benefits (10, 17).

Consequently, most studies report improvements in individual traits such as IR, soil strength or yield separately, rather than explicitly tracing the sequential pathway linking soil physical changes to root development and ultimately crop productivity. As a result, the integrated soil-root-yield cascade and the potential non-linear interactions between hydraulic properties and rooting depth remain less frequently quantified within a single analytical framework. However, such mechanistic insights are critical for designing subsoiling programs that can justify their greater fuel demand and carbon footprint in an era of rising energy costs.

To address these gaps, we evaluated subsoiling beyond the conventional ANOVA framework by deploying 3 complementary statistical tools. First, Hedges-g mapping provided a single, intuitive matrix that provided both the size and significance of the treatment effects across 6 key traits. Second, a piece-wise structural equation model partitioned direct, indirect and latent-factor pathways running from tillage intensity (TI) through infiltration and rooting to fruiting behaviour and final yield. Third, a quadratic response surface regression identified the optimum joint zone of infiltration and root depth for maximum seed cotton productivity. Together, this integrated toolkit allows us to move from asking whether subsoiling works to understanding why it works, by how much and under which soil-root combinations the practice delivers the greatest agronomic returns.

Materials and Methods

The study was carried out during 2 consecutive cotton seasons, 2015 and 2016, at the Punjab Agricultural University (PAU) Regional Research Station, Bathinda and 2015 at the PAU Regional Research Station, Abohar, both located in the semi-arid southwestern cotton belt of Punjab, India (30°09'49" N, 74°55'18" E, 211 m asl for Bathinda; 30°08'22" N, 74°12'12" E, 188 m asl for Abohar). The long-term mean annual rainfall is approximately 440 mm at Bathinda and 284 mm at Abohar, with 70–80 % of the total rainfall occurring during the southwest monsoon (July–September). The surface soils at both sites are deep alluvial loamy sands (Typic Ustipsamments) with a slightly alkaline reaction (pH 8.15–8.31), low organic carbon (0.32–0.37 %) and modest available nutrient status (e.g. 123–206 kg N ha⁻¹).

Experimental design and treatments

A randomised complete block design with 4 replications was established on permanent plots (10 × 5 m). At Bathinda the same plots were maintained across the 2 seasons to evaluate persistence of subsoil loosening effects, whereas the experiment at Abohar was conducted for a single season. Five tillage treatments

were compared: conventional shallow tillage (CT, no sub-soiling), single-pass sub-soiling at 1.0 m spacing (+SS1), single-pass sub-soiling at 1.5 m spacing (+SS1.5), cross sub-soiling at 1.0 × 1.0 m (+CSS1) and cross sub-soiling at 1.5 × 1.5 m (+CSS1.5). Subsoiling was performed immediately after the harvest of the previous crop, with a tractor-drawn sub-soiler operated at 0.45–0.50 m depth, followed by pre-sowing irrigation and then conventional seed-bed preparation (2 disc-harrow, 2 cultivator and one plank pass).

Crop husbandry

The Bt cotton hybrid *NCS855 BG-II* was hand-dibbled on May 15, 2015 and May 10, 2016, at Bathinda and on May 17, 2015, at Abohar. Six rows were sown in each plot at row-to-row spacing of 0.675 m and plant to plant spacing of 0.75 m. Two seeds were sown at each hill, which was thinned to one plant per hill after first irrigation. Net sown area in each plot was 4.05 × 9 m. All plots received the state-recommended doses of 150 kg N, 26 kg P and 25 kg K ha⁻¹, through urea, single super phosphate and murate of potash respectively. Nitrogen was applied in 2 equal splits (thinning and first flower) and 4 protective irrigations of 60 mm each through gated pipe surface channels. Other cultural, pest and weed control operations followed the PAU guidelines to ensure that tillage was the sole experimental variable.

Measurements

The field-saturated IR was determined 60 days after sowing with concentric 30/60 cm double-ring infiltrometers under a constant 5 cm head until quasi-steady intake (≈45 min) was reached and expressed in millimetre per hour. Maximum rooting depth was assessed at peak flowering (≈90–100 DAS) by excavating a 1 m trench perpendicular to the 2 centre rows, smoothing the exposed profile, overlaying a 10 × 10 cm grid and recording the deepest live root intersection (≥0.5 mm diameter). Seed-cotton yield (SCY) was obtained from all pickings (two in 2015 and two in 2016) on the whole plot, adjusted to 8 % moisture and converted to kilogram per hectare.

Statistical analysis

Trait data were subjected to analysis of variance for an randomised complete block design (RCBD) using the Proc GLM in SAS 9.3. Normality and homogeneity of variances were checked and treatment means were separated by Fisher's protected least significant difference at $p \leq 0.05$. Site-year × treatments interactions were examined in the ANOVA model and were not significant for the principal response variables. However, primary ANOVA results are presented separately for each site-year combination to reflect seasonal variability.

Effect-size analysis and visualisation

To compare each tillage treatment with the conventional control (CT) across multiple response variables, we calculated Hedges g, a bias-corrected standardised mean-difference (18), for 6 agronomic traits: field-saturated IR, maximum root length (RL), sympodia per plant, bolls per square metre, mean boll weight and SCY.

