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With rising energy costs, expensive deep tillage needs to be reevaluated. In 2002 and 2003, tillage treatments were evaluated for effectiveness in increasing cotton yield when noninversion deep tillage was either performed annually or not. Tillage treatments included a nontilled control, a straight-legged subsoil shank with bedding, and strip tillage with each of the following: a straight-legged subsoil shank, a Paratill, and a Terra-Max. In 2003, treatments were split with half the plots tilled and half not. No-tillage treatment significantly reduced penetration resistances better than others. Tillage decreased penetration resistance and improved yield but differences were significant only half the time. Treatments not tilled in the second year did not have significantly reduced penetration resistance because of a lack of recompaction during a dry first growing season. Tilling the second year improved yield marginally. Producers need to decide whether to till after a dry year on a case-by-case basis.

Keywords Drought, rhizosphere, soil water

Introduction

In the southeastern U.S. Coastal Plains and similar areas, productivity can be limited by short periods of drought and by sandy soils with low water-holding capacities and shallow high-strength layers that restrict root growth. Deep tillage of these coastal soils is recommended annually (Porter and Khalilian 1995; Simoes et al. 2009) to reduce soil strength and promote root growth throughout the profile to encourage water and nutrient uptake. In some studies, residual effects of deep tillage were shown to be effective for years (Munkholm, Schjønning, and Rasmussen 2001; Scanlon et al. 2009), especially if traffic is limited to specific midrows (Frederick et al. 1998), whereas in other studies tillage effects were gone after 3 years or less (Busscher et al. 1995; Shukla, Lal, and Ebinger 2003). Still other studies suggested that rainfall promotes reconsolidation (Busscher et al. 2002; Ward et al. 2006) or that tillage need not be performed every year (Busscher and Bauer 2003).

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Producers typically till these sandy coastal soils annually with a noninversion method of deep tillage, breaking up surface and subsurface hard layers. Deep tillage loosens the soil to allow root growth into deeper horizons that have a greater degree of structural development with greater water-holding capacities than surface horizons; this can encourage root growth and improve yield (Akinci et al. 2004).

However, as fuel prices increase, deep tillage becomes more unaffordable because it requires 14 to 20 kw per subsoil shank and uses 20 to 25 L of fuel ha^{-1} (Karlen et al. 1991). High fuel prices and substantial energy requirements make deep tillage a significant part of the cost of plant management, despite the fact that the loosening effect is usually temporary (Carter et al. 1996; Busscher, Frederick, and Bauer 2000). More research needs to be performed to support data on soil reconsolidation and frequency of deep tillage.

The objective of this study was to (1) compare penetration resistance differences between no deep tillage and deep tillage with each of several implements and (2) compare annual deep disruption with disruption a year after tillage ceased. We hypothesized that implements would differ in their disruption and this difference would affect soil recompaction and cotton (*Gossypium hirsutum*) productivity.

Materials and Methods

This study was conducted at both the Clemson University Pee Dee and Edisto Research and Education Centers located at N 34.29217, W 79.73476, 11 km north northeast of Florence, South Carolina, USA, and N 33.35883, W 81.33092, 5.5 km west of Blackville, South Carolina, USA, respectively. Treatments were laid out in Florence on a Noboco loamy sand (fine-loamy, siliceous, subactive, thermic Oxyaquic Paleudult) and at Blackville on an Orangeburg loamy sand (fine-loamy, kaolinitic, thermic typic Kandiudult). These soils were formed in Coastal Plain marine sediments (Table 1) and were categorized as Acrisols in the FAO classification. Both soils had Ap horizons that had been tilled over the years to a depth of about 0.20 m.

Table 1

General soil characteristics based on mapping soils and collecting information; differences between the Ap and E horizons were based on previous tillage that mixed surface organic matter into the Ap

	Soil type			
	Noboco		Orangeburg	
Characteristics	Ap/E	Bt	Ap	Bt
Texture	Loamy sand	Sandy clay loam	Loamy sand	Sandy clay loam
Water table[a] (m)	0.75–1.05	0.75–1.05	>1.8	>1.8
CEC (cmol kg^{-1})	4–10	5–8	1–3	2–4
OM (g kg^{-1})	5–20	0–5	5–10	0–5
Clay (g kg^{-1})	20–80	200–430	40–100	180–350
Depth (m)	0.18–0.33	1.20–2.00	0.25–0.40	1.35–2.00

Sources. http://soils.usda.gov/technical/classification/scfile/ and http://soils.usda.gov/survey/online_surveys/south_carolina/#bamberg2007.

