In-Row Subsoiling: A Review and Suggestions for Reducing Cost of this Conservation Tillage Operation

R. L. Raper, J. S. Bergtold

Abstract. *In-row subsoiling has been used in the southern United States as a standard production practice to reduce the ill effects of soil compaction. Much of the subsoiling literature from the southern United States indicates that significant increases in productivity are found when in-row subsoiling is used, with the most success being found on sandier soils. However, the cost of this operation is relatively expensive and significant gains in crop yield must be obtained to pay for the tillage practice. Much can also be done to reduce the cost of the in-row subsoiling operation. A number of research studies are presented that indicate various methods that can be used to reduce the cost of in-row subsoiling, primarily through reductions in energy costs via fuel consumption. These methods include: proper selection of subsoiler shanks, appropriate selection of subsoiler depth, appropriate selection of soil moisture for subsoiling, reducing frequency of subsoiling, controlling vehicle traffic, and consideration of other methods of compaction reduction, including the use of cover crops. The fuel portion of the cost of subsoiling is approximately 25% without energy-saving strategies but can be reduced to approximately 16% of the total cost of subsoiling, which includes labor, fuel, repair and maintenance, and fixed costs. The estimated cost of in-row subsoiling using data from 2005 can be reduced from $33.52 to $29.79/ha which is a savings of $3.73/ha. Use of these methods should allow in-row subsoiling to continue to be a valuable part of conservation agricultural systems.*

Keywords. *Subsoiling, Compaction, Cover crops, Conservation tillage, Conservation agriculture.*

Soil compaction was only widely recognized as a possible limitation to crop yields in the early 1900s when large agricultural vehicles began to be used for agricultural production and compaction was more easily observed due to vehicle rutting. Reduced infiltration, increased ponding on the soil surface, reduced crop growth, and reduced production was often found in the ruts left from previous passes of tractors or implements. Thus, one of the two causes of soil compaction was diagnosed, i.e. vehicle traffic.

A second cause of soil compaction that was not as easily observed was a hardpan that can limit rooting and crop yields. Hardpans often have two causes: (1) repeated interaction with tillage equipment (typically discs or rotary tillers sometimes used for years at the same depth), and (2) naturally occurring layers that are caused by interactions of small and large soil particles that tend to eliminate porosity.

Tillage was first used and continues to be the most common method used to alleviate soil compaction. Disrupting the compacted soil profile often provides immediate visual relief to rutting. However, in many soil types and climatic regions, the damage caused by these tillage events probably outweighs the benefits associated with this process. Deep tillage (often referred to as subsoiling), while adequately disrupting compacted soil conditions, may excessively disturb the soil surface. The subsoiling process may leave soil unprotected by crop residue and susceptible to rainfall that causes runoff and erosion. Also, excessive and unnecessary tillage decreases soil organic matter which provides many benefits for soils and crops including increased water storage capacity, reduced soil compaction, greenhouse gas sequestration, etc. (Hudson, 1994; Ekwue and Stone, 1995; Thomas et al., 1996).

Subsoiling is defined as tillage below a depth of 35 cm (*ASAE Standards*, 1999). Soils compacted from traffic or natural processes often benefit greatly from subsoiling by creating larger pores that increase rooting and infiltration. Much research has been conducted that provides evidence about the overall benefit of subsoiling. However, some research has shown no overall positive benefits of subsoiling to crop productivity. Reasons for discrepancies in these research results consist of differences in equipment, climatic regions, cropping systems, management practices, and soil types.

The combination of subsoiling and modern conservation tillage systems that emphasize large amounts of crop residues on the soil surface has allowed subsoiling to be conducted without increased runoff or soil erosion. Maximizing the amount of crop residue on the soil surface requires eliminating surface tillage and maximizing cover crop growth. In conservation systems, subsoiling is often conducted only in the row area instead of broadcast over the entire field. It is then referred to as in-row subsoiling or strip-tillage. If appropriate measures are taken to minimize surface disturbance caused by subsoiling, in-row subsoiling can be a valuable resource to combat soil compaction. Furthermore, conservation tillage can help reduce energy costs by requiring fewer

Submitted for review in January 2007 as manuscript number PM 6831; approved for publication by the Power & Machinery Division of ASABE in March 2007. Presented at the 2006 ASABE Annual Meeting as Paper No. 061039. The use of company names or trade names does not indicate endorsement by USDA-ARS.