For every trait the effect size was computed as

$$g = J \frac{(X_{trt} - X_{ct})}{S_{pooled}}$$

$$S_{pooled} = \sqrt{\frac{((n_{trt} - 1)s_{trt}^2 + (n_{CT} - 1)s_{CT}^2)}{(n_{trt} + n_{CT} - 2)}}$$

$$\text{where } J = 1 - \frac{3}{(4(n_{\text{trt}} + n_{\text{CT}}) - 9)}$$

corrects small-sample bias.

Trait means were based on the pooled data over site years; unequal sample variances were accommodated by reporting a two-sided Welch *t*-test *p*-value for each treatment-trait contrast. The significance thresholds were set at $p < 0.05$ (*), $p < 0.01$ (**) and $p < 0.001$ (***). The *g*-values were rendered as a colour-graded heat map (Matplotlib v3.8).

Structural-equation modelling (SEM)

A piecewise latent-variable SEM was used to quantify the effect of TI on SCY via the IR, RL and fruit production. The TI was entered as an ordinal exogenous variable representing increasing soil disturbance intensity (CT < +SS1.5 < +SS1 < +CSS1.5 < +CSS1). The numeric scores (0–2.5) were used only to preserve this rank order within the SEM, thereby, interpreted as relative levels of TI. The field-saturated IR (mm h⁻¹) and maximum RL (cm) were modelled as sequential mediators. Yield components, such as sympodia per plant, bolls per square metre and mean boll weight (g), served as reflective indicators of a latent ‘fruiting capacity’ (FR). The structural portion specified the path TI → IR → RL → FR → SCY and allowed direct links from TI and IR to FR and SCY. All variables were z-standardised; parameters were estimated with robust maximum-likelihood (MLR) in lavaan v0.6-17. Model fit was considered acceptable when $\chi^2/\text{df} < 2$, comparative fit index (CFI) ≥ 0.95 , root mean square error of approximation (RMSEA) ≤ 0.06 and standardised root mean square residual (SRMR) ≤ 0.08 . The final solution met all criteria ($\chi^2/\text{df} = 1.34$, CFI = 0.96, RMSEA = 0.045, SRMR = 0.041) and accounted for 65 % of the variance in SCY; indirect and total effects were derived from standardised coefficients (β) with 10000-draw bootstrap CIs.

Quadratic response surface regression

To visualise the joint influence of IR and RL on SCY, a full second-order polynomial was fitted using ordinary least squares in stats models v0.14 with HC3 standard errors. Lack-of-fit was evaluated against a cubic model ($\Delta\text{AIC} = +38$; lack-of-fit $p = 0.12$). Predicted values were generated on a 200 × 200 grid spanning the convex hull of the observed IR-RL combinations and rendered as a filled-contour map. The graph was produced using Matplotlib v3.8.

Results

Soil physical properties

The bulk density in the 0–15 cm layer ranged from 1.48 to 1.62 g cm⁻³ across site-years (Table 1). Values were highest under CT and lowest under cross sub-soiling at 1.0 m spacing (+CSS1), although the absolute differences were modest (≤ 0.09 g cm⁻³). A similar pattern was observed at 15–30 cm depth, where +CSS1 reduced density by 0.02–0.06 g cm⁻³ relative to that of CT. The field-saturated IR responded sharply to profile loosening. The IR increased consistently with subsoiling intensity, with cross-subsoiling treatments showing the highest value across all site-years (Table 1).

Seasonal soil-water dynamics

The volumetric water content (θ_v) profiles after the first irrigation and again at the final picking are plotted in Fig. 1 a–c. Across all 3 site-years, the upper 0–30 cm curves for CT, single-pass (SS1, SS1.5) and cross-pass (CSS1, CSS1.5) treatments virtually overlapped, confirming that the initial wetting front saturated the tilth to a common level. Differences emerged only at depths below 30 cm. Immediately after irrigation, the two cross subsoiled treatments consistently stored more water between 45 and 90 cm than CT, with the single-pass treatments intermediate. This deeper wetting agrees with the faster infiltration measured in the same plots and demonstrates that loosening the pan allows a larger fraction of the irrigation water (and any preceding rainfall) to percolate into the sub-root-zone storage rather than run off or evaporate at the surface.

However, by harvest, the moisture ranking inverted: CT profiles retained the highest θ_v below ~60 cm, whereas subsoiled plots had drawn the subsoil reservoir down to levels indistinguishable from their surface layers. The shift mirrors the root-length data, which shows deeper exploration under CSS1 and CSS1.5. In other words, deep ripping not only stores more water early in the season but also enables the crops to mine that storage more completely as reproductive demand peaks, leaving less residual moisture in the profile at harvest.

