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Abstract

Soil crusting is a major constraint in agricultural production, as it hinders seedling emergence and crop development. This problem is especially critical for small-seeded crops, such as vegetables, as well as larger seeds like soybeans and cotton. When a crust layer forms after seeding, a substantial proportion of seeds may fail to emerge, reducing potential yield. While preventive measures exist, mechanical intervention is necessary once the crust has developed. In this study, three manually operated prototype soil crust breakers were developed and evaluated for their effectiveness. Experiments were conducted on artificially formed crusts in two soil types: silty-clay soil at the Akdeniz University Aksu Research and Application Field and clay-loam soil at the Campus Research and Application Field, using cotton seeds, and testing three crust breaker designs: rolling-type blade, rolling-type finger, and sled-type. Measured parameters included penetration resistance, mean emergence time, emergence rate index, and percentage of emergence. Results indicated that all three crust breakers effectively disrupted the soil crust. In silty-clay soil, the rolling-type blade crust breaker achieved the highest emergence rate (82.3%), while no significant differences were observed between the rolling-type finger and sled-type designs. In clay-loam soil, performance differences among the three crust breakers were not statistically significant. Overall, the tested crust breakers improved cotton emergence by at least 23.8% in silty-clay soil and 8% in clay-loam soil, demonstrating their practical effectiveness in mechanical control of soil crusting.

Key words: Cotton, crust breaker, crust breaking, emergence, seedling, crusted soils

Introduction

Successful plant cultivation hinges on creating optimal conditions for seed germination and the emergence of seedlings from the soil. One critical factor affecting this process is the formation of a crust layer on the soil surface. This solid, rigid, and brittle layer, known as the soil crust layer, results from various external forces acting on soil aggregates. The formation of the soil crust layer is influenced by two primary factors. Firstly, climatic conditions, such as raindrop impact and solar radiation, significantly affect processes like soil aggregate fragmentation, surface compaction, and hardening. The kinetic energy from raindrops, specifically, causes soil aggregate dispersal, muddy surface formation, and general soil compaction. Secondly, the properties of the soil, including the particle size distribution (silt, clay, and sand content), lime, organic matter, exchangeable sodium, magnesium, calcium content, and electrical conductivity, together determine the characteristics and hardness of the crust layer.

Soil crust formation is prevalent in various soil types, but its adverse impact on seed emergence is most pronounced in regions with rapid soil surface drying after rainfall and soils rich in silt and sand immediately after seeding (Öztürk and Özdemir, 2006; Sjoblom, 2014; Taboada-Castro *et al*., 2015; Almajmaie *et al*., 2017; Zhu *et al*., 2022). Crust formation is less common in soils with low silt content, such as fine sand or coarse sandy soils, but soils with fine sand and silt content are more susceptible to crust layer development (Baumhardt *et al*., 2004; Bal *et al*., 2011). The formation of the soil crust layer leads to several detrimental consequences, including reduced soil pore space, diminished soil aeration, shallow root development, impaired water infiltration and drainage, decreased nutrient uptake, heightened risk of erosion through surface runoff, and negative effects on plant health and yield. In severe cases, it may necessitate reseeding due to poor plant emergence (Manyevere *et al*., 2015; Laker and Nortjé, 2019; Crucil & Oost, 2021).

Farmers or researchers commonly tested various methods, such as conservative tillage methods, mulching, irrigation, mechanical disruption of the soil crust, and reseeding, to prevent or mitigate the potential adverse effects of soil crust on crop emergence and yield. Karayel and Šarauskis (2024) explored the effect of various tillage techniques on soil crust hardness. They conducted their study on silty-loam soil, analysing the effects of four distinct tillage approaches, two of which were conventional and the remaining two were conservation methods. Their findings revealed notable disparities in soil crusting hardness among the various tillage techniques, with conservation practices demonstrating superior effectiveness in reducing penetration resistance. Specifically, the conservation tillage methods facilitated higher emergence rates due to the decreased soil crust hardness. Conversely, the conventional approach, utilizing a chisel plough and rotary tiller, led to the formation of a harder soil crust with the highest recorded penetration resistance at 408 kPa. Consequently, this led to a longer emergence period of 9.8 days, a lower emergence rate index of 0.4 seedlings·m^{-1}·day^{-1}, and a reduced percent emergence of 49%. Gicheru *et al*. (2004) conducted a study in semi-arid fields of Eastern Kenya to investigate the impact of various practices on crust layer strength and thickness, as well as plant emergence. The study concluded that the application of farm manure in conjunction with reduced tillage or mulching significantly reduced crust layer formation and improved field seedling emergence by enhancing soil infiltration and drainage. Research by Šimansky *et al*. (2014) in Slovakia demonstrated that the application of farm manure reduced the thickness of the crust layer and the crust layer index. Soil tillage operations with farm manure resulted in a 0.56 cm thinner crust layer compared to operations without, and this difference was statistically significant. Almajmaie *et al*. (2017) investigated the effectiveness of using paper waste, phosphoric acid, and gypsum in preventing soil crust formation. The researchers applied gypsum at 250 and 500 g m^{-2}, paper waste at three different rates of 1000, 2500, and 7500 g m^{-2}, and phosphoric acid at two rates of 0.08 and 0.16 *l* m^{-2}. The trial results showed that using paper, gypsum, and phosphoric acid effectively reduced soil crusting. Paper waste and gypsum were the most influential amendments throughout the trial, while phosphoric acid only reduced the severity of crust formation in the 14 days following application. The researchers suggested using penetration resistance as the preferred method for measuring soil crusting due to its strong correlation with other techniques and its efficiency.

Once the crust layer has formed, mitigating its adverse effects becomes essential, often requiring mechanical intervention through specialized agricultural machinery. Among these, shallow tillage is a common technique for loosening the soil surface and breaking up the crust.

However, using traditional tillage tools over seed rows can be detrimental, as they may uproot or crush emerging seedlings. Cassel *et al*. (1995) highlighted these risks, cautioning against mechanical disruption with conventional tillage tools due to the potential harm to young plants and seeds.

To address this issue, researchers have explored alternative mechanical methods. Bakhtiyar (2019) investigated the use of disc implements, analyzing the effects of disc diameter, spacing, forward speed, and vertical load on crust-breaking efficiency and seedling protection. The study identified optimal operating conditions—such as a disc diameter of 240–250 mm, a disc spacing of 50 mm, a vertical load of 225–250 N, and a speed of 5–8 km/h—to maximize effectiveness while minimizing plant damage. Similarly, Awadhwal and Thierstein (1983) developed a rolling-type soil crust breaker, demonstrating its ability to improve seedling emergence rates from 8–38% under crusted conditions to 44–96% after mechanical treatment.