[a]Seasonally high depth to the water table.

Treatments

In spring of 2002, five treatments were established at the two locations in four replicates. Treatments consisted of the following: (1) conventional tillage (disking twice, subsoiling with a straight shank, and bedding); (2) reduced tillage (deep tillage with a straight shank followed by strip tillage); (3) Paratill (deep tillage with a bent-leg Paratill [Bigham Brothers, Lubbock, Tex., USA] followed by strip tillage); (4) Terra-Max (deep tillage with a bent-leg Terra-Max [Worksaver, Inc., Litchfield, Ill., USA] followed by strip tillage); and (5) no surface or deep tillage. Strip-till attachments (Unverferth, Kalida, Ohio) were installed on a special toolbar that could attach to and follow the deep-tillage implements. Treatments 2, 3, and 4 were not disked or bedded. At Florence, plots were planted with a Case-IH no-till planter (Case-IH, Racine, Wisc., USA) and at Blackville with a John Deere MaxEmerge2 planter (John Deere, Moline, Ill., USA). Plots were split so that each treatment–replicate combination could be tilled in 2002 only and in both 2002 and 2003.

Management

Cotton (var DP 555BR) was planted in 0.96-m-wide rows in early to mid-May. Cotton was managed for fertility, weed/insect control, and defoliation according to Clemson University (2001) extension recommendations. Cotton was fertilized based on soil-test results and extension recommendations. Typically, 2 months before planting, 20 kg phosphorus (P) ha^{-1}, 34 kg potassium (K) ha^{-1}, 2.25 kg boron (B) ha^{-1}, and 11.5 kg sulfur (S) ha^{-1} were broadcast applied. Nitrogen (135 kg N ha^{-1} as ammonium nitrate) was applied in a split application, one third at planting and two thirds 1 month later. Nitrogen applications were all banded approximately 0.05 m deep and 0.15 m to the side of the rows.

Weeds were controlled with a combination of herbicides pendimethalin [N-(1-ethylpropyl)-2,6-dinitro-3,4-xylidine] and fluometuron [1,1-dimethyl-3-(α,α,α-trifluoro-m-tolyl)urea] at planting. MSMA (sodium hydrogen methylarsonate), glyphosate [N-(phosphonomethyl)glycine], and sethoxydim 2-[1-(ethoxyimino)butyl]-5-[2-(ethylthio)propyl]-3-hydroxy-2-cyclohexen-1-one were applied one to three times a season at labeled rates as needed. Thrips [Frankliniella occidentalis (Pergande)] were controlled by applying Temik [0.5 ai kg ha^{-1} (2-methyl-2-(methylthio) propionaldehyde O-(methylcarbamoyl)oxime)] at planting.

In mid- to late October, cotton was chemically defoliated with thidiazuron (N-phenyl-N′-1,2,3-thiadazol-5-ylurea), S,S,S-tributyl phosphorotithioate, and ethephon [(2-chloroethyl) phosphonic acid]. In early November, seed cotton was harvested from the two interior rows of each plot using a two-row spindle picker and bagged. Each harvest bag was subsampled; the subsample was saw-ginned to determine lint percentage. Lint percentage was multiplied by seed cotton yield to calculate lint yield.

Penetration Resistance

Penetration resistance was measured in cotton plots after tillage. Penetration-resistance data (cone indices) were taken with a 12.5-mm-diameter cone-tipped penetrometer on 11 June 2002 and 22 July 2003 at the Florence location and on 20 June 2002 and 30 July 2003 at the Blackville location. Cone indices were measured by pushing the penetrometer into the soil to a depth of 0.55 m at nine positions spaced 0.12 m apart starting at the middle of the plot (a non-wheel-track midrow) and moving outward to a wheel-track midrow. Cone index data were digitized into the computer at 0.05-m depth intervals and log transformed before analysis according to Cassel and Nelson (1979). Gravimetric soil water content samples were taken along with soil strength data at the first and fifth positions of the cone index readings. Water contents were measured at 0.1-m depth intervals to 0.6 m deep. These water contents were taken as representative of the water contents of the plot.

