Force Requirements and Soil Disruption of Straight and Bentleg Subsoilers for Conservation Tillage Systems

R. L. Raper

Abstract. *In conservation tillage systems, belowground soil disruption should be maximized while aboveground disruption should be minimized. To assist in choosing the best shank for strip-tillage systems, comparisons among several shanks commonly used to provide in-row subsoiling prior to planting in conservation systems were made. A three-dimensional dynamometer measured draft, vertical, and side forces for the experiments, which were conducted in the USDA-ARS National Soil Dynamics Laboratory soil bins in Auburn, Alabama. A portable tillage profiler measured both above- and belowground soil disruption. Two parameters, spoil resistance index and trench specific resistance, were developed from the data to assess draft force, aboveground soil disruption and belowground soil disruption. Based on these selection criteria, the two best shanks for conservation tillage systems were the Bigham Brothers Paratill shank and the Worksaver Terramax shank, both of which were bentleg shanks.*

Keywords. *Subsoiling, Tillage, Soil compaction, Draft force, Vertical force, Bentleg, Shanks.*

Many producers use conservation tillage systems to maximize amounts of crop residue on the soil surface. However, some farmers report that yields may not be sustainable and attribute this to soil compaction (Raper et al., 2000b; Raper et al., 2000a; Schwab et al., 2002). In the Southeastern United States, many producers must use a deep tillage system to ameliorate compacted soil profiles (Campbell et al., 1974; Garner et al., 1987). Subsoiling, however, can bury surface residue and reduce the benefits of conservation tillage.

Strip tillage was developed as one solution to this problem. In this cropping system, a cover crop often is grown during the winter months. Prior to spring planting, subsoiling is conducted such that it disturbs only a limited area directly under the row. This in-row subsoiling process leaves most of the crop residue in place, thus improving infiltration, increasing soil moisture, reducing compaction and soil erosion (Mullins et al., 1992; Raper et al., 1994, 1998; Reeves and Mullins, 1995).

Strip-tillage seeks to leave maximum amounts of residue in place and minimally disturb the soil surface. However, belowground disruption is necessary to reduce the effects of compaction on plant roots and allow them to grow to depths adequate to obtain soil moisture. Several shanks are available for use by producers to conduct strip-tillage. Most shanks are straight and are angled with a slight forward incline to reduce draft. The belowground disruption from these shanks is symmetric, with equal amounts of soil being disturbed on either side of the shank. Another type of shank that is commonly used in conservation tillage systems is the bentleg shank (Pidgeon, 1982; Pidgeon, 1983). This shank disrupts the soil in a slightly different manner than straight shanks, with most of the disruption occurring on one side of the shank (Spoor and Godwin, 1978). These shanks are thought to require slightly more energy than straight shanks, but their use is advised primarily because they leave the soil surface relatively undisturbed (Anonymous, 1999). Some research, however, has found that similar amounts of draft force are required for bentleg shanks as for straight shanks (Khalilian et al., 1988).

Producers have many choices when selecting shanks to perform subsoiling operations. They may, however, not have adequate scientific information to make an informed decision about which shank will leave their soil in the best condition. Their desired soil condition would include alleviating any belowground soil compaction, while leaving the soil surface undisturbed. These aboveground and belowground soil disturbances should be performed with a minimum of tillage energy and tillage forces.

Therefore, this experiment was conducted to determine:

- draft, vertical, and side forces of several common straight and bentleg shanks,
- the amount of aboveground soil disruption caused by the tillage process,
- the amount of belowground soil disruption caused by the tillage process, and
- the shank (or shanks) with minimal draft force requirements, minimal aboveground soil disruption, and maximum belowground soil disruption.

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The use of trade names or company names does not imply endorsement by USDA-ARS. The author is **Randy L. Raper, ASABE Member Engineer,** Agricultural Engineer, Lead Scientist, USDA-ARS National Soil Dynamics Laboratory, 411 S. Donahue Drive, Auburn, Alabama 36832; phone: 334-844-4654; fax: 334-887-8597; e-mail: rlraper@ars.usda.gov.