Despite these advancements, research on prototype designs tailored for diverse soil conditions and crop types remains limited. Additionally, comparative evaluations of different mechanical methods under standardized conditions are lacking. Given that soil crusting poses a global challenge, increasing production costs and reducing crop yields, further innovation is needed. This study aims to bridge this gap by developing and comparing prototype soil crust breakers, evaluating their effectiveness in improving seedling emergence and contributing to more efficient and sustainable agricultural practices.

Materials and Methods

Experimental fields and conditions

In this research, three models of crust breakers were manufactured and tested to determine their efficiency. The experiments were conducted using cotton seeds in two different fields with silty-clay and clay-loam soils at Akdeniz University, Faculty of Agriculture, Aksu, and Campus Research and Application Centres. The soil texture of the experimental fields varied between locations. In the Aksu Research and Application Field, the soil was classified as silty clay, containing 2% sand, 56% silt, and 42% clay. In contrast, the Campus Research and Application Field had a clay loam texture, comprising 41% sand, 26% silt, and 33% clay.

On May 24, 2022, cotton seeds were sown in a field with silty-clay soil. The field was irrigated just after seeding, and on May 28, 2022, the crust-breaking process was applied. On June 2, 2022, the field with clay-loam soil was sown and irrigated the next day. The crust-breaking process was conducted on June 8, 2022.

The temperature and humidity range during the experiment dates are presented in Figure 1. Weather conditions were recorded over a period of time in the region where the field with silty-clay soil is located. The maximum temperature on May 27, 2022, was 35.8°C, while the lowest temperature on June 1, 2022, was 15.8°C. The minimum air humidity percentage was noted on May 24, 2022, at 15%, whereas the highest air humidity percentage was observed on May 31, 2022, at 52%.

Similarly, weather conditions were also recorded over a period of time in the region where the field with clay-loam soil is located. The minimum air temperature recorded was 16.1°C on June 2, 2022, while the maximum air temperature of 32.2°C was noted on June 8, 2022. The minimum air humidity was observed at 15% on June 2 and June 3, 2022. On the other hand, the maximum air humidity recorded was 59.8% on June 13, 2022.

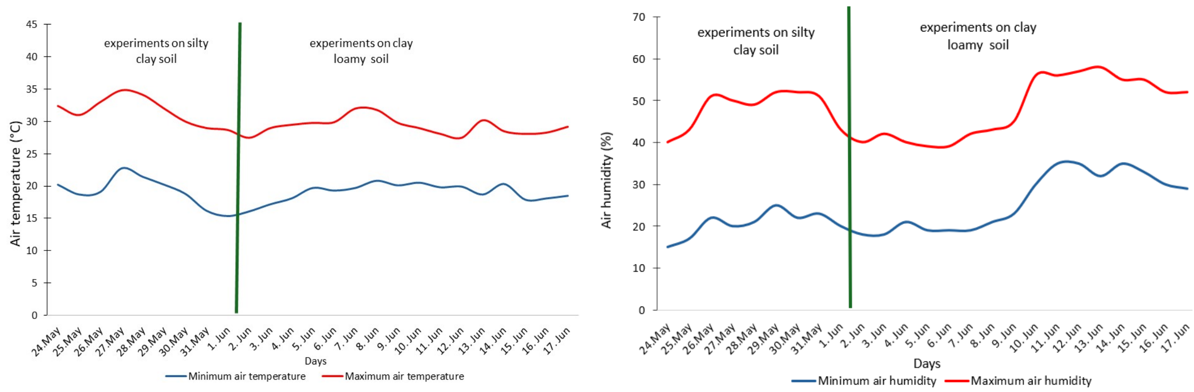


Figure 1. Air temperature and humidity ranges in the experimental field region during the experiments (from May 24 to June 17, 2022).

The conventional tillage method was employed to prepare the seedbed, involving ploughing, disc harrowing, and a leveling operation to evenly smooth and slightly firm the soil. Cotton seeds were sown to a depth of 60 mm using a precision vacuum seeder with shoe-type furrow openers. Following seeding, the fields were irrigated using a sprinkler irrigation system. The silty-clay soil was allowed to dry for four days, while the clay-loam soil was allowed to dry for six days, promoting the formation of a surface crust layer on the soil in the fields.

Before sowing, the penetration resistance and moisture content of the soil were measured in the top 60 mm, which encompassed the seed placement zone and the immediate surrounding soil. This depth was selected because it directly influences seed germination and early root development. Penetration resistance was measured using the hand-held penetrometer described in the following paragraph, while soil moisture content was determined using the gravimetric method (oven drying at 105°C for 24 h). The silty-clay soil had a penetration resistance of 215 kPa and a moisture content of 16.8%, while the clay-loam soil had a penetration resistance of 202 kPa and a moisture content of 15.7%.

After the crust layer formed, penetration resistance was measured in the top 30 mm. This depth was chosen because soil crusting primarily affects the upper soil layer, which creates a mechanical barrier that inhibits seedling emergence (Baumhardt *et al*., 2004; Peralta *et al*., 2020). Measuring penetration resistance at this depth allowed for a precise evaluation of the crust's strength and the effectiveness of the mechanical crust-breaking process in facilitating seedling emergence. The crust-breaking process was then applied using three different designs of crust breakers, with each application replicated three times.

The soil crust thickness was measured ten times for each plot just before crust breakage, as shown in Figure 2. In the silty-clay soil, the average crust thickness was 23.4 mm with a standard deviation of 4.5 mm, while in the clay-loam soil, it was notably thinner, averaging 6.7 mm with a standard deviation of 0.8 mm.

Figure 2. The measurements of soil crust thickness

Seed specifications

Progen cotton seeds of the laser variety (Progen Corp., Hatay, Turkey) were sown using a two-row precision vacuum seeder during the experiments. Table 1 presents some physical characteristics of the seeds used. The sphericity ratio and geometric mean diameter were calculated using Eqs. (1) and (2), respectively, following the methodology outlined by Wang *et al*. (2024).

$$\Phi = \left[\frac{D_g}{L}\right] x\ 100 \qquad \text{(Eq. 1)}$$

$$D_g = (LWT)^{1/3} \quad \text{(Eq. 2)}$$

where Φ is the ratio of sphericity, D_g is the geometric mean diameter, W is width, L is length, and T is thickness.