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  ISSN 0883−8542

trips across the field, which can be optimized through proper management of subsoiling operations when needed.

However, with rapidly escalating fuel prices, many producers have questioned the continued use of in-row subsoiling due to the overall expense of the tillage practice. Planning budgets (Mississippi State University Department of Agricultural Economics, 2006) estimate the total cost of using a 4-row Paratill™ bedding operation on a 1-m spacing to be \$33.52/ha for 2005 which has increased significantly from \$26.31/ha in 2003 and \$27.45/ha in 2004. More than 28.9% of the total cost of subsoiling in 2005 is attributed to fuel costs which were \$8.40/ha. Other components of the total cost of subsoiling included labor (\$7.24/ha), repair and maintenance (\$3.18/ha), and fixed costs (\$14.70/ha). Changes in variable costs across alternative subsoiling implements are negligible, varying by only about \$0.40/ha. Fixed costs of subsoiling may vary due to differences in the purchase price of subsoilers. More specialized machinery, such as Paratill™ and Terratill™ subsoilers, can increase fixed costs by \$1.14 to \$1.31/ha (Mississippi State University Department of Agricultural Economics, 2006).

Reducing energy requirements of subsoiling emerges as the most likely method of reducing the overall cost of this operation. Therefore, our objective was to examine the pertinent literature on subsoiling that has been conducted in the Southeastern United States and to suggest opportunities to increase the effectiveness of subsoiling while minimizing energy requirements associated with its use.

In-Row Subsoiling Benefits for Soils and Crops

Campbell et al. (1974) studied the effect of subsoiling to a 0.38-m depth in sandy loam soils in South Carolina. They found that subsoiling adequately disrupted the A2 horizon, reduced soil strength, increased infiltration, and increased rooting depth. Reicosky et al. (1977) noted several studies that pointed to increased crop yields and reduced soil strength owing to subsoiling. However, most of these studies gave little cropping information and it is assumed that conventional tillage practices were employed. They also noted that some acid subsoils in the Southeastern United States might contain toxic levels of soluble aluminum would not benefit from deep tillage. Deep placement of lime might be useful to overcome this soil limitation.

Threadgill (1982) conducted a study over 4 years on a sandy loam soil in Georgia that evaluated the long-term effects of soil strength reduction caused by subsoiling to a depth of 0.36 to 0.38 m. He concluded that soil strength was reduced for one year but was not detected after the second year. He advocated the use of a controlled-traffic system as a method of increasing the longevity of reduced soil strength.

Box and Langdale (1984) evaluated the effect of subsoiling in a sandy loam soil in Georgia. Subsoiling was conducted with points which were 6.4 cm wide and at a depth of 0.36 m. In-row subsoiling and irrigation treatments were found to significantly increase grain yields. However, the effect of irrigation was much greater as it provided a 56% increase in yield while in-row subsoiling provided a 10% increase in yield.

Busscher et al. (1986) also studied the longevity of subsoiling on a loamy sand soil in South Carolina. A non-parabolic angled forward shank that was 20 mm wide and had a 65-cm wide point was used to disrupt soil compaction down to depths of 0.5 to 0.6 m. One year following subsoiling, the evidence of the previous year's tillage was found, but the soil strength had increased to levels of 1.5 to 2.5 MPa which were root-limiting. They advised that annual subsoiling was a mainstay of all cropping systems in the Southeastern Coastal Plain.

Touchton et al. (1986) found that in a two-year study in Alabama, in-row subsoiling gave different results on two soil types. On a sandy loam soil, in-row subsoiling was conducted prior to planting by pulling a shank through a soil which had a root-restricting hardpan at a 0.2-m depth. In-row subsoiling was conducted at a depth of 0.3 m. On a silt loam soil, which had no hardpan, in-row subsoiling was conducted at a 0.20-m depth prior to planting. Results on the sandy loam soil showed that in-row subsoiling produced the highest cotton yields for both years of the study, while results for the silt loam soil only showed significantly higher yields for in-row subsoiling for one year of the study.