Materials and Methods

The experiment was conducted in the soil bins at the USDA-ARS National Soil Dynamics Laboratory in Auburn, Alabama. Two Southeastern U.S. soils, a Norfolk sandy loam soil (*fine loamy, kaolinitic, thermic Kandiudults*) and a Decatur clay loam soil (*fine, kaolinitic, thermic Rhodic Paleudults*), were selected. Norfolk sandy loam soil is a Coastal Plain soil commonly found in the Southeastern United States and along the Atlantic Coast. Decatur clay loam soil is a Tennessee Valley soil found in Northern Alabama along the Tennessee River.

Soil Preparation

The hardpan condition was formed in the indoor soil bins to simulate a condition commonly found in the Southeastern United States. This naturally occurring and sometime traffic-induced hardpan, is found approximately 0.1 to 0.3 m below the soil surface and is quite impervious to root growth, particularly at low moisture levels. Root-limiting conditions with cone index values exceeding 2 MPa are often found in field conditions at these depths (Taylor and Gardner, 1963). The hardpan condition was created using a moldboard plow to laterally move the soil, followed by a rigid wheel which packed the soil left exposed in the furrow. Approximately 0.2 m of the soil bin was packed at a time, with the procedure repeated until the entire width of the bin had been traversed. The surface soil was then bladed and leveled. Although, variations did occur between bins, within a bin the same depth of the hardpan was usually achieved.

Shank Description

The shanks used for the experiment were from four different manufacturers (table 1). Deere and Co. (Moline, Ill.) manufactured a straight shank that was 32 mm thick and was used on the John Deere 955 Row Crop Ripper (fig. 1). Two different sizes of LASERRIP™ Ripper Points were used for this experiment. A wide point of 178 mm and a narrow point of 69.9 mm were used. The shank with the wide point was referred to as SDW (straight, Deere, wide point) and the shank with the narrow point was referred to as SDN (straight, Deere, narrow point). The three other straight shanks used in this experiment were all manufactured by Kelley Manufacturing Co. (Tifton, Ga.; table 1, fig. 1). Two different shank designs were used, one having an angle of 45° and the

Table 1. Description of shanks used in experiment.

Treatment Key	Shank Type	Manufacturer	Common Name	Shank Thickness (mm)
SDW	Straight	Deere	Straight standard with 178−mm L LASERRIP™ Ripper Points	32
SDN	Straight	Deere	Straight standard with 69.9−mm LASERRIP™ Ripper Points	32
SK45W	Straight	Kelley	Straight standard with 45° angle and wing	25
SK15W	Straight	Kelley	Straight standard with 15° angle and wing	25
SK45	Straight	Kelley	Straight standard with 45° angle	25
BBP	Bentleg	Bigham Brothers	Paratill™	25
BBT	Bentleg	Bigham Brothers	Terratill™	25
BWT	Bentleg	Worksaver	Terramax™	15

Figure 1. Straight shanks used in test. Shank codes are: SDW − straight shank, Deere, wide point; SDN − straight shank, Deere, narrow point; SK45W − straight shank, Kelley, standard, wing; SK15W − straight shank, Kelley, modified, wing; SK45 − straight shank, Kelley, standard.

Figure 2. Bentleg shanks used in test. Shank codes are: BBP − Bentleg, Bigham Brothers, Paratill; BBT − Bentleg, Bigham Brothers, Terratill; BWT − Bentleg, Worksaver, TerraMax.

other having an angle of 15° degrees. Each shank had the same 25-mm width and used the same wear tips (44-mm width). Replaceable wear plates attached to the front of the shanks were used for the experiments because these would be used in actual field use. In addition, a flexible wing was included on the rear of the shanks, which was designed to improve belowground soil disruption. This wing was not fixed and was allowed to rotate upward or downward freely. It was mounted 6.4 cm from the bottom edge of the point on the rear of the 45° shank and 12.7 cm from the bottom edge of the point on the rear of the 15° shank. These shanks were referred to as SK45W (straight, Kelley, 45° angle shank, wing), SK15W (straight, Kelley, 15° angle shank, wing), and SK45 (straight, Kelley, 45° angle shank).