Table 1. Physical characteristics of cottonseed.

Physical characteristics	Minimum	Maximum	Mean	Standard deviation
Length (mm)	8.21	10.11	9.11	0.43
Width (mm)	3.84	5.23	4.50	0.36
Thickness (mm)	3.30	4.55	4.01	0.27
Geometric mean diameter (mm)	5.00	5.93	5.47	0.24
Sphericity ratio (%)	54.95	64.51	60.10	2.70
Seed weight (g 1000 seeds^{-1})	81.5	83.1	82.30	1.7
Percent emergence in laboratory conditions (%)	93.8	95.2	94.50	1.3

Hand penetrometer

The efficacy of soil crust breakers was evaluated through pre- and post-treatment measurements of soil penetration resistance. A precision hand-held surface penetrometer (MA20X76, Bilgin-Arge, Turkey) was employed to conduct these measurements. The penetrometer is designed to measure penetration resistance within the top 60 mm of the soil profile, with a measuring range of 0 to 3000 kPa and an accuracy of ±5%. The tip, which contacts the soil surface, has an area of 100 mm^2.

The device features depth markings at 10 mm intervals, enabling the recording of penetration resistance at various depths. However, for this study, measurements taken after the formation of the soil crust were specifically focused on the top 30 mm of soil. This depth was chosen because it represents the soil layer most affected by crust formation and directly influences seedling emergence. A total of 10 measurements/replications were taken for each treatment to ensure reliable and accurate data collection.

Crust breakers

Three different models of crust breakers were produced and tested in the study. Table 2 presents the main dimensions for each model.

Table 2. Dimensions of crust breakers.

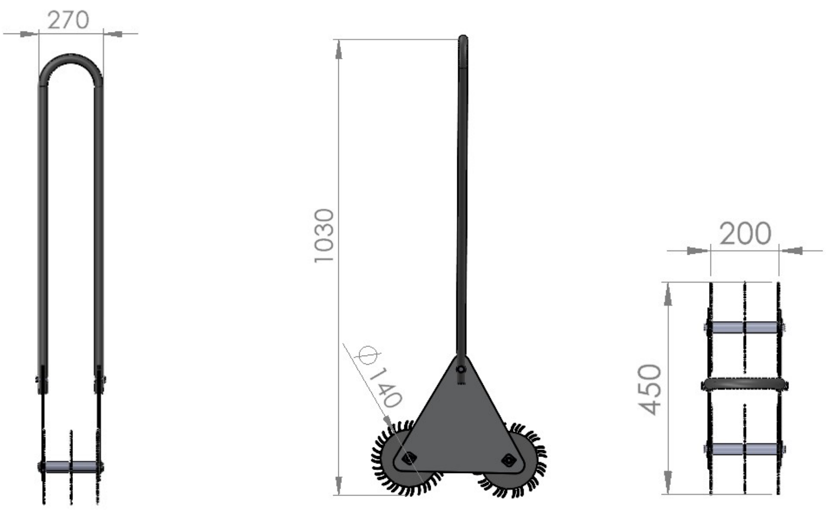
Dimensions	Type of the crust breaker		
	Rolling-type finger (RTF)	Rolling-type blade (RTB)	Sled-type (ST)
Height (mm)	1030	1140	930
Length (mm)	450	435	400
Width (mm)	270	270	220
Operating width (mm)	200	200	200
Weight (N)	91	101	47

Rolling-type finger crust breaker

The rolling-type finger (RTF) crust breaker is a machine with circular discs attached to its main shaft, each disc having protruding fingers. Its design is intended for single-row use, with a triad arrangement that enhances its efficiency in breaking the crust layer. This specific crust breaker design comprises two primary shafts, each supporting six discs and mounted on vertical plates with bearing housings on both sides of the primary shafts. The discs on the RTF crust breaker are securely welded to the primary shaft at 100 mm intervals. Each disc has 12 fingers that measure 30 mm in length and 5 mm in thickness. The discs themselves have a diameter of 140 mm (Figure 3).

The RTF crust breaker features a working width of 200 mm and includes auxiliary mechanisms on the plates, enabling manual operation through hand pushing. Additionally, a hopper positioned directly above the discs, without interfering with or contacting the fingers, enhances the breaking ability by adding weights to break diverse soil crust strength effectively.

(a)



front side top view

(b)

Figure 3. Photographs (a) and three-view drawings (b) of the rolling-type finger (RTF) soil crust breaker.

Rolling-type blade crust breaker

The rolling-type blade (RTB) crust breaker is an innovative piece of equipment used for breaking crusts. It combines two distinct profiles of horizontally oriented blades, as shown in Figure 4, to offer an alternative approach.

It consists of six circular discs assembled onto two primary shafts, with horizontal blades firmly attached to them. Each disc has a diameter of 160 mm, while the horizontal blades welded onto the main shafts are 35 mm in length and 10 mm in thickness. The equipment operates with a working width of 20 cm, featuring 8 horizontally arranged blades on each shaft. The two primary shafts were assembled onto another plate assembly through bearing housings on both flanks. An 80 cm handle was incorporated, making manual operation possible through hand-pushing. A hopper is positioned directly above the discs, without interfering with or contacting the blades, to enhance the breaking ability by adding weights to break diverse soil crust strengths effectively. No additional weight was required for tests carried out on both fields.