Root system development

Subsoiling treatments produced markedly longer and heavier roots (Table 1). In Bathinda-2015, the mean RL under +CSS1 was 33 % greater than CT and the fresh root weight per plant rose by 49 %. The advantage widened in 2016, when +CSS1 outweighed CT roots by 75 % on a fresh-weight and dry-weight basis. Root responses at Abohar were equally pronounced: +CSS1 extended roots by 33 % and increased dry mass by 30 % relative to CT. In Bathinda, cross subsoiling outperformed single subsoiling; however, at Abohar, all subsoiling treatments were at par with

Table 1. Bulk density, water infiltration rate and root growth parameters under different tillage treatments

Location (year)	Treatments	Bulk density of soil (g cm ⁻³)		Infiltration rate (mm hr ⁻¹)	Root length (cm)	Fresh root weight plant ⁻¹ (g)	Dry root weight plant ⁻¹ (g)
		0–15 cm	15–30 cm				
Bathinda (2015)	CT	1.57	1.58	34.0 c	89.8 c	40.2 c	14.3 c
	+SS ₁	1.56	1.57	40.0 b	108.8 ab	52.5 b	19.8 b
	+SS _{1.5}	1.57	1.57	36.0 c	105.3 b	57.7 ab	21.7 b
	+CSS ₁	1.55	1.56	45.0 a	120.1 a	59.8 a	23.6 a
	+CSS _{1.5}	1.56	1.55	42.0 ab	113.4 ab	57.7 ab	21.6 b
Bathinda (2016)	CT	1.62	1.64	31.0 d	93.5 b	41.5 d	15.8 d
	+SS ₁	1.61	1.63	38.0 bc	114.8 a	60.7 bc	23.0 bc
	+SS _{1.5}	1.62	1.63	35.0 c	110.0 a	57.1 c	21.2 c
	+CSS ₁	1.60	1.62	44.0 a	122.5 a	72.8 a	27.6 a
	+CSS _{1.5}	1.61	1.62	39.0 b	117.1 a	65.4 b	24.8 b
Abohar (2015)	CT	1.57	1.58	28.4 d	91.8 b	40.0 b	15.2 b
	+SS ₁	1.52	1.54	35.0 bc	117.5 a	49.5 a	18.9 a
	+SS _{1.5}	1.54	1.55	32.6 c	116.5 a	49.5 a	19.4 a
	+CSS ₁	1.48	1.52	41.7 a	122.5 a	52.5 a	19.8 a
	+CSS _{1.5}	1.50	1.52	37.5 b	119.0 a	50.3 a	a