Rainfall data were collected at on-site weather stations for each research center. Because data from the beginning of 2002 until July 12 were unavailable at Edisto, it was filled in using weather from the nearby Savannah River National Laboratory's station 100-P, which was located 25 km SW of the research center.

Data Analyses

Cone index, water content, and yield data were analyzed using GLIMMIX and the least square mean separation procedures (SAS Institute 1999). Yield data were analyzed using a randomized complete block design. Cone index and water content data were analyzed using a split-split plot randomized complete block design with position across the rows as subplot and depth as sub-subplot. Data were tested for significance at the 5% level.

Results and Discussion

Gravimetric Water Contents

Soil water contents were taken along with cone indices. For the Blackville plots, water contents treatment differences were nonsignificant varying by 2% (13% to 15%) (Table 2). For the Florence plots, water contents were dryer; they differed nonsignificantly by 2% (7% to 9%) in 2002 and significantly by 3% (7% to 10%) in 2003.

When analyzed by year and location, water contents differed significantly with depth (Table 3); treatment-by-depth interactions were not significant. In the Blackville plots, water contents generally increased with depth, varying by 10% or 11%. In the Florence plots, water contents generally decreased with depth but varied by only 2%. Water contents

Table 2
Mean profile water contents (g g^{-1}) by treatment at time of cone index measurements

		Blackville		Florence	
Tillage	Till 2nd year	2002	2003	2002	2003
Conventional	N	0.13a[a]	0.14a	0.081a	0.082ab
	Y	NA	0.14a	NA	0.073b
Paratill	N	0.15a	0.14a	0.079a	0.083ab
	Y	NA	0.13a	NA	0.081ab
Reduced till	N	0.14a	0.14a	0.070a	0.094a
	Y	NA	0.15a	NA	0.083ab
Terra-Max	N	0.14a	0.15a	0.085a	0.096a
	Y	NA	0.14a	NA	0.095a
No tillage	Na	0.14a	0.14a	0.081a	0.094a

[a]Means in columns with the same letters are not significantly different according to the LSD test at 5%.

Table 3
Mean profile water contents (g g^{-1}) by depth at time of cone index measurements

	Blackville		Florence	
Depth (m)	2002	2003	2002	2003
0.05	0.10e[a]	0.10e	0.09a	0.10a
0.15	0.09e	0.09e	0.09a	0.09b
0.25	0.11d	0.12d	0.09a	0.09b
0.35	0.15c	0.15c	0.07b	0.08c
0.45	0.19b	0.19b	0.07b	0.08c
0.55	0.20a	0.21a	0.07b	0.09b

[a]Means in columns with the same letter are not significantly different according to the LSD test at 5%.

at positions across the rows did not vary significantly for either location or either year; treatment-by-position interactions were also not significant. When water contents were different, they could affect cone indices, and this difference was taken into account when analyzing affected data.

Cone Indices

In both years at both locations, cone indices differed with tillage treatment, soil depth, and position across the row. Cone index differences across the row were based on traffic and tillage. Cone indices with position ranked as follows: values beneath the wheel-track midrows (position 0.96 m in Table 4) >values under the non-wheel-track midrows (position 0.0 m) > values where deep tillage was performed under the rows (position 0.48 m).

Table 4
Mean profile cone index measurements (MPa) for positions across the profile

	Blackville		Florence	
Position (m)	2002	2003	2002	2003
0	1.43e[a]	2.99c	1.06b	1.37c
12	1.72cd	3.42b	1.03b	1.24cd
24	1.98bc	3.57b	1.11b	1.31c
36	1.61de	3.22bc	1.00b	1.14d
48	1.15f	2.35d	0.66c	0.83e
60	1.60de	3.45b	1.10b	1.30c
72	1.96c	4.09a	1.41a	1.60b
84	2.29ab	4.28a	1.46a	1.68ab
96	2.61a	4.52a	1.69a	1.88a

[a]Means in columns with the same letters are not significantly different according to the LSD test at 5%.