In Figure 5, Point *N* denotes the endpoint of the finger in the RTF crust breaker and the blade in the RTB crust breaker. The trajectory of Point *N*, situated at a distance *A* from the center of a circle with radius *R*, is defined by the following equations during linear rolling, as described by Karayel and Šarauskis (2024):

$$X = R\,\theta - \mathrm{A}\,\mathrm{Sin}(\theta) \qquad \text{(Eq. 3)}$$

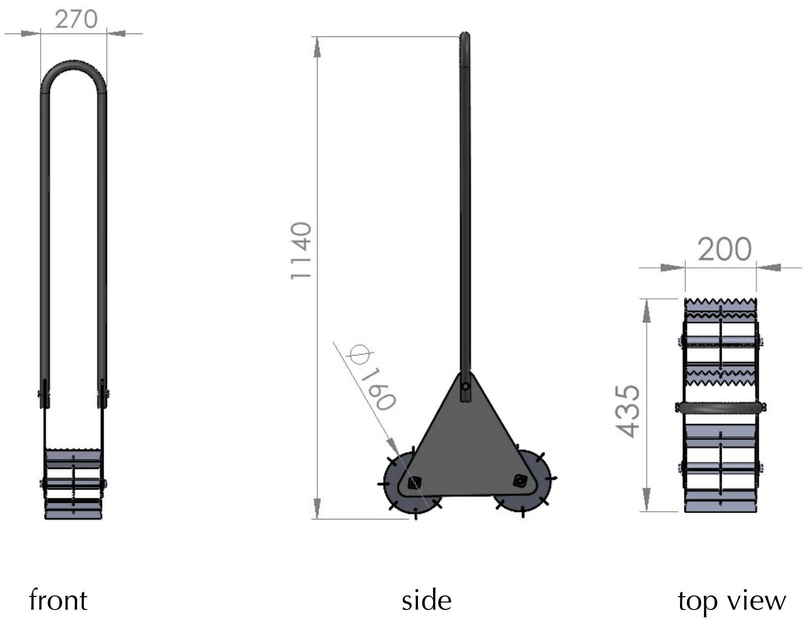
$$Y = R\,\theta - \mathrm{A}\,\mathrm{Cos}(\theta) \qquad \text{(Eq. 4)}$$

Here, *X* and *Y* depict the disc axes, while θ indicates the vertical whirl angle of the circle. When $R<A$, the point traces a cycloidal path (Figure 5). Consequently, if the length of the finger or blade is fixed radially on the disc with radius *R* (i.e., $A=R+h$), and the disc rolls over the soil, the finger or blade will excavate the topsoil to a depth determined by *h*. The maximum values of excavation depth and bite length will be *h* and *2b*, respectively. The *b* can be calculated by the equation below:

$$b = R\,Cos^{-1}(\mathrm{R/A}) - \mathrm{A}\,\mathrm{Sin}(Cos^{-1}(\mathrm{R/A})) \qquad \text{(Eq. 5)}$$

Rolling-type crust breakers are designed to eliminate any unbroken soil crust, with fingers or blades spaced 2 b between rows.

(a)



(b)

Figure 4. Photographs (a) and three-view drawings (b) of the rolling-type blade (RTB) crust breaker.

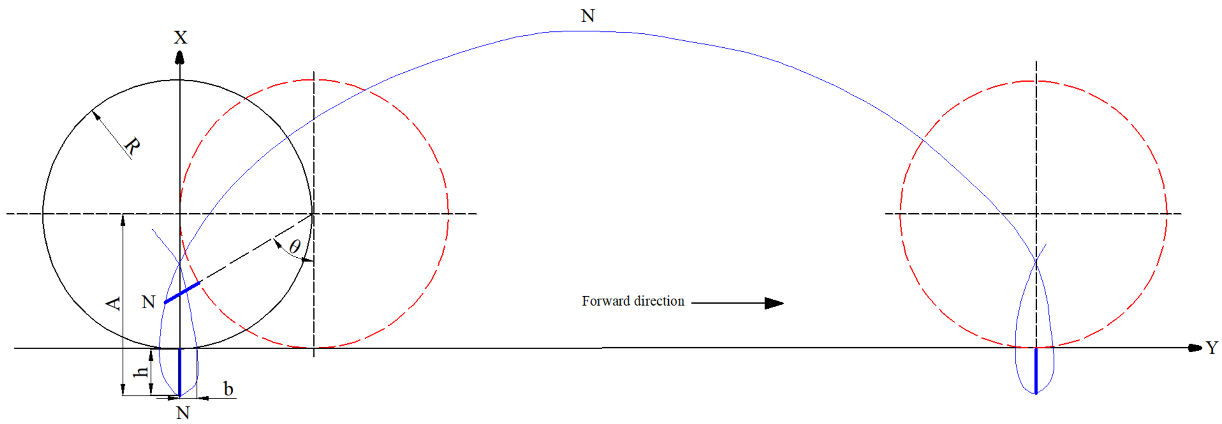


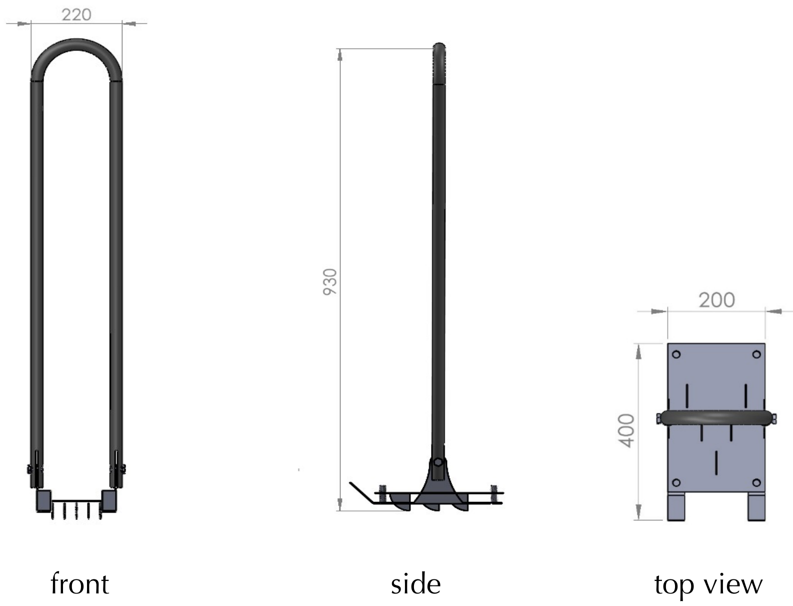
Figure 5. The trajectory of a finger or blade on the crust breakers' disc. A represents the distance from the center of the disc to the tip of the finger or blade, *R* is the radius, *N* is the top point of the finger or blade, *h* is the length of the finger or blade, *θ* is the angle of the rotation of the circle, and *b* is half of the finger's or blade's bite length (Karayel and Šarauskis, 2024). The blade bite lengths of the RTB and RTF crust breakers are 35 mm and 30 mm, respectively.