Busscher et al. (1988) studied in-row subsoiling on loamy sand in South Carolina for two years. They used three subsoilers to unspecified depths: Brown-Harden Super Seeder (Ozark, Ala.), Tye Paratill™ (currently manufactured by Bigham Brothers Inc., Lubbock, Tex.), and Kelly Manufacturing Company subsoiler (KMC; Tifton, Ga.). Soil strength was evaluated with and without surface tillage. All three implements effectively disrupted compacted subsoil but a reduced stand establishment (67%) was found for the non surface-tilled treatments. The narrower KMC subsoiler provided a narrower zone of disruption because the shank was 32 mm wide with a 32-mm wide point. The wider shank of the Super-Seeder (50 mm) and wider point (73 mm) provided a larger disrupted area and overall lower soil strength.

Clark et al. (1993) evaluated the use of a Paratill™ on a clay soil in Georgia. Grain sorghum was no-till planted into wheat residue each year of a two-year study. Six shanks with equal spacing of 61 cm were pulled approximately 0.3 m deep. Soil strength was found to increase significantly in the 0.14- to 0.21-m depth range as the frequency of the use of the Paratill™ also increased. This result further indicates that this operation may need to be performed in this soil on an annual basis.

Mullins et al. (1997) evaluated the effect of in-row subsoiling on a silt loam soil in northern Alabama, as well as sandy loam and sandy clay loam soils in central Alabama. Subsoiling was conducted with a deep fertilizer applicator described by Tupper and Pringle (1986) to a depth of 0.38 m. In-row subsoiling caused a 22% increase in cotton yield over the three-years of the study for the sandy loam soil. In all other soil types, no significant benefit of subsoiling was found on crop production.

Smith (1995) used a controlled-traffic system to evaluate the effect of subsoiling in the fall in a clay soil in Mississippi. Subsoiling was conducted after harvest with a parabolic subsoiler to a depth of 40 cm on 50-cm centers. Row spacing of cotton was 1 m. When irrigation was not present, yield increases averaged 15%. When irrigation was present, yield increases averaged 8%. Using soybeans instead of cotton in this same experiment, Wesley and Smith (1991) found dramatically increased yields, 73% to 132% higher when compared to non-irrigated check treatments.

Busscher and Bauer (2003) studied the relationship between soil strength and cotton yield in a controlled traffic system on loamy sand in South Carolina. Subsoiling was conducted with a KMC subsoiler to a depth of 0.4 m. This shank was 2.5 cm wide and was angled forward by 44°. Soil strength was reduced by subsoiling and this coincided with an increase in root growth. However, cotton yield was not influenced by subsoiling. The positive effects of a rye cover crop were also noted even though increased yields did not result.

Raper et al. (1994) used soil strength to measure the effects of subsoiling and controlled traffic on a sandy loam soil in Alabama five years after the experiment was initiated. One of the initial tillage treatments consisted of using a Deere & Co. (Moline, Ill.) V-frame subsoiler operating on 0.25-m centers to completely disrupt the soil profile down to a depth of 0.5 m. Another tillage treatment consisted of using a KMC in-row subsoiler to a depth of 0.4 m prior to planting. Traffic was eliminated on half of the plots using an experimental wide-frame tractive vehicle which could span a distance of 6 m. Results from this study showed that when in-row subsoiling was used on an annual basis, recompaction caused by traffic was not found to affect crop yields (fig. 1). The advantages normally attributed to controlled traffic did not materialize due to the annual disruption provided by in-row subsoiling. Another study that was conducted using the same tillage treatments (Raper et al., 1998) concluded that when traffic was not controlled, the plots that received the initial complete disruption treatment with the V-frame subsoiler recompacted similar to plots that had never been subsoiled (fig. 2).