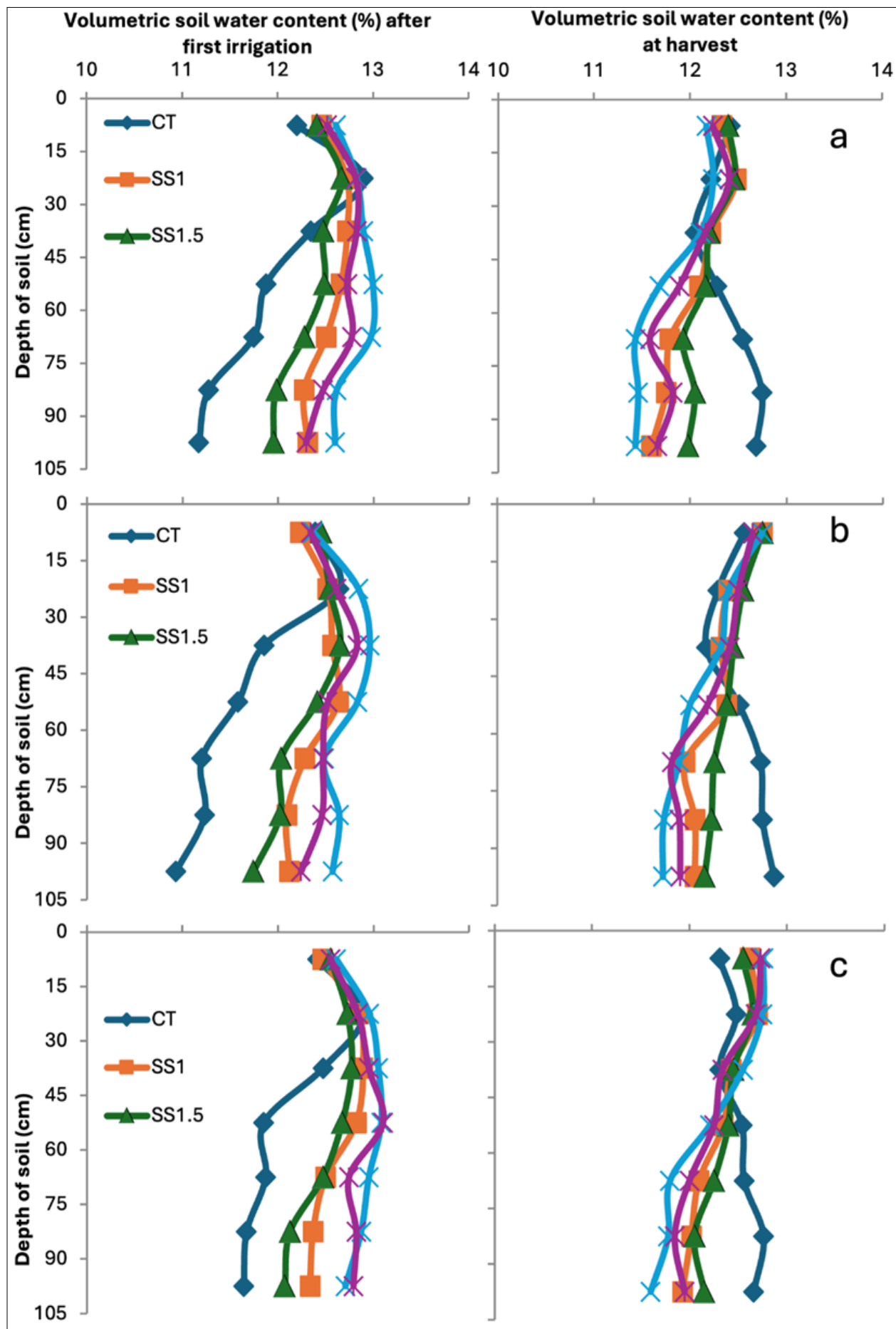


Fig. 1. Seasonal soil-water profiles under contrasting tillage. Depth-wise volumetric water content (θ_v) measured (left column) 24 hr after the first irrigation and (right column) at final picking for (a) Bathinda 2015, (b) Bathinda 2016 and (c) Abohar 2015. The lines represent the five tillage treatments: conventional tillage (CT), single-pass subsoiling at 1.0 m (SS1 + CT) and 1.5 m (SS1.5 + CT) shank spacing and the corresponding cross-subsoiling treatments (CSS1 + CT, CSS1.5 + CT). Deep-ripped plots stored 2–3 % more water below 45 cm after irrigation, yet depleted that reserve more completely by harvest, reflecting both enhanced infiltration and deeper root water uptake.

each other but outperformed CT.

Vegetative and reproductive growth

Plant stature was largely unaffected by subsoiling; however, reproductive branching responded strongly (Table 2). At Bathinda-2015, +CSS1 raised sympodial branches per plant by 30 % over CT and produced the highest monopod number. Similar increases in sympods (+42 %) and bolls per square metre (+59 %) were recorded in the higher-yielding 2016 season. In Abohar, +CSS1 again generated the greatest sympodial count and boll density, exceeding CT by 19 % and 27 % respectively. Intermediate improvements followed the order +SS1 > +SS1.5 > CT in all the cases.

Seed-cotton yield

Yield trends mirrored the combined soil and canopy responses (Table 2). In Bathinda-2015, +CSS1 produced 30 % increase over CT and 10–14 % more than the single pass treatments. The benefit intensified in 2016, when +CSS1 yielded 34 % above CT. At Abohar, the same treatment increased SCY by 32 % when compared with CT, while all sub-soiling treatments produced statistically similar yields. Across the 3 site-years, the average advantage of +CSS1 over CT was 33 %, while +SS1 and +SS1.5 provided mean gains of 23 % and 17 % respectively.

Effect-size analyses

The Hedges *g* heat map (Fig. 2, Supplementary Table 1) distills

treatment performance into standard deviation units relative to conventional control. The two cross sub-soiling options (+CSS1 and +CSS1.5) showed the largest hydraulic effect sizes in the pooled analysis, indicating stronger improvements in infiltration and root depth relative to the conventional control. The IR increased by 4.63 and 2.95 SD, root depth by 5.26 and 3.88 SD ($p < 0.001$), far exceeding the ≥ 0.80 threshold usually interpreted as large effect. Single-pass sub-soiling showed a clear intensity gradient: +SS1 raised infiltration by 2.18 SD, whereas the less intense +SS1.5 achieved only 1.19 SD.

These hydraulic improvements were associated with moderate increases in reproductive traits such as boll number and boll weight. Boll number responded strongly ($g = 1.68$ SD for +CSS1), boll weight moderately (1.75 SD), while sympodial branches exhibited only small-to-medium shifts (0.40–0.97 SD). In the pooled dataset, +CSS1 showed the largest yield effect size (1.05 SD), followed by +CSS1.5 (0.88 SD), whereas single-pass treatments showed smaller and statistically non-significant effect sizes. Taking together, the matrix suggests a general trend in which greater soil loosening is associated with stronger improvements in soil hydraulic traits and rooting depth, although the magnitude of yield responses varied among site-years.