Three bentleg type shanks were included in the study (fig. 2). Bigham Brothers (Lubbock, Tex.) manufactured two 25-mm thick shanks that were tested (table 1). One of these shanks was referred to as the Paratill™ shank and was formerly manufactured by Howard Rotovator and ICI (Harrison, 1988). This shank was bent 45° to one side and with the leading edge rotated forward by 25°. Its forward projection was 216 mm wide. The Paratill has a 57-mm wide point. Bigham Brothers also made a slightly narrower version of this shank and referred to it as the Terratill™. Its forward projection was a narrower width of 127 mm. The Terratill has a 76-mm wide point. These shanks were referred to as the BBP (bentleg, Bigham Brothers, Paratill) and the BBT (bentleg, Bigham Brothers, Terratill). The third bentleg shank used in the study was manufactured by Worksaver Company (Litchfield, Ill.) and was referred to as the TerraMax™ (table 1). This shank was slightly thinner, at 15 mm, was rolled about a 0.43-m radius, and was rotated forward by 15°. It was referred to as the BWT (bentleg, Worksaver, TerraMax).

Measurements

For the tests, the shanks were mounted on a three-dimensional dynamometer, which has an overall draft load capacity of 44 kN. Draft, vertical force, side force, speed, and depth of operation were recorded at a sampling rate of 25 Hz during each shank test. Speed for all tests was held constant at 0.45 m/s. Depth of operation was 0.33 m for all tests.

Four subsoiling runs were conducted side-by-side across the width of the bin, with eight runs being conducted along the length of the bin. This arrangement allowed all 32 runs to be conducted in one bin. The approximate size of each plot was 1.5 m wide × 5 m long. The spacing across the bin was sufficient to ensure that disturbed soil resulting from a previous tillage operation would not affect the next test. All of the force values obtained from each run were averaged to create one specific value per plot of draft, vertical force, and side force.

Before the shank tests were carried out in each plot, a set of five cone index measurements was acquired with a multiple-probe recording penetrometer. This set of measurements was taken with the five-cone index measurements equally spaced at a 0.2-m interval across the soil, with the middle measurement being directly in the path of the shank. After the test , another set of five cone index measurements was taken in close proximity to the original cone index measurements.

Samples were collected in undisturbed regions of each plot immediately after the conclusion of the experiment for bulk density and moisture content determination. These samples were obtained near the surface at a depth of 0 to 5 cm, and in the hardpan. They were weighed and dried at 105°C for 24 h to obtain averaged gravimetric water content and dry bulk density.

After each set of tillage experiments was complete, a portable tillage profiler [(Raper et al., 2004); fig. 3] was used to determine the width and area of soil that was disturbed by the tillage event in each plot. This measurement was referred to as the 'spoil.' The disturbed soil was then manually excavated from the trenched zone for each plot for approximately 1 m along the travel path to allow five independent measurements to be made of the area of the subsoiled or

Figure 3. Portable tillage profiler consisting of a laser distance measuring system, a linear actuator, and an aluminum frame. In this photograph, the profiler is being used to measure the trench cross-sectional area.

trenched zone. This measurement was referred to as the 'trench.' Care was taken to ensure that only soil loosened by tillage was removed.

An index was created to assist in assessing differences due to draft forces and spoil cross-sectional area. The index was determined by simply multiplying these two parameters as follows:

$$SRI = D \times SCA \tag{1}$$

where
SRI = spoil resistance index (kN × m^2)
D = draft (kN)
SCA = spoil cross-sectional area (m^2)

The advantage of using this parameter was that both parameters used to compute it, draft and spoil cross-sectional area, were desired to be small. By multiplying them, trends in the data were easier to see as SRI should be minimized for the best results.

In an effort to understand the effects of draft force on trenched cross-sectional area, another relationship was developed and considered these parameters. The trench specific resistance was defined as:

$$TSR = \frac{D}{TCA} \tag{2}$$

where
TSR = trench specific resistance (kN/m^2)
D = draft (kN)
TCA = trench cross-sectional area (m^2)

Again it was advantageous for TSR to be small, because this indicated small values of draft coupled with large values of belowground disruption.

Experimental Design

Each soil bin was treated as a randomized complete block design with four replications and eight shank types. Pre-planned single degree of freedom contrasts and Fisher's protected least significant difference (LSD) were used for mean comparison. A probability level of 0.10 was assumed to test the null hypothesis that no differences existed between shanks in terms of the various parameters measured and/or developed.