Sled-type crust breaker

The sled-type (ST) crust breaker has a base length of 320 mm with a sloping front part measuring 80 mm. This culminates in a total length of 400 mm and a working width of 200 mm. An 80 cm handle was integrated to enable manual operation (Figure 6). This design comprises two primary base plates. The blades were welded onto the upper plate, while the upper and lower plate assembly was secured through bolts and nuts. Its most notable advantage over other crust breakers lies in its adjustability regarding the incision depth, thanks to the strategically positioned nuts.

The primary objective of the ST crust breaker is to create incisions in the surface crust layer. This effectively shatters the crust layer and facilitates the emergence of seeds buried beneath this layer. The cutting blades can be finely tuned to achieve the desired depth. This is contingent upon the depth at which seeds are to be sown and the thickness of the surface crust layer. This dynamic adjustability can significantly reduce the potential damage to seeds during the crust-breaking process. The adjustable mechanism was adapted from the design of the Hawkins Crust Breaker Inc. (Indianola, USA). During field tests of this study, the depth of the cutting blades was precisely configured to 3 cm for both field conditions.

(a)



(b)

Figure 6. Photographs (a) and three-view drawings (b) of the sled-type (ST) crust breaker.

The force necessary to deform the soil (i.e., the blade moving through the soil) is influenced by the surcharge load generated by the weight of the soil overlying the blade, its cohesive properties, and the surcharge load applied to it. In addition to soil characteristics, the resistance force is also contingent upon the geometry of the blade (tool) and the strength properties at the blade-to-soil interface (Cviklovič *et al.*, 2022; Guan *et al.*, 2022; Zhang *et al.*, 2024).

The vertical component of the frictional force F_T opposes the surcharge load (sinkage force) F_S, resulting in the lifting of the cutting blade, as illustrated in Figure 7. The normal force F_N acting on the cutting blade is equal to the specific surcharge load multiplied by the contact length of the cutting blade with the soil. For the cutting blade to penetrate the soil, the surcharge load F_S must exceed the perpendicular force F_P. Additionally, the draft force must be greater than the horizontal force F_H to ensure the blade advances through the soil.

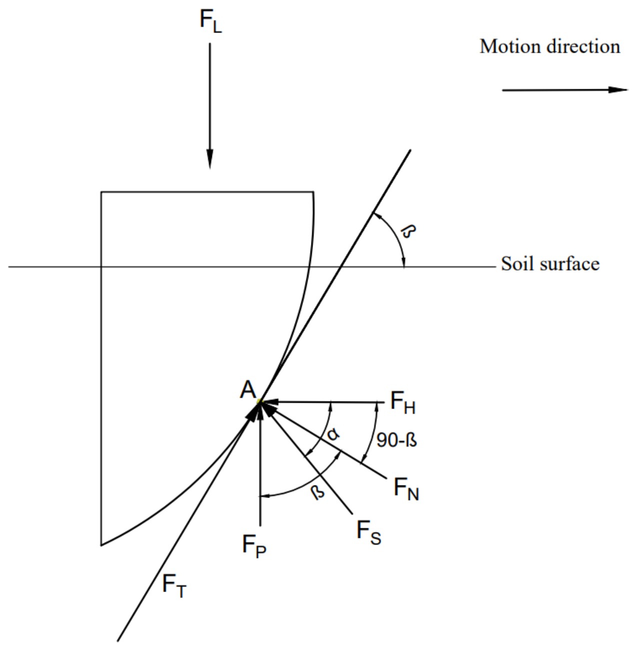


Figure 7. Forces acting on the cutting blade of sled-type (ST) crust breaker: F_L- Surcharge load, F_N- Normal force, F_T- Frictional force, F_H- Horizontal force, F_P- Perpendicular force, F_S-Soil cutting force (resultant force of soil resistance), *A*- Point of action.

The forces acting on the cutting blade of an ST crust breaker can be described by the following equations (Cviklovič *et al.*, 2022; Guan *et al.*, 2022; Karayel *et al.*, 2024).

$$F_s = \sqrt{((F_N\ .Sin(\beta))^2 + (F_T + F_N\ .Cos(\beta))^2} \qquad \text{(Eq. 6)}$$

$$\alpha = tan^{-1}(\frac{F_T+F_N.Cos(\beta)}{F_N.Sin(\beta)}) \qquad \text{(Eq. 7)}$$

$$F_P = F_S\ .Cos(\propto) \qquad \text{(Eq. 8)}$$

$$F_H = F_S\ .Sin(\propto) \qquad \text{(Eq. 9)}$$

where F_S is soil cutting force, F_N is normal force, F_T is frictional force, F_P is perpendicular force, F_H is horizontal force.

Performance indicators

The following parameters were considered to assess the effect of the soil crust-breaking process on seedling emergence and to compare the effectiveness of crust breakers: penetration resistance, mean emergence time, emergence rate index, and percentage of emergence. The penetration resistance of the top 30 mm of soil in each plot was measured using the hand-held surface penetrometer. Seedling counts were conducted daily for each treatment in a 25-meter row during the emergence period. The mean emergence time, emergence rate index, and percentage of emergence were calculated based on these counts, following the method described by Sun *et al*. (2023).

$$MET = \frac{N_1D_1+N_2D_2+\dots N_nD_n}{N_1+N_2+\dots N_n} \quad \text{(Eq. 10)}$$

$$ERI = \frac{Number\ of\ total\ emerged\ seedlings\ per\ meter}{MET} \quad \text{(Eq. 11)}$$

$$PE = \frac{Number\ of\ total\ emerged\ seedlings\ per\ meter}{n} x\ 100 \quad \text{(Eq. 12)}$$

where $N_{1\dots n}$ is the number of seedlings emerging since the time of the previous count, $D_{1\dots n}$ is the number of days after seeding, *MET* is the mean emergence time (day), *ERI* is the emergence rate index (seedlings·m^{-1}·day^{-1}), *PE* is the percentage of emergence (%), and n is a number of seeds sown per meter.

Design of experiments and statistical procedures

The experiment comprised four treatments, including three different designs of crust breakers and a control plot. A designated control plot underwent no crust-breaking operation. These treatments were randomly arranged and replicated three times using a completely randomized design. The average area of each plot was approximately 0.05 ha, with lengths ranging from 50 to 60 m. The plots were positioned side by side in a completely randomized manner. The manually operated crust breakers were applied at a forward speed corresponding to the walking pace of the operator (approximately 4–5 km/h), ensuring consistent and uniform operation across all plots. No transformation was deemed necessary after conducting a normality test on the variable. The GLM procedure in the SPSS package was used to analyse the datasets using an analysis of variance method. Duncan's multiple-range tests were applied to identify significantly different means within dependent variables.