Table 2. Growth, yield attributes and seed cotton yield under different tillage treatments

Location (year)	Treatments	Plant height (cm)	Monopods plant ⁻¹	Sympods plant ⁻¹	Bolls m ⁻²	Boll weight (g)	Seed cotton yield (kg ha ⁻¹)
Bathinda (2015)	CT	89.8a	1.70 b	15.0c	56.4 b	3.10 b	1429 c
	+SS ₁	95.5 a	2.12 a	17.6 ab	65.5 a	3.63 a	1682 ab
	+SS _{1.5}	94.1 a	2.05 a	17.0 bc	64.1 a	3.48 ab	1622 bc
	+CSS ₁	98.5 a	2.33 a	19.5 a	70.4 a	3.83 a	1853 a
	+CSS _{1.5}	96.6 a	2.10 a	18.2 ab	68.5 a	3.70 a	1729 ab
Bathinda (2016)	CT	130.5 a	1.85 a	20.7 b	62.6 b	3.25 b	2044 b
	+SS ₁	138.5 a	1.90 a	27.3 a	91.7 a	4.04 a	2525 a
	+SS _{1.5}	138.3 a	1.85 a	24.6 ab	87.4 a	3.79 a	2398 ab
	+CSS ₁	141.0 a	2.00 a	29.3 a	99.8 a	4.16 a	2733 a
	+CSS _{1.5}	139.8 a	1.95 a	26.6 a	98.6 a	3.91 a	2569 a
Abohar (2015)	CT	107.5 b	1.86 d	13.0 bc	78.8 c	3.36 a	1222 b
	+SS ₁	110.5 ab	2.05bc	14.3 abc	88.4 bc	3.39 a	1555 a
	+SS _{1.5}	110.3 ab	1.93 cd	12.8 c	82.1 c	3.36 a	1502 a
	+CSS ₁	114.0 a	2.24 a	15.5 a	100.1 a	3.57 a	1611 a
	+CSS _{1.5}	113.3 ab	2.13 ab	14.9 ab	95.9 ab	3.46 a	1595 a

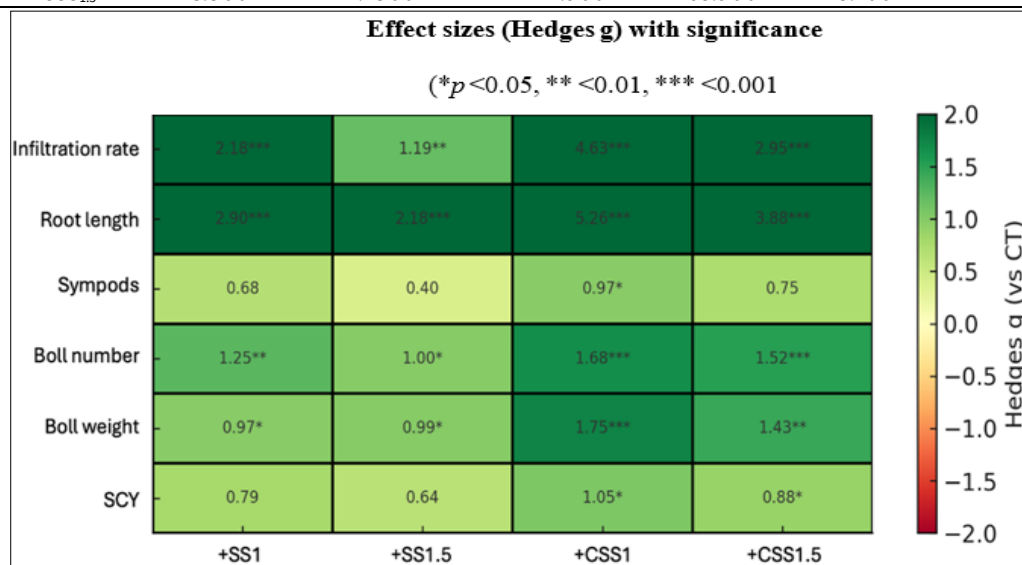


Fig. 2. Effect size heat map comparing tillage treatments with CT. Hedges *g* values (colour scale) and Welch *t* significance levels for six agronomic traits: infiltration rate, maximum root length, sympodia plant⁻¹, bolls m⁻², mean boll weight, and seed-cotton yield (SCY). Cells carry significance stars ($p < 0.05 = *$, $p < 0.01 = **$, $p < 0.001 = ***$). Large positive effects of CSS1 + CT and CSS1.5 + CT on hydraulic traits cascaded to moderate gains in canopy traits and yield, whereas single-pass treatments showed smaller, trait-specific responses.

Structural equation modelling for trait inter-relationships

The final SEM (Fig. 3, Supplementary Table 2) explained 65 % of the variance in seed cotton yield and met all recommended fit thresholds ($\chi^2/df = 1.34$; CFI = 0.96; RMSEA = 0.045; SRMR = 0.041). The TI exerted a strong direct influence on the field-saturated IR ($\beta = 0.71, p < 0.001$) and a smaller, non-significant direct effect on RL ($\beta = 0.19, p = 0.10$). Faster infiltration promoted deeper rooting (IR $\rightarrow$ RL, $\beta = 0.42, *p = 0.002$).

A latent factor labelled 'Fruiting capacity' (FR), reflected by sympodia (loading = 0.71), bolls per square metre (0.88) and mean boll weight (0.64), captured 68 % of the shared variance among these yield components. While TI and IR both showed positive but statistically non-significant paths to FR ($\beta = 0.18$ and 0.21 respectively), RL tangibly contributed ($\beta = 0.29, p = 0.06$). Crucially, FR exerted the single largest direct influence on yield ($\beta = 0.55, p < 0.001$), eclipsing the smaller yet significant hydraulic shortcut from IR to yield ($\beta = 0.31, p = 0.03$) and the weak, non-significant TI $\rightarrow$ yield path ($\beta = 0.18$).