Results and Discussion

The gravimetric moisture content of the Norfolk soil was 7.2% between depths of 0 to 5 cm and 8.8% in the hardpan. In the Decatur soil, the moisture content was 12.5% near the surface and 13.6% in the hardpan. The dry bulk density in the Norfolk soil was 1.73 Mg/m^3 near the surface and 1.94 Mg/m^3 in the hardpan. In the Decatur soil, the dry bulk density was 1.46 Mg/m^3 near the surface and 1.76 Mg/m^3 in the hardpan.

The cone index values that were taken to quantify soil strength were shown in figure 4. The approximate depths of the hardpan were at 0.10 m for the Norfolk sandy loam soil and 0.8 m for the Decatur clay loam soil. The 2-cm difference was due to differences in soils and their interaction with machinery. The magnitudes of cone index and the overall profiles are quite similar to actual field measurements commonly found in these soil types.

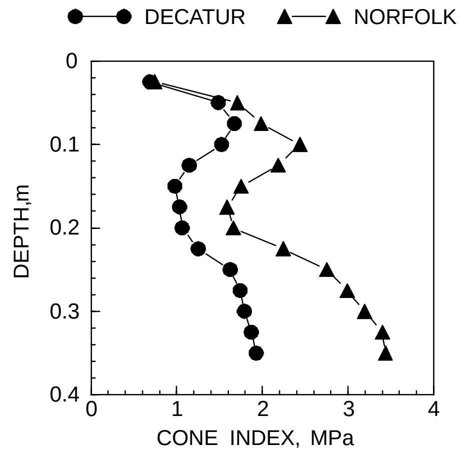

Figure 4. Initial cone index profiles for the two soil types.

Draft Force
Norfolk Sandy Loam Soil

The straight shanks required higher tillage draft force compared to the bentleg shanks. The SDN subsoiler shank required 9.25 kN, which was the largest draft force required, while the smallest draft force of 5.85 kN was measured for the BBP shank (table 2).

Several statistically significant paired comparisons were also found. The SK45W shank required significantly reduced draft force (7.77 kN) compared to the SK15W shank (8.99 kN; $P \leq 0.015$). This result indicates that the modified shank

Table 2. Tillage forces for the Norfolk sandy loam soil and the Decatur clay loam soil.[a]

	Draft Force (kN)	Vertical Force (kN)	Side Force (kN)
Norfolk sandy loam soil[b]			
SDW	8.72 ac[c]	3.49 ab	0.48 bc
SDN	9.25 a	3.14 bcd	0.31 cd
SK45W	7.77 cd	2.79 d	0.23 d
SK15W	8.99 a	3.17 abc	0.51 bc
SK45	8.02 bc	2.97 cd	0.43 cd
BBP	5.85 f	3.55 a	0.68 b
BBT	7.22 de	3.14 bcd	1.11 a
BWT	6.72 e	3.17 abc	0.49 bc
Decatur clay loam soil			
SDW	13.14 a	3.77 b	0.52 cd
SDN	11.58 abc	3.08 cd	0.53 cd
SK45W	12.79 ab	3.44 bcd	0.39 d
SK15W	12.29 ab	3.28 bcd	0.84 c
SK45	10.20 cd	3.54 bc	0.48 cd
BBP	10.15 cd	4.49 a	1.58 b
BBT	11.08 bcd	3.75 b	2.10 a
BWT	9.65 d	2.93 d	0.82 c

[a] Shaded zones indicate the statistically best shanks for each parameter.
[b] Treatment key:
SDW − straight shank, Deere, wide point.
SDN − straight shank, Deere, narrow point.
SK45W − straight shank, Kelley, standard, wing.
SK15W − straight shank, Kelley, modified, wing.
SK45 − straight shank, Kelley, standard.
BBP − Bentleg, Bigham Brothers, Paratill.
BBT − Bentleg, Bigham Brothers, Terratill.
BWT − Bentleg, Worksaver, TerraMax.
[c] Letters indicate LSD statistical differences at the 0.10 level.

angle for the Kelley straight shank required slightly more tillage force.

The BBP shank required less tillage force (5.85 kN) than the BBT shank (7.22 kN; $P \leq 0.007$) or the BWT shank (6.72 kN; $P \leq 0.074$). This may indicate that the newer bentleg designs may not be as efficient in minimizing force as the Paratill for this soil type.