Cone indices in the softer zone below the row were related to the tillage management technique of getting the roots into and through the hard soil into the structured Bt horizons. Differences by position of some treatments were expected to be more pronounced in 2003 because they had been tilled more recently than others that were tilled in 2002 only. However, for both locations, tillage treatments were not significantly different when contrasted by year of deep disruption. This was likely caused by a lack of reconsolidation between growing seasons, which has been correlated with rainfall (Busscher, Bauer, and Frederick 2002). Rainfall for both locations in 2002 and early 2003 was low (Figure 1) when compared to the long-term annual mean of 1145 mm (125-year mean) for Florence and 1253 mm (30-year mean) for Blackville. In 2002, rainfall was so low that statewide average corn (*Zea mays* L.) yields were 2.95 Mg ha^{-1} while they were 6.78 in 2001 and 6.59 Mg ha^{-1} in 2003 (Davis 2006).

We expected to see greater cone indices at 0.25- to 0.40-m depths, consistent with a genetic eluviated hard layer in the Noboco soil and a tillage pan in the Orangeburg soil. However, cone indices generally increased in value with depth (Table 5). In some cases, greater cone indices could be found at these selected depths, but differences were small and they may or may not be significantly greater than cone indices for the depths below them. Cone index differences with depth were confounded by water contents differences. For the Blackville location, both cone indices and water contents increased with depth, assuring that soils got harder with depth because the greater water contents should have softened the soil (Dexter, Czyz, and Gat 2007). If cone indices happened to be lower below the depth of the hard layer, soil may be softer because of either reduced cone index or increased water content; the two could not be distinguished. For the Florence location, differences

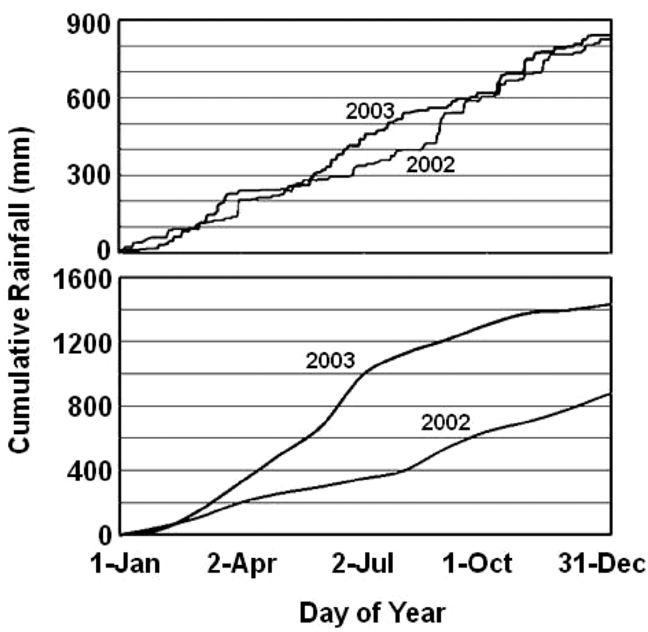

Figure 1. Cumulative rainfall for Florence (a) and Blackville (b) for the years 2002 and 2003. Data from the beginning of 2002 until July 12 were unavailable for Blackville and were filled in using a weather station from the nearby Savannah River National Laboratory's weather station 100-P (http://www.srs.gov/Weather/info/wxcenter/MeteorologicalMeasurements2.pdf, acessed 14 May 2010).

Table 5
Mean profile cone index measurements (MPa) for depths into the profile

	Blackville		Florence	
Depth (m)	2002	2003	2002	2003
0.05	0.46i[a]	1.71h	0.41g	0.57g
0.10	0.76h	2.52g	0.68f	0.84f
0.15	1.06g	3.20f	0.85e	1.02e
0.20	1.45f	3.69e	0.90de	1.08e
0.25	1.85e	3.78de	0.92de	1.08e
0.30	2.28d	3.98cd	0.94d	1.21d
0.35	2.55c	4.24ab	1.19c	1.61c
0.40	2.86b	4.04bc	1.67b	2.10b
0.45	2.95ab	3.89cd	2.11a	2.27a
0.50	3.05ab	4.07bc	2.16a	2.13b
0.55	3.16a	4.36a	2.16a	2.05b

[a]Means in columns with the same letters are not significantly different according to the LSD test at 5%.

were smaller; nevertheless, the whole profile including the hard layer was dry and that may have caused the high cone index readings. Regardless of its cause, increased cone indices with depth caused by greater penetration resistance, drier soil, or both would limit plant roots. Limited root proliferation limits crop access to water and nutrients and limits yield potential. Deep tillage alleviates high strength in hard layers and encourages growth deeper in the profile where soil has texture and roots can grow along ped faces. Of course, if soils only partially reconsolidate because of limited rainfall, growers will have to decide whether to deep till the following year; this was consistent with other research that suggests that annual subsoiling need not be a blanket recommendation (Busscher and Bauer 2003).