Summing coefficients along all pathways revealed that TI raised yield by 0.66 standard deviations in total: 57 % of that effect flowed through the hydraulic route (TI $\rightarrow$ IR $\rightarrow$ yield), 9 % through root deepening (TI $\rightarrow$ IR $\rightarrow$ RL $\rightarrow$ yield) and the remaining 34 % was mediated via fruiting capacity (TI $\rightarrow$ IR/RL $\rightarrow$ FR $\rightarrow$ yield). Therefore, the model supports a conceptual cascade in which improvements in soil hydraulic properties are associated with deeper rooting and enhanced fruiting capacity, although some individual pathways were weak or statistically non-significant.

Response-surface regression

The second-order model relating SCY to field-saturated IR and maximum RL explained 80 % of the observed variance ($R^2 = 0.80$) and showed no lack of fit when tested against a cubic alternative ($p = 0.12$). Neither linear coefficient differed from 0 (IR: -19 ± 149 kg

$\text{ha}^{-1} \text{mm}^{-1}, p = 0.90$; RL: $+67 \pm 93$ kg $\text{ha}^{-1} \text{cm}^{-1}, p = 0.47$), indicating that the yield does not rise in a simple, additive fashion. Instead, curvature and synergy dominated the surface: both quadratic terms were negative and highly significant (IR²: $-12.2 \pm 4.1, p = 0.003$; RL²: $-1.72 \pm 0.51, p = 0.001$), whereas the IR $\times$ RL interaction was positive and equally significant ($+8.58 \pm 2.67, p = 0.001$). This function generates a concave, saddle-shaped landscape (Fig. 4, Supplementary Table 3) whose ridge of maximum productivity lies at IR $\approx 38\text{--}42$ mm h^{-1} and RL $\approx 110\text{--}120$ cm. The predicted yield across this crest approaches 2.4 t ha^{-1} , nearly 500 kg ha^{-1} higher than the overall mean. Deviating from the ridge in either dimension is costly: at a root depth of 110 cm, a 5 mm h^{-1} drop in IR lowers yield by ≈ 250 kg ha^{-1} , whereas deepening roots beyond ≈ 125 cm confers little additional benefit once IR exceeds 40 mm h^{-1} . The analysis, therefore, pinpoints a practical target zone for sub-soiling programmes: hydraulic conductivity of ≈ 40 mm h^{-1} coupled with rooting fronts of 110 cm that surpass the plough pan.

Discussion

Subsoiling reshaped the soil-plant continuum far beyond the modest reductions in bulk density that we measured. By fracturing the plough pan, the cross-subsoiling 1×1 m treatment (+CSS1) lifted field-saturated infiltration by 10–13 mm h^{-1} and drove roots 31–33 % deeper than the conventional check, gains that match those reported from comparable loamy-sand cotton soils in Turkey (infiltration +28 mm h^{-1} ; root depth +46 %) and Alabama (RL density +54 %) (13, 19). Large hydraulic jumps are typical when sub-soiling breaches dense horizons because macroporosity, not matrix porosity, controls the intake under ponded heads (20). Our results extend this principle by showing the hydrologic benefits associated with subsoiling during both years.