Schwab et al. (2002) conducted an experiment on a silt loam soil in Alabama to evaluate non-inversion subsoiling. Subsoiling was conducted with a Paratill™ to a depth of 0.45 m or a KMC subsoiler to a depth of 0.43 m. Results from this experiment indicated that non-inversion subsoiling or in-row subsoiling conducted in the fall of the year resulted in the highest seed cotton yields; 16% greater than conventional tillage and 10% greater than strict no-tillage. Significant compaction reduction was found with both subsoiling treatments, contributing to the increased seed cotton yields.

Truman et al. (2003) evaluated rainfall infiltration and runoff on the same plots that Schwab et al. (2002) used on the silt loam soil in Alabama. They conducted rainfall simulation experiments during fall and summer months and measured infiltration and runoff at the end of 1- and 2-h time periods. They concluded that no-till/Paratill™/rye plots had 34% to 10 times less runoff than from other tillage systems, while conventional-till plots had 1.5 to 5.4 times more soil loss than from other tillage systems (fig. 3). Subsoiling with the Paratill™ had more influence on runoff and soil loss than surface cover did in these soils. They recommended that a no-till system combined with the use of the Paratill™ in the fall and a rye cover was the best system to increase infiltration and plant available water, while reducing runoff and soil loss for the Tennessee Valley region.

Self-Davis et al. (1996) conducted one of the few studies involving subsoiling in pastures. They evaluated the use of a Paratill™ and an Aer-way (Wylie, Tex.) pasture renovator in a study in Alabama on a sandy loam soil. Tillage was conducted down to a depth of 0.32 m with the Paratill™. These methods of renovation tillage effectively loosened the compacted soil and caused an increase in dry matter production, but recompaction by cattle traffic caused the bulk density to

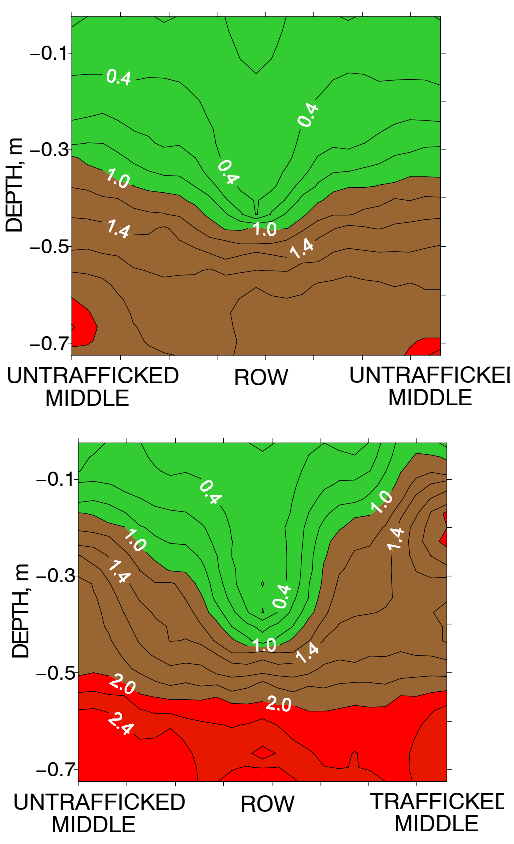

Figure 1. Cone index isoprofiles (MPa) showing the effect of annual in-row subsoiling <u>without</u> traffic (top) and <u>with</u> traffic (bottom) (Raper et al., 1998).