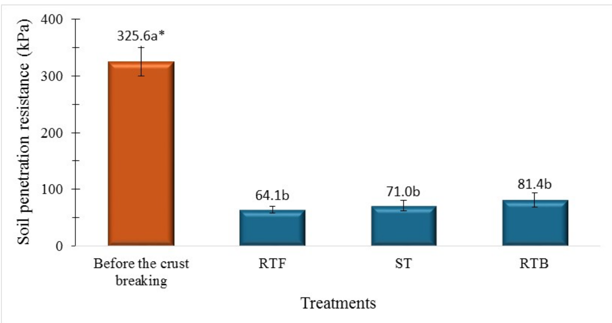
Results and Discussion

Penetration resistance

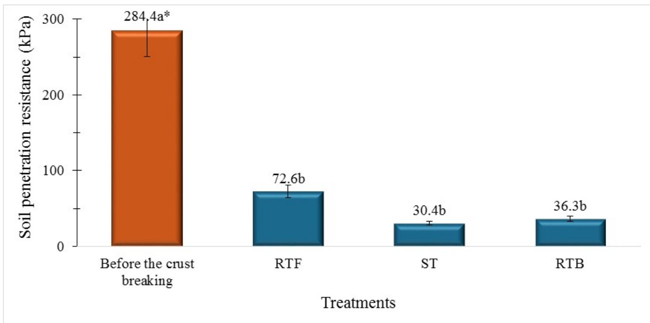
The penetration resistance data for the top 3 cm of soil in the control and crust-broken plots are presented in Figure 8. In the Aksu field, characterized by a silty-clay soil structure, the penetration resistance is slightly higher compared to the Campus field, which features clay-loam soil. The presence of a rigid crust layer in the Aksu field is attributed to its silty-clay soil structure. The tendency for crust formation in the Aksu field's soil structure has been corroborated by a study conducted by Sari *et al*. (2009).

The control plots represent the penetration resistance of the soil crust prior to any crust-breaking treatments. The average resistance to crust penetration in the control plots was 326 kPa for silty-clay soil and 248 kPa for clay-loam soil. Although notable differences in the degree of soil crusting were observed across treatments in both fields, no statistically significant variations were found between the different crust breakers. As a result, all three crust breakers demonstrated effective penetration of the soil crust.

The findings align with those of Awadhwal and Thierstein (1983), who investigated the effect of a rolling-type soil crust breaker on soil penetration resistance, a device similar to the one used in this study. Their research showed a significant decrease in penetration resistance after using the crust breaker, which is consistent with the results of the current study.



(a)

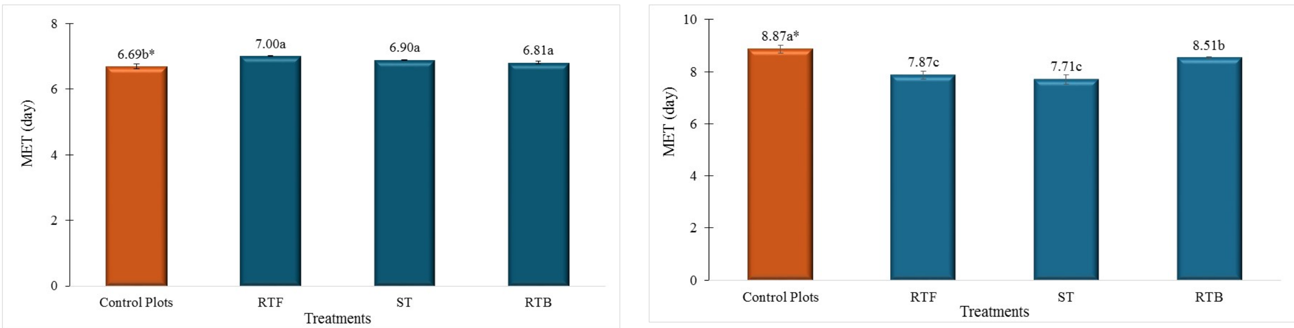


(b)

Figure 8. Penetration resistance measurements in the silty-clay (a) and clay-loam (b) fields. *Statistically significant differences are indicated by different letters ($p<0.05$).

Mean emergence time

Following the variance analysis, a statistically significant effect of the crust breakers on the Mean Emergence Time (MET) was observed ($p<0.05$). Duncan's multiple comparison tests revealed no significant differences in MET between the various soil crust breakers, with values ranging from 6.81 to 7.0 days. The control plot, however, recorded the lowest MET at 6.69 days in the silty-clay field. In the silty–clay field, the dense crust layer severely restricted seedling emergence in the control plot, resulting in only a very small number of seedlings being able to break through the crust. Because MET is calculated solely from emerged seedlings (excluding non-emerged ones), the calculation was based only on these few early-emerging seedlings. This created an artificially low MET value that does not indicate better emergence performance but instead reflects a selection bias caused by the extremely poor emergence conditions in the control plot. In the clay-loam field (Campus), the control plot exhibited the highest MET at 8.87 days, while the lowest MET was observed with the RTF crust breaker application at 7.87 days and the ST crust breaker application at 7.71 days (Figure 9).



(a) (b)

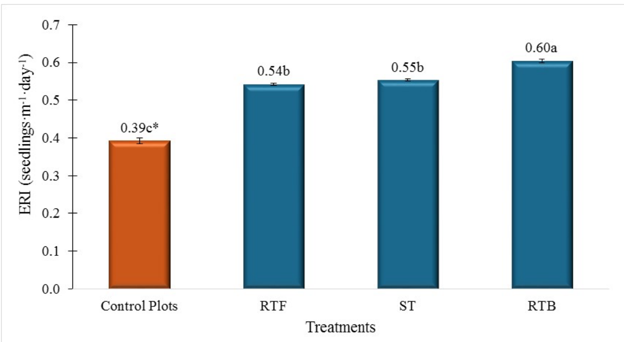
Figure 9. Mean emergence time for the silty-clay (a) and clay-loam (b) fields. *Statistically significant differences are indicated by different letters ($p<0.05$).