Decatur Clay Loam Soil

Increased draft forces were required for the Decatur clay loam soil compared to the Norfolk sandy loam soil (table 2). The maximum tillage force was found for the SDW shank (13.14 kN) while the minimum force was for the BWT shank (9.65 kN). Only a single one-way comparison was found to be significantly different for this soil type, with the effect of the wing causing increased tillage force for the SK45W shank (12.79 kN) compared to the SK45 shank (10.20 kN; $P \leq 0.021$).

Vertical Force

Norfolk Sandy Loam Soil

All shanks generating a suction force with smaller values were assumed to be the most desirable. Some suction was desired as a method of keeping the shank inserted into the soil, but large values could cause excessive penetration and increased draft forces. The BBP shank required the largest vertical force (3.55 kN) while the SK45W shank required the least (2.78 kN; table 2). In this soil, the SK45W shank required significantly smaller values of vertical forces (2.78 kN) than did the SK15W shank (3.17 kN; $P \leq 0.090$). The decreased slope of the SK15W shank was probably responsible for the increased amount of vertical force. The BBP shank also required increased values of vertical force (3.55 kN) compared to the BBT shank (3.14 kN; $P \leq 0.081$), probably because of the aggressiveness of the point.

Decatur Clay Loam Soil

In this soil type, the BBP shank required the maximum vertical force (4.49 kN) with the minimum value required by the BWT shank (2.93 kN; table 2). In regards to the one-way comparisons, several significant differences were found. The SDN shank required significantly reduced vertical force (3.08 kN) compared to the SDW shank (3.77 kN; $P \leq 0.037$). The increased width of the foot on this shank required additional vertical force. The BBP shank required significantly higher vertical force (4.49 kN) compared to either of the other two bentleg shanks; BWT (2.93 kN; $P \leq 0.001$) or BBT (3.75 kN; $P \leq 0.027$). The BWT shank also required reduced vertical force than the BBT shank ($P \leq 0.015$).

Side Force

Norfolk Sandy Loam Soil

Even though the largest side forces for this soil type were found with the BBT shank (1.11 kN) and the next largest for the BBP shank (0.68 kN), it was somewhat surprising that several of the straight shanks also required significant amounts of side force (table 2). Properly designed bentleg shanks have had this tendency minimized and were relatively close (numerically) to straight shanks. Also, the below-ground disturbance was fairly symmetrical for the bentleg shanks. The SK45W shank had the minimum side force (0.23 kN). The SK45W shank has reduced side force compared to the SK15W shank (0.51 kN; $P \leq 0.034$). The BBT shank had elevated values of side force compared to both of the other bentleg shanks; BWT (0.49 kN; $P \leq 0.001$) and BBP (0.68 kN; $P \leq 0.002$).

Decatur Clay Loam Soil

The largest values of side force in the Decatur clay loam soil were required by the BBT shank (2.10 kN) while the minimum values were required by the SK45W shank (0.39 kN; table 2). Increased shank angle required significantly smaller values of side force for the SK45W shank compared to the SK15W shank (0.84 kN; $P \leq 0.070$). The BBT shank had higher values of side force compared to the other bentleg shanks; BWT (0.82 kN; $P \leq 0.001$) or BBP (1.58 kN; $P \leq 0.036$). The BWT shank required reduced values of side force compared to the BBP shank ($P \leq 0.004$).

Spoil Cross-Sectional Area

Example graphs of the spoil and the trench are shown in figure 5 for each of the shanks operating in the Norfolk sandy loam soil. These graphs showed a great amount of variability and it was difficult to draw conclusions without statistical analysis. However, one observation noted was the symmetry in spoil and trench area for the bentleg shanks. These shanks were expected to disrupt the soil mostly on one side of the shank, but the graphs clearly showed almost symmetrical disruption on both sides of the shanks. This observation was proven by a statistical comparison of the trenched area in the Norfolk sandy loam soil which found no difference between shanks (data not shown). Despite the different appearance and construction of the shanks, similar amounts of disruption were found on each side of a vertical line drawn from the deepest point. A hypothesis that we considered was that the bentleg shanks were properly designed with a side angle of 45°. This 45° angle was similar to the angle that straight shanks created on either side of the shank in these soils. In different soil types or stratified soil conditions, this performance could vary.