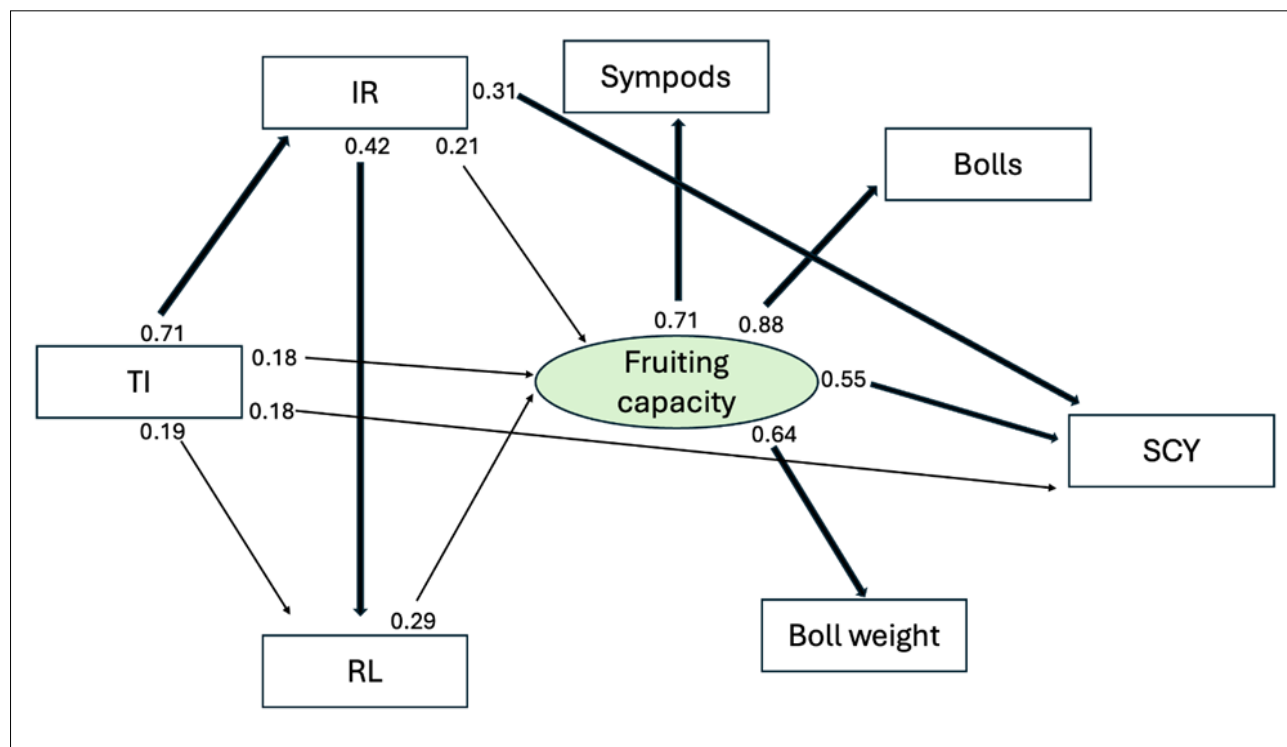


Fig. 3. Piecewise structural equation model (SEM) for the soil-root-yield cascade. Standardised path coefficients (β) are shown next to each arrow; bold lines are significant at $p < 0.05$ and dashed lines are non-significant. Tillage intensity (TI) increases the infiltration rate (IR), which deepens the root length (RL); both traits contribute directly and via the latent factor fruiting capacity (sympodia, bolls and boll weight) to seed cotton yield (SCY). The model explained 65 % of the yield variance and met all global fit indices (CFI = 0.96; RMSEA = 0.045; SRMR = 0.041).

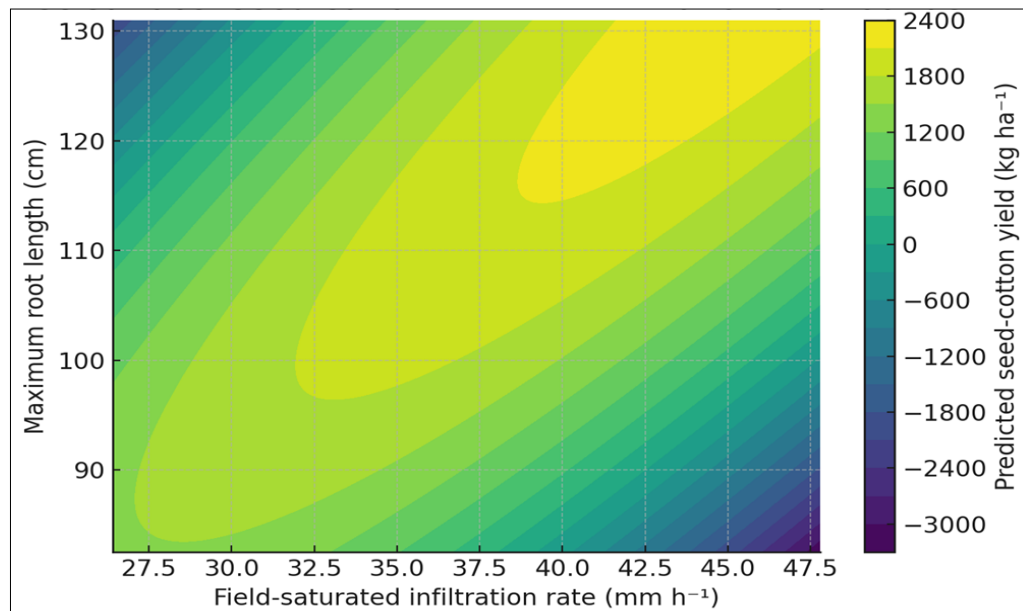


Fig. 4. Quadratic response surface of seed cotton yield as a joint function of infiltration and rooting depth. Predicted yield (colour bar, kg ha^{-1}) from the second-order polynomial fitted to the entire dataset; axes span the observed convex hull. A curved ridge of maximal productivity lies around 38–42 mm h^{-1} infiltration and 105–115 cm maximum root length. Yield declines steeply when either variable fall below this zone, indicating that sub-soiling programs should aim for hydraulic conductivities of $\approx 40 \text{ mm h}^{-1}$ and root fronts that extend below the pre-existing plough pan.