A lower MET indicates rapid germination and seed emergence, which is a desirable condition for reducing the risk of the soil crust layer's negative effect on seedling emergence (Hou *et al*., 2022; Karayel *et al*., 2024). In the experiments conducted in the silty-clay field, the soil structure exhibited a significant tendency to form a crust, leading to a substantial reduction in seedling emergence in the control fields. MET calculations were based on emerged seedlings, with non-emerged seedlings excluded from the analysis. Consequently, the MET calculation was performed only on a limited number of seedlings that emerged in the control plot, contributing to the lower MET value.

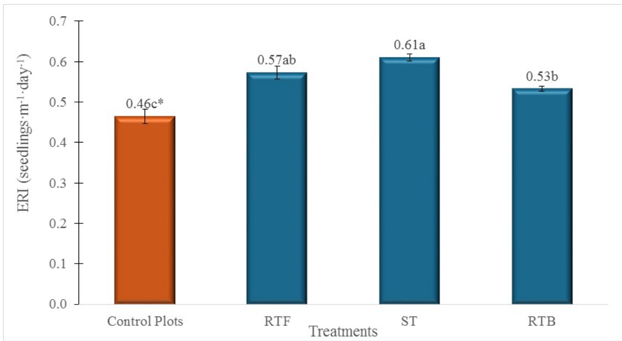
In contrast, in the clay-loam field, the low resistance of the soil crust layer allowed seedlings to partially break the crust and emerge in the control plots. This facilitated MET calculations based on a more substantial number of seedling emergence instances, providing a more accurate representation of the impact of soil crust breaker applications on emergence dynamics.

Emergence rate index

The impact of crust breaker applications on the emergence rate index (ERI) is statistically significant ($p<0.05$). The highest ERI, reaching 0.60 seedlings·m^{-1}·day^{-1}, was achieved through the RTB crust breaker application, while the lowest ERI of 0.39 seedlings·m^{-1}·day^{-1} was observed in the control plot within the silty-clay field (Aksu). In the clay-loam field (Campus), the highest ERI values were 0.61 seedlings·m^{-1}·day^{-1} and 0.57 seedlings·m^{-1}·day^{-1}, obtained with the ST and RTF crust breaker applications, respectively. The control plot exhibited the lowest ERI at 0.46 seedlings·m^{-1}·day^{-1} (Figure 10).



(a)



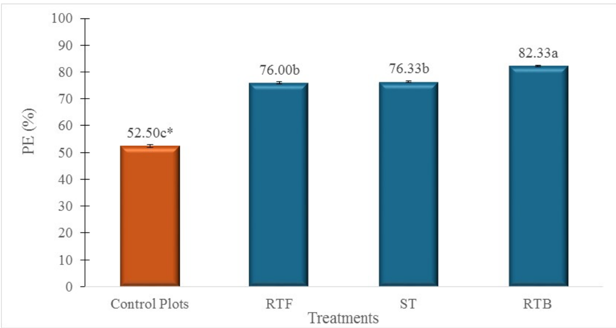
(b)

Figure 10. Emergence rate index for the silty-clay (a) and clay-loam (b) fields. *Statistically significant differences are indicated by different letters ($p<0.05$).

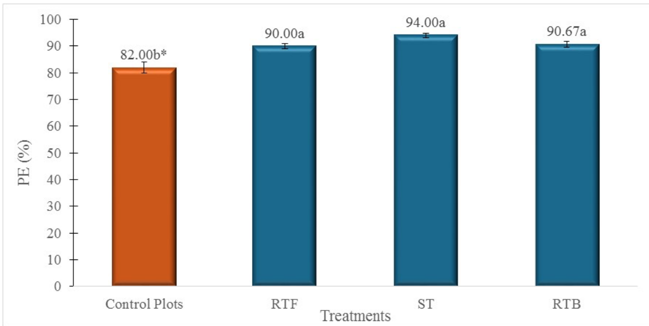
Breaking the crust layer formed after seeding had a positive impact on the ERI, leading to more seedlings emerging per unit area per day. This finding reinforced the effectiveness of crust breaker applications in accelerating emergence, potentially resulting in the faster establishment of plant stands within rows. The study highlighted the practical significance of these techniques for optimizing seedling emergence and ensuring robust stand establishment across diverse soil conditions.

Percent emergence

The conducted variance analysis reveals a statistically significant effect of the crust breakers on the percent emergence (PE) ($p<0.05$). Duncan's multiple comparison test results show that, in the silty-clay field, the RTF model (design) of crust breakers achieved the highest PE at 82.33%, while the control plot recorded the lowest PE at 52.5%. In the clay-loam field, the application of crust breakers increased PE, but the differences among the crust breakers were not statistically significant (Figure 11).



(a)



(b)

Figure 11. Percent emergence for the silty-clay (a) and clay-loam (b) fields. *Statistically significant differences are indicated by different letters ($p<0.05$).

In the silty-clay field, the soil structure's propensity for crust formation and the consequent thicker crust layer elucidated differences in crust breaker effectiveness, resulting in statistically significant differences in PE. According to the data, the RTB crust breaker showed the highest effectiveness, with no statistically significant difference observed between the ST and RTF crust breaker applications. In the control plot, PE remained at the lowest level. This was evident during field observations while taking measurements. The subterranean seedlings in the control plots exhibited hooked growth patterns (yellow folds) in their direction of growth, as they were unable to penetrate the crust layer (Figure 12).

Figure 12. The hooked growth patterns (yellow folds) of cotton seedlings under the soil crust formed in the control plots.

Results from both fields with different soil textures unequivocally demonstrate that crust breaker applications significantly impact field seedling emergence rates. In other words, there is a statistically significant difference between plots where crust breaking was applied and control plots where it was not. Breaking the crust layer formed after seeding had a positive influence on PE. Due to its high susceptibility to crust formation in the silty-clay soil, the crust breakers had a greater impact on increasing the PE in these soil plots.

The findings in this study support those of Hemmat *et al.* (2003), who conducted research on the clayey loam (0-20 cm) soil texture. These researchers investigated the effect of crust breaking on PE in cotton cultivation, reporting an increase from 43% to 73% in plots where a secondary tillage implement of a rolling cultivator was applied and up to 70% in plots where the crust breaks with two spike-tooth drums in tandem, as designed in this study, were applied.

Conclusions

This research investigated the effectiveness of three prototype crust breaker designs (rolling-type finger, rolling-type blade, and sled-type) on seedling emergence in silty-clay and clay-loam soils. The results demonstrate that all three crust breaker models effectively fractured the soil crust layer. Statistically significant differences in their performance were observed in some cases, particularly with respect to Percent Emergence in the silty-clay field, but not across all metrics or in both soil types.