The 2003 Florence location data had the only water contents that differed among tillage treatments. For this data, a relationship could be seen between water content and cone index (Figure 2) where treatment mean water content varied inversely with treatment

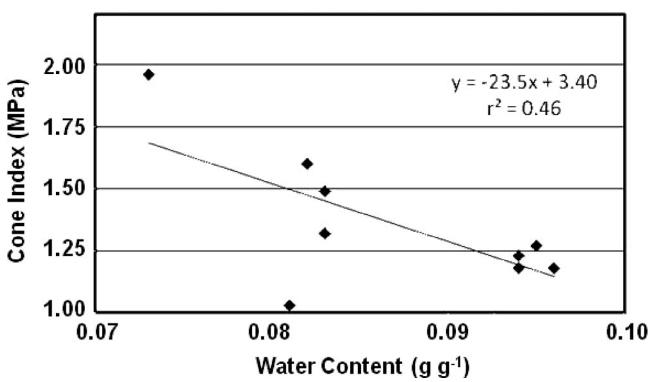

Figure 2. Correlation of cone index and water content for the Florence location data in 2003; if the Paratill data are omitted (bottom 2 near the center of the water content axis), the r^2 increased to 0.96.

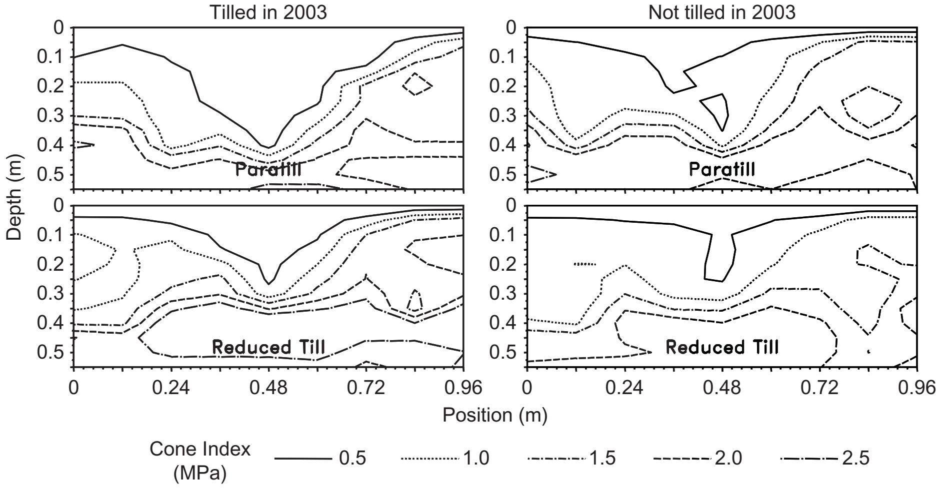

Figure 3. Cone index contours from the Florence location in 2003 across treatment profiles for paratill and reduced-till treatments that were tilled in both 2002 and 2003 on the left and tilled only in 2002 on the right.

mean cone index, yielding an r^2 of 0.46. Of course, water content would not be the only parameter affecting cone index; tillage treatments would also affect it (Figure 3). For example, if Paratill data (the midgraph lower two data points in Figure 2) were removed from the relationship, its r^2 increased to 0.96. The high r^2 for the non-Paratilled treatments suggests that their differences were related more to water content than tillage. This relationship suggests that when the producer decides whether to till, he or she will need to correct penetration resistance data to a common water content.