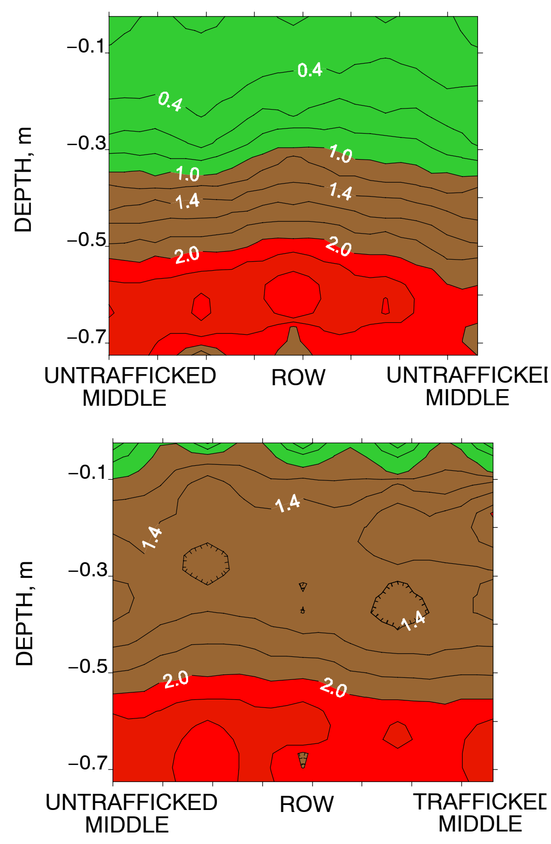

Figure 2. Cone index isoprofiles (MPa) showing the effect of the complete disruption conducted 5 years earlier <u>without</u> traffic (top) and <u>with</u> traffic (bottom) (Raper et al., 1998).

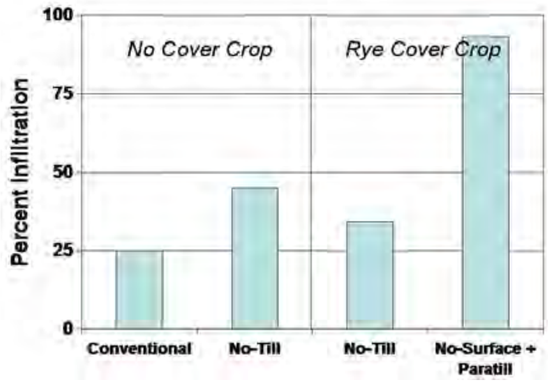

Figure 3. Percent infiltration measured during the second hour of rainfall infiltration studies on a silt loam soil in Alabama with and without cover crops (Truman et al., 2003).

return to values similar to those measured prior to renovation treatments.

Baumhardt and Jones (2002) conducted a study on a semi-arid clay loam soil in Texas where they evaluated the effect of non-inversion subsoiling on soil strength. They found decreased cone index and bulk density. Stubble-mulch tillage conducted following Paratill™ subsoiling diminished the benefits afforded to cone index and bulk density in this study.

One of the major reasons to subsoil is to extend rooting depth into the soil profile where soil moisture is more readily available. However, if moisture is made available to the plants by other means (irrigation or frequent rainfall) it is possible that subsoiling will have little effect. This hypothesis was verified in a study conducted by Camp and Sadler (2002) examining a sandy loam Coastal Plains soil. They found that irrigation increased corn yields all years between 8% and 135% while subsoiling increased yield in only two years by 4% to 6%.

Coates (1997) also studied the effects of subsoiling and irrigation in a silt loam soil in Arizona. Subsoiling was conducted with a triplex subsoiler following a cotton stalk puller. Neither plant counts nor crop yields were affected by subsoiling when the field was irrigated.

Increasing Effectiveness and Reducing Costs of In-Row Subsoiling

As illustrated by the previous studies, subsoiling is a valuable tillage practice that has proven effective to reduce soil compaction, increase infiltration, reduce runoff, and increase crop yields on some soil types. These benefits are usually afforded to soil and plants managed in conventional or conservation systems. However, the use of subsoiling in conservation systems requires that extra measures be taken to reduce soil disturbance and maximize residue coverage. The choice of shank and choice of tillage depth may prove of extreme importance in making decisions about whether or not subsoiling is a viable option for conservation systems. Particularly with higher fuel prices that producers must now pay, the cost of subsoiling should be minimized using every method available.

Reducing Energy through Shank Alignment and Controlled Traffic

Currently, subsoiling is practiced on a routine basis throughout the world. Many soils respond positively to subsoiling, with yield improvements normally being found. Tillage tools used for subsoiling vary widely and result in differences in residue remaining on the soil surface, draft force requirements, and belowground soil disruption. However, when soils are managed using controlled traffic systems that segregate vehicle traffic to certain areas of the field and rows are also kept within very close proximity of previous rows, in-row subsoiling may have longer lasting effects. Also, in-row subsoiling conducted in conjunction with controlled traffic may take reduced amounts of energy as compared to in-row subsoiling conducted in zones of the field where traffic may have been conducted or where the soil had not been previously loosened.