Norfolk Sandy Loam Soil

Similar results were found for the cross-sectional area for the Norfolk sandy loam as for the width of the spoil (table 3). The maximum amount measured with the portable tillage profiler was 43.5×10^{-3} m^2 for the SDW shank, and the minimum amount was 28.7×10^{-3} m^2 for the BWT shank. It was thought that the increased width of the point on the SDW shank caused the statistically significant difference to be found compared to the SDN shank (35.9×10^{-3} m^2; $P \leq 0.020$). The BWT shank had a significantly reduced spoil cross-sectional area compared to the BBT shank (34.8×10^{-3} m^2; $P \leq 0.061$).

Decatur Clay Loam Soil

The maximum spoil cross-sectional area for this soil type was found for the SDW shank (53.1×10^{-3} m^2) with the minimum values for the BBP shank (36.3×10^{-3} m^2;

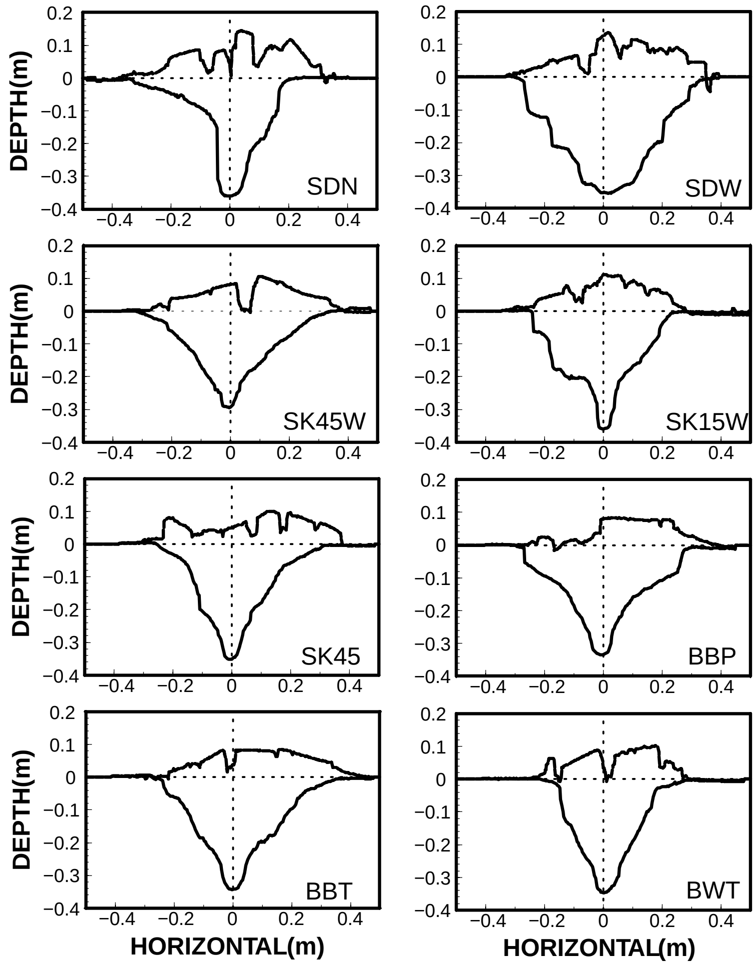

Figure 5. Example spoil and trench graphs as measured with the portable tillage profiler for the Norfolk sandy loam soil.

table 3). It was thought that the increased point width of the SDW shank caused increased spoil cross-sectional area compared to the SDN shank (46.7×10^{-3} m^2; P ≤ 0.018). The wing mounted on the SK45W shank (45.0×10^{-3} m^2) probably caused spoil cross-sectional area for this shank compared to the SK45 shank (39.9×10^{-3} m^2; P ≤ 0.052). The BBP shank produced a reduced spoil cross-sectional area compared to the BBT shank (41.6×10^{-3} m^2; P ≤ 0.043).

Trench Cross-Sectional Area
Norfolk Sandy Loam Soil

The maximum amount of trench cross-sectional area was found with the SDW shank (105.7×10^{-3} m^2; table 3) while the minimum amount was found with the SK45W shank (74.6×10^{-3} m^2). The only statistically significant difference was found between the SDW shank and the SDN shank (74.8×10^{-3} m^2; P ≤ 0.004).