The study revealed that crust breaking significantly improved seedling emergence rates, particularly in the silty-clay field, which had a higher tendency for crust formation. In this field, the rolling-type finger crust breaker achieved the highest percent of emergence (82.33%), followed by the rolling-type blade crust breaker. While all three crust breakers enhanced emergence compared to the control plot (52.5%), the differences between the crust breaker types were not statistically significant in the clay-loam field.

These results highlight the potential of these prototype crust breakers as valuable tools for agricultural practices. Breaking the soil crust layer after seeding facilitates faster and more uniform seedling emergence, potentially leading to improved crop establishment and yield. However, sustainable agricultural practices, such as reviewing tillage methods and incorporating cover crops, should also be applied to reduce or limit soil crust formation.

When crust formation occurs, the prototype crust breakers tested in this study can effectively mitigate its negative effects on cultivated crops. However, their performance was evaluated under specific soil textures, moisture conditions, and seeding depths, and may vary under different field conditions, crop types, or larger-scale operations. Further research is needed to develop practical solutions for managing soil crust formation and promoting sustainable agricultural practices.

References

Almajmaie A, Hardie M, Acuna T, Birch C, 2017. Can soil crusting be reduced through application of gypsum, organic waste, and phosphoric acid? J Soil Water Conserv 72:597–606.

Awadhwal NK, Thierstein GE, 1983. Development of rolling-type soil crust breaker. Ama-Agr Mech Asia Af 14:31-34.

Bakhtiyar A, 2019. Optimization of parameters and modes of operation of the disk of the working organ to the cotton cultivator to destroy the soil crust. Int J Eng Adv Technol 9:6888–6889.

Bal L, Şeker C, Gümüş IE, 2011. [Kaymak tabakası oluşumuna fiziko-kimyasal faktörlerin] etkileri].[Article in Turkish with English abstract]. Selcuk J Agric Food Sci 25:96-103.

Baumhardt RL, Unger PW, Dao TH, 2004. Seedbed surface geometry effects on soil crusting and seedling emergence. Agron J 96: 112-1117.

Cassel DK, Raczkowski CW, Denton HP, 1995. Tillage effects on corn production and soil physical conditions. Soil Sci Soc Am J 59:1436–1443.

Crucil G, Van Oost K, 2021. Towards mapping of soil crust using multispectral imaging. Sensors (Basel) 21:1850.

Cviklovič V, Mojžiš M, Majdan R, Kollárová K, Tkáč Z, Abrahám R, Masarovičová S, 2022. Data acquisition system for on-the-go soil resistance force sensor using soil cutting blades. Sensors (Basel) 22:5301.

Gicheru P, Mare E, Gachene C, Mbuvi J, 2004. Effects of soil management practices and tillage systems on surface soil water conservation and crust formation on a sandy loam in semi-arid Kenya. Soil Tillage Res 75:173–184.

Guan C, Fu J, Xu L, Jiang X, Wang S, Cui Z, 2022. Study on the reduction of soil adhesion and tillage force of bionic cutter teeth in secondary soil crushing. Biosyst Eng 213:133–147.

Hemmat A, Khashoei AA, Ranjbar I, 2003. Assessment of irrigated cotton seedling emergence in flatland mechanized planting systems. J Agric Sci Technol 5:87-98.

Hou S, Zhu Y, Zhu X, Wang Y, Ji W, Chen H, 2022. Design and experiment of a straw clearing mulching no-tillage planter. Biosyst Eng 221:69–80.

Karayel D, Šarauskis E, 2024. Influence of tillage methods and soil crust breakers on cotton seedling emergence in silty-loam soil. Soil Tillage Res 239:106054.

Karayel D, Jotautienè E, Šarauskis E, 2024. The effect of furrow opener and disc coulter configurations on seeding performance under different residue cover densities. AgriEngineering 6:1277-1288.

Laker MC, Nortjé GP, 2019. Review of existing knowledge on soil crusting in South Africa. Adv Agron 155:189-242.

Manyevere A, Munjonji L, Bangira C, Gotosa J, Chikwari E, 2015. Characteristics and management options of crusting soils in a smallholder farming area of the Zambezi metamorphic belt in northern Zimbabwe. S Afr J Plant Soil 32:157–164.

Öztürk E, Özdemir N, 2006. [Topraklarda kabuk tabakası oluşumu, çeşitleri ve önlenmesi].[Article in Turkish with English abstract]. Anadolu J Agric Sci 21:275-282.

Peralta GE, Taboada MA, Kantolic A, Rubio G, 2020. Topsoil hardening: Effects on soybean root architecture and water extraction patterns. J Soil Sci Plant Nutr 20:2182-2194.

Sari M, Sonmez N, Altunbaş S 2009. [Aksu araştırma ve uygulama istasyonu topraklarının morfolojik, fiziksel ve kimyasal özellikleri].[Article in Turkish with English abstract]. Akdeniz Univ J Fac Agric 22:157–168.

Sun J, Yang L, Zhang D, Hu J, Cui T, He X, Zhao H, 2023. Development of a prediction model to determine optimal sowing depth to improve maize seedling performance. Biosyst Eng 234:206–222.

Šimansky V, Pollakova N, Halmo S, 2014. Soil crust in agricultural land. Acta Fytotechn Zootechn 17:109–114.

Sjoblom KJ, 2014. Modelling soil crust formation by discrete element method. Geotech Spec Publ 234:1042-1051.

Taboada-Castro MM, Rodríguez-Blanco ML, Palleiro L, Taboada-Castro MT, 2015. Soil crusting and surface runoff in agricultural land in Galicia (NW Spain). Span J Soil Sci 5:72–81.

Wang Z, Su W, Lai Q, Li J, Gao X, 2024. Boundary modelling of the effective suction domain of an air-suction seed-metering device for quasi-spherical seeds. Biosyst Eng 238:212–226.

Zhang X, You Y, Wang D, Wang Z, Liao Y, Li S, 2024. Soil failure characteristics and loosening effectivity of compacted grassland by subsoilers with different plough points. Biosyst Eng 237:170–181.

Zhu X, Liang Y, Qu L, Cao L, Tian Z, Gu Z, et al., 2022. Quantification of physical soil crust thickness and its effects on runoff and sediment yield. Soil Sci Soc Am J 86:630–642.