Raper et al. (2005b) used an RTK automatic-steering system that maintained vehicle traffic and in-row subsoiling treatments to within 2 to 3 cm accuracy to compare four subsoiler treatments in a 4-year experiment in a silt loam soil in Alabama. The subsoil treatments compared were: (1) no-till, (2) KMC in-row subsoiler, (3) Paratill™, and (4) Terratill™. The Paratill™ and Terratill™ were manufactured by Bigham Brothers Inc. (Lubbock, Tex.). The depth of subsoiling was set to be 0.33 m because the depth of compaction was found at a slightly shallower depth of 0.30 m. Autumn subsoiling was conducted in varied years to allow comparisons to be made between none, annual, biennial, and triennial treatments all in the same year. A rye cover crop was also used for all plots due to the tremendous success realized in previous experiments with this cropping practice. Results obtained in 2003 showed that annual subsoiling (22.6 kN) reduced draft forces compared to biennial subsoiling (24.9 kN; $P \le 0.002$) and triennial subsoiling (26.9 kN; $P \le 0.001$). Biennial subsoiling was also found to differ significantly from triennial subsoiling ($P \le 0.007$) (fig. 4). These results verify the results of Threadgill (1982) and Busscher et al. (1986) which advocated subsoiling on an annual basis to remove soil compaction and to improve crop yields.

From Raper et al. (2005b), we recognize that there is a 9% improvement in annual in-row subsoiling draft forces as compared to biennial in-row subsoiling or a 16% improvement in annual in-row subsoiling draft forces as compared to triennial in-row subsoiling (table 1). Using several conserva-

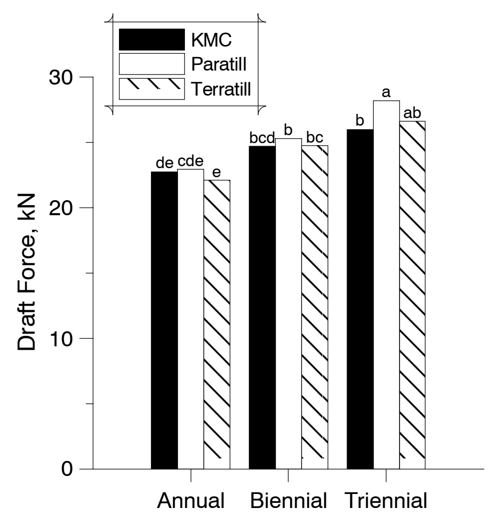

Figure 4. Draft forces for 2003 showing differences in subsoiling implements and subsoiling frequency. Letters were used to indicate statistical differences ($LSD_{0.1}$) (Raper et al., 2000b).

tive assumptions, we can estimate the amount of fuel that could be conserved by proper subsoiler selection. These assumptions include: (1) JD 8310 tractor used for in-row subsoiling operation capable of delivering 133-kW drawbar power, (2) 4-shank Paratill™ subsoiler with 1-m row spacing, and (3) 8-km/h in-row subsoiling speed. Based on these assumptions and data obtained from the Nebraska Tractor Testing Facility for the JD 8310 tractor (Leviticus et al., 1995), the total amount of fuel estimated to be used for fourshanks of the maximum draft force (13.14 kN) found by Raper (2005) was 36.07 L/h (table 1). Assuming the conservative value of a 9% improvement in draft forces from the use of controlled traffic and proper shank alignment, estimations can be made using previously discussed procedures that indicate a reduction in 6% in fuel usage. The total cost of subsoiling would be reduced to $32.98/ha based on fuel savings of $0.54/ha.

REDUCING ENERGY THROUGH TIMING OF SUBSOILING

Soil strength varies considerably with moisture content. Likewise, the energy required for subsoiling also varies substantially with varying moisture content. Targeting the moisture content when soil strength is minimal could provide for decreased subsoiling energy.