Decatur Clay Loam Soil

The greatest trench cross-sectional area was found for the SDW shank (127.8×10^{-3} m^2) while the minimum was with the SK15W shank (92.5×10^{-3} m^2; table 3). It was thought that the wide point on the SDW shank disturbed a larger zone than the SDN shank (112.2×10^{-3} m^2; P ≤ 0.097). It was also thought that the wing on the SK45W shank (110.9×10^{-3} m^2) increased values of trench cross-sectional area compared to the SK45 shank (94.6×10^{-3} m^2; P ≤ 0.085), which did not have the wing. The SK45W shank had reduced trench cross-sectional area compared to the SK15W shank (92.5×10^{-3} m^2; P ≤ 0.054) perhaps due to the effect of the increased angle.

Spoil Resistance Index
Norfolk Sandy Loam Soil

The maximum SRI was calculated for the SDW shank (0.379 kN × m^2) and the minimum with the BBP shank (0.176 kN × m^2; table 3). A statistically significant difference was found between the SDW shank and the SDN shank (0.379 kN × m^2; P ≤ 0.093). The BBT shank (0.249 kN × m^2) had a statistically higher SRI than the other bentleg shanks: the BWT shank (0.194 kN × m^2; P ≤ 0.072) or the BBP shank (0.176 kN × m^2; P ≤ 0.023).

Two bentleg shanks, BBP or BWT, seemed to be exceptional at requiring minimal draft while causing minimal soil surface disruption in this soil type. Either of these shanks should be able to work in this soil type and leave maximum amounts of residue on the soil surface, while requiring lower amounts of tillage energy.

Decatur Clay Loam Soil

The maximum SRI in the Decatur soil was 0.696 kN × m^2 for the SDW shank, while the minimum value was 0.368 kN

Table 3. Soil disruption parameters for the Norfolk sandy loam soil and the Decatur clay loam soil.

	Spoil Width[a] (m)	Spoil Cross-Sectional Area ($m^2 \times 10^{-3}$)	Spoil Resistance Index ($kN \cdot m^2$)	Trench Width (m)	Trench Cross-Sectional Area ($m^2 \times 10^{-3}$)	Trench Specific Resistance (kN / m^2)
Norfolk sandy loam soil[b]						
SDW	0.717 a	43.5 a	0.379 a	0.548	105.7 a	83.5 cde
SDN	0.568 bc	35.9 b	0.319 b	0.397	74.8 b	126.7 a
SK45W	0.590 bc	32.4 bc	0.253 c	0.453	74.6 b	106.1 abc
SK15W	0.594 bc	33.3 bc	0.293 bc	0.494	88.5 b	106.9 ab
SK45	0.654 ab	36.0 b	0.289 bc	0.510	82.4 b	100.2 bcd
BBP	0.584 bc	30.0 c	0.176 d	0.520	88.0 b	66.8 e
BBT	0.653 ab	34.8 b	0.249 c	0.503	88.1 b	82.6 de
BWT	0.553 c	28.8 c	0.194 d	0.470	80.3 b	85.0 bcde
Decatur clay loam soil						
SDW	0.753 a	53.1 a	0.696 a	0.593	127.8 a	102.3 bcd
SDN	0.691 bcd	46.7 b	0.542 bc	0.576	112.2 b	105.0 bc
SK45W	0.664 def	45.0 bc	0.574 b	0.591	110.9 bc	117.0 b
SK15W	0.645 ef	42.7 bcd	0.523 bc	0.516	92.5 d	133.4 a
SK45	0.631 f	39.9 de	0.409 de	0.523	94.6 d	108.8 bc
BBP	0.733 ab	36.3 e	0.368 e	0.515	102.8 bcd	98.8 cd
BBT	0.711 abc	41.6 cd	0.466 cd	0.528	95.8 cd	115.5 b
BWT	0.685 cde	39.7 de	0.382 de	0.576	107.5 bcd	89.7 d

[a] Shaded zones indicate the statistically best shanks for each parameter.
[b] Treatment key:
SDW − straight shank, Deere, wide point.
SDN − straight shank, Deere, narrow point.
SK45W − straight shank, Kelley, standard, wing.
SK15W − straight shank, Kelley, modified, wing.
SK45 − straight shank, Kelley, standard.
BBP − Bentleg, Bigham Brothers, Paratill.
BBT − Bentleg, Bigham Brothers, Terratill.
BWT − Bentleg, Worksaver, TerraMax.