Cone index was expected to be greater for no tillage than the other treatments. In three out of four cases (Table 6), no tillage had greater cone indices or was among the treatments with greater cone indices. In the fourth case, at Florence in 2003, the no-tillage

Table 6
Mean profile cone index measurements (MPa) for tillage treatments

		Blackville		Florence	
Tillage	Till 2nd year	2002	2003	2002	2003
Conventional	N	1.58b[a]	3.17ab	1.12a	1.60ab
	Y	Na	2.89b	Na	1.96a
Paratill	N	1.44b	3.51ab	0.78b	1.32bcd
	Y	Na	3.30ab	Na	1.03e
Reduced till	N	1.57b	3.63ab	1.39a	1.23*c*de
	Y	Na	3.34ab	Na	1.49bc
Terra-Max	N	1.85b	4.08a	1.15a	1.18de
	Y	Na	3.57ab	Na	1.27*c*de
No tillage	NA	2.63a	4.03a	1.36a	1.18de

[a]Means in columns with the same letters are not significantly different according to the LSD test at 5%.

treatment had one of the greater soil water contents (Table 3) and lower strengths. It is not unusual for no-tillage treatments to have greater water contents (Stone and Schlegel 2010).

Bent-leg shanks often disrupt more of the profile than straight-leg shanks, as seen in the Paratill data of Karlen et al. (1991). This was seen at Florence in 2002; cone indices were significantly lower for the Paratill than the other tillage treatments. In 2003, as seen previously, cone indices at Florence were affected by significantly different water contents among treatments. Cone index data correlated well with water content except for the Paratill data, which fell below the correlation line implying a greater amount of disruption with this implement than the others (Figures 2 and 3).

Yield

Yield differences were generally not significant among treatments. In two out of four site years, yields were significantly lower for the no-tilled treatments than any of the tilled treatments, and in three of four site years, they were numerically lower. This would be expected given the standard recommendation to deep till annually (Wiatrak, Dunphy, and Norsworthy 2010). Yields were not consistently greater for any implement when compared to the others. One reason for consistent yields may be that the varieties were selected and developed for growth in the dry and hard coastal soils.

In 2003, when treatments were split by deep tillage and no deep tillage, yields were still not very different. At Blackville, yields were 1871 kg ha^{-1} vs. 1814 kg ha^{-1} for treatments tilled or not at the beginning of the season (and 1323 kg ha^{-1} for the no-till treatment, Table 7). At Florence, yields were 944 kg ha^{-1} vs. 882 kg ha^{-1} for treatments tilled or not at the beginning of the season (and 746 kg ha^{-1} for the no-till treatment). Yields were not significantly different between any of the treatments tilled one vs. both years, despite the fact that all except one (reduced till in Florence) had numerically greater yields when tilled both years. Yield differences are likely not different enough to warrant tillage; but given the effect of low rainfall in this case and high correlation of penetration resistance with water

Table 7
Lint yield (kg ha^{-1}) in 2003 and 2003 for treatments tilled only in the first or both the first and second years

		Blackville		Florence	
Tillage	Till 2nd year	2002	2003	2002	2003
Conventional	N	967a[a]	1717a	498a	882ab
	Y	—	1770a	—	910ab
Paratill	N	935a	1827a	511a	903ab
	Y	—	1920a	—	1005a
Reduced till	N	1021a	1887a	513a	903ab
	Y	—	1937a	—	851b
Terra-Max	N	949a	1825a	511a	893ab
	Y	—	1859a	—	956a
No tillage	NA	770b	1323a	559a	746c

[a]Means in columns with the same letters are not significantly different according to the LSD test at 5%

content, producers would do well to decide this on a year-by-year basis for their individual situations.

Conclusions

Four tillage treatments were compared at two sites where deep tillage was performed annually or not. Tillage generally reduced soil penetration resistance and improved yield but differences were significant only about half of the time. Though the bent-leg implements usually disrupt the profile more than straight-leg implements, the effect could only be seen with the Paratill. Compared to not tilling, tilling the second year did not significantly reduce penetration resistance, probably because of an exceptionally dry first year where recompaction was reduced by lack of infiltration. Tilling the second year improved yield but only marginally (nonsignificantly when compared on an implement-by-implement basis). Producers will have to decide each year whether it would be to their benefit to till and base their decision on both recompaction caused by the previous season's rainfall and soil moisture at the time of measurement. More research needs to be performed to help producers make their decision based on quick tests of soil strength, economic predictions of market futures, and expected growing season rainfall from long-range forecasts.

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