From soil physics to root exploration

The SEM suggested that the primary pathway from TI to yield was hydraulic rather than mechanical. Although the SEM provided a coherent representation of the soil-root-yield relationships observed in this experiment, it should be interpreted as a hypothesis-driven statistical framework rather than definitive proof of causality and alternative pathway structures could also explain part of the observed variance. A standard deviation rise in infiltration propagated half that size directly to yield ($\beta = 0.31$) and a further 0.42 SD into deeper rooting, which, in turn, influenced the latent fruiting capacity construct. The $\text{IR} \rightarrow \text{RL}$ path corroborates controlled-environment evidence that cotton roots elongate until mechanical impedance exceeds $\approx 2 \text{ MPa}$ or soil water drops below $0.06 \text{ cm}^3 \text{ cm}^{-3}$ (21). Field data from China likewise showed that lint yield increased linearly ($r^2 = 0.78$) with the percentage of profile penetrated by roots when soil strength declined after paratillage (22). Our effect-size matrix reinforces this sequence: the largest g -values appear in infiltration (+4.6 SD) and root depth (+5.3 SD), decline in boll number (+1.7 SD) and attenuate further in SCY (+1.05 SD). Stepwise attenuation is a reminder that ample soil water is necessary but not sufficient for high yields and carbon partitioning to reproductive sites sets an additional ceiling (23).

Yield response and diminishing returns

Cross-ripping at a narrow 1 m grid produced the largest yield gains in the Bathinda site-years, although the differences among subsoiling treatments were smaller at the Abohar site, indicating that the advantage of closely spaced cross subsoiling was more pronounced under the Bathinda site conditions. A similar spacing response was documented in Australian picker-traffic studies, where 1 m shanks reduced the cone index below 1 MPa across most of the trafficked strip, while 1.5 m spacing left a substantially larger compacted zone (6). The agronomic benefits must be weighed against the higher fuel demand associated with deep tillage, emphasising the need to optimise subsoiling frequency and spatial intensity to balance productivity gains with energy use and carbon footprint. Our quadratic surface shows why: the yield ridge bends upward

more steeply with infiltration than with root depth, each 10 mm h^{-1} jump in IR at 110 cm RL adds $\sim 150 \text{ kg ha}^{-1}$, but extending roots another 10 cm confers only $\sim 35 \text{ kg ha}^{-1}$ once infiltration is already fast. A similar curvature was predicted by Ritchie's cotton model, where water uptake saturated above $\approx 120 \text{ cm}$ because most fine roots concentrated in the upper half metre (24). The observed enhancement in infiltration and deeper root exploration has broader agronomic implications for water management in semi-arid cotton systems. Improved soil water conductance can increase the fraction of rainfall and irrigation stored within the soil profile, potentially improving water-use efficiency and buffering crops against intermittent drought stress. In regions such as northwestern India where rainfall variability and heat stress are increasing, practices that enhance soil water capture and rooting depth may therefore contribute to greater production stability under climate variability.

Integrating effect sizes with agronomic relevance

The interpretation of g alongside p -values helped prioritise treatments with practical clarity. For instance, +SS1.5 produced a statistically significant increase in infiltration ($p < 0.01$); however, the effect magnitude ($g = 1.19$) was only one-quarter of that of +CSS1. The effect sizes with confidence intervals convey richer information than binary significance tests, particularly in agronomic trials, where replication is limited by field logistics (25). The boxed heat map thus complements ANOVA tables by illustrating how hydraulic traits respond exponentially to TI, whereas canopy traits lag, highlighting the areas where management refinements should be targeted.

Wider implications and future work

Our findings align with those previous reports whose field trial on sandy loams showed approximately 15 % lint gains ($g \approx 0.6$) from subsoiling, consistent with multi-study averages (10). The larger response here ($>30 \%$) likely reflects the extremely low organic C of Indo-Gangetic alluvia and the cumulative plough-pan traffic from pre-sowing irrigation. Whether benefits persist beyond 2 cotton seasons warrants longer trials; in Coastal Plain Ultisols, annual ripping maintained low cone resistance, but summer cover crops achieved similar porosity restoration within four years (26). Evaluating such

biological alternatives under the conditions of Punjab would quantify the trade-offs between energy use and carbon footprints. Finally, coupling our empirical surface with process-based cotton models could test how climate change scenarios (e.g. erratic monsoon onset) shift the optimum IR–RL zone, as demonstrated in cotton systems modelled under arid-region irrigation scenarios (27). Since our study was conducted on single Bt cotton hybrid and therefore the responses observed here may not fully represent the range of genetic variation in rooting behaviour and compaction tolerance reported among cotton cultivars; evaluating subsoiling responses across diverse genotypes would further strengthen the generality of these findings.

Conclusion

Deep, closely spaced cross subsoiling improved soil hydraulics and root permeability and these physical gains propagated through root architecture to fruit retention and yield. The integrated use of effect-size maps, SEM and response-surface analysis provides a novel and transparent framework for quantifying such cascades and should be transferable to other crop-soil contexts. Future studies should include detailed measurements of soil physical properties such as pore-size distribution, soil water retention and continuous profile moisture dynamics to further clarify the mechanistic pathways linking subsoiling-induced structural changes with crop water uptake and yield responses.

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Authors' contributions

HSB conducted the experiment in Bathinda and MS conducted the experiment in Abohar. MS performed the statistical analysis. HSB wrote the first draft of the manuscript. Both the authors read and approved the final manuscript.

Compliance with ethical standards

Conflict of interest: Authors do not have any conflict of interest to declare.

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