$\times$ m^2 for the BBP shank (table 3). These values were almost twice that measured in the Norfolk soil, mostly because of increased draft energy requirements. The SDW shank had a statistically higher SRI than the SDN shank (0.542 kN $\times$ m^2; $P \leq 0.012$). The wing also caused the SK45W shank (0.574 kN $\times$ m^2) to have a higher value than the SK45 shank (0.409 kN $\times$ m^2; $P \leq 0.008$). Lastly, the BBP had shank-reduced values of SRI compared to the BBT shank (0.466 kN $\times$ m^2; $P \leq 0.098$).

Again, two bentleg shanks, BBP or BWT, seemed to function exceptionally well as did one of the straight shanks, SK45. Minimal power requirements as well as small amounts of spoil should allow any of these three shanks to be acceptable for this soil type.

Trench Specific Resistance

Norfolk Sandy Loam Soil

The maximum TSR was calculated for the SDN shank (12.7 kN/m^2) and this arose primarily because of its large draft force requirement and its relatively small trench cross-sectional area (table 3). The minimum value was found with the BBP shank (6.68 kN/m^2). This came about because it had minimal values of draft and large values of trench cross-sectional area. The only one-way significant difference was found between the two shanks: SDN (12.7 kN/m^2) and SDW (8.3 kN/m^2; $P \leq 0.004$).

Statistically similar values were found for the BBP, BBT, SDW, and the BWT shanks. Either of four shanks would satisfy the requirement of having minimal values for trench specific resistance for this soil type.

Decatur Clay Loam Soil

The largest values of TSR were found for the SK15W shank (13.3 kN/m^2) with the smallest values for the BWT shank (9.0 kN/m^2; table 3). The shank angle appeared to increase the values of TSR for the SK15W shank, compared to the SK45W shank (11.7 kN/m^2; $P \leq 0.076$). The BBT shank (11.6 kN/m^2) also had increased values of TSR compared to the other bentleg shanks: BWT shank ($P \leq 0.008$) and BBP shank (9.88 kN/m^2; $P \leq 0.071$).

Three shanks had statistically similar values of TSR for the Decatur clay loam soil: the BWT, BBP, and SDW shanks. These three shanks also had the lowest TSR for the Norfolk sandy loam soil. If maximum amounts of belowground soil disruption were needed without consideration for spoil cross-sectional areas, these three shanks would be good candidates for subsoiling.

Summary and Conclusions

When both aboveground and belowground disruptions were considered, the two shanks that performed the best were the BBP shank and BWT shank. The BBP shank had the lowest SRI for both soil types and one of the two lowest values for TSR. Statistically similar results were also found for the BWT shank. Either of these two shanks should be very useful in conservation tillage systems where draft force and aboveground soil disruption should be minimized and belowground soil disruption should be maximized.

Even though soil bin experiments were limited in their scope compared to actual field experiments, important trends were detected that provided engineers with enhanced capabilities to design better field equipment. Differences found in this experiment from actual field conditions included soil condition and speed of operation. Because the soil used in the soil bin experiment did not contain any organic material and was not stratified with depth, the magnitude of the results obviously differed from actual field results. However, the trends in the data were similar and allowed important differences in forces and disruption to be found.

Also, the speed of operation for soil bin experiments was typically slower than found in actual field experiments. Speed obviously affects aboveground and belowground disruption. However, increased speed should result in increased disruption for all implements and still result in significant differences being found.

The conclusions that were drawn from this experiment were:

- The bentleg shanks had the lowest draft requirements as compared to the straight shanks for both soil types. Also requiring small amounts of draft was the SK45 straight shank.
- The bentleg shanks were found to generate more side force than the straight shanks.
- The BBP and BWT shanks had the lowest aboveground soil disruption.
- The SDW shank had the largest belowground soil disruption.
- Using the two parameters defined in this article, spoil resistance index and trench specific resistance, enables two shanks to stand out in their ability to require minimal draft force and aboveground soil disruption while providing maximum belowground soil disruption. The two best shanks for conservation tillage systems based on these selection criteria were the BBP shank and the BWT shank.

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