Raper and Sharma (2004) evaluated the effect of moisture content on subsoiling energy and soil disruption on a sandy loam soil in a soil bin at the USDA-ARS National Soil Dynamics Laboratory in Auburn, Alabama. Subsoiling was conducted with two different shanks: a Deere & Co. straight shank used on the John Deere 955 row crop ripper and a Deere minimum-tillage shank used on the John Deere 2100 minimum-till ripper. The depth of operation was 0.33 m. Four different soil moisture contents were used in this experiment with two representing extremes: 'wet' soil moisture being a fully saturated condition (11.2% gravimetric), and the 'very dry' soil moisture containing only hygroscopic water (6.1% gravimetric). Two intermediate soil moisture conditions were also included in the study: moist (9.9% gravimetric) and dry (6.5% gravimetric). Results from this experiment showed that the draft and vertical subsoiling forces obtained from the 'very dry' soil condition were the largest (fig. 5). However, this 'very dry' soil condition also produced the largest amount of above-ground disruption. The optimum soil condition for subsoiling occurred at the next soil moisture condition, which was dry. At the 'dry' soil moisture level, the draft forces were reduced by 25% to 32% which were not statistically different than any of the other soil moisture levels except for the 'very dry' soil moisture condition. The

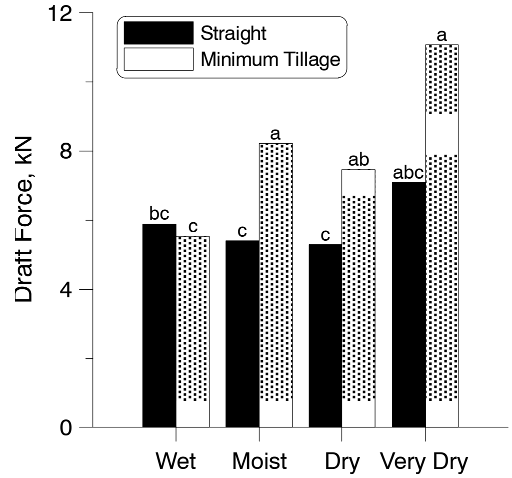

Figure 5. Draft force for a straight and a minimum-tillage shank used in a Norfolk sandy loam soil. Letters were used to indicate statistical differences ($LSD_{0.1}$) (Raper and Sharma, 2004).

above-ground disruption was also reduced by 13% at this 'dry' soil condition as compared to the 'very dry' soil moisture level. The minimum-tillage subsoiler shank was found to require on average 33% increased draft force over the straight shank. However, the minimum-tillage shank was also found to reduce surface disturbance on average by 13%.

Assuming an average 28% reduction in draft force based on the results from Raper and Sharma (2004), estimations can be made using previously discussed procedures that indicate an additional reduction in 19% in fuel usage for proper moisture content and for a cumulative total of 25% savings in fuel usage using all previously suggested fuel-saving strategies (table 1). The total cost of subsoiling would be further reduced to $31.52/ha based on the additional fuel savings of $1.46/ha.

REDUCING DRAFT FORCE THROUGH SHANK SELECTION

The shape and use of subsoiler shanks can vary greatly for conservation systems. Nichols and Reaves (1958) studied several shapes of subsoilers in the soil bins of the USDA-ARS National Soil Dynamics Laboratory (NSDL) in Alabama (fig. 6). The shape of the subsoilers ranged from a straight configuration to a deeply curved configuration. Their research indicated that subsoilers with the most curvature required the least amount of energy. They also indicated similar amounts of soil breakup for all tool shapes. However, other experiments in sandy loam soils found that straight shanks

Table 1. Estimated draft force reductions, fuel usage, fuel savings, and subsoiling costs when appropriate conservation measures are taken.

	Estimated Draft Force (kN)		Fuel Usage (L/h)			Calculated Subsoiling Cost ($/ha)
	Percent Reduction	Cumulative Estimate[a]	Total Used	Savings (%)[b]	Cumulative Savings (%)	
Worst-case	---	52.56	36.07	---	---	33.52
Shank alignment/controlled traffic	9	47.83	33.75	6	6	32.98
Proper soil moisture	28	34.44	27.07	19	25	31.52
Efficient shank selection	32	23.42	21.46	15	40	30.53
Reduced tillage depth	41	13.82	16.54	14	54	29.79

[a] The cumulative entries take into account the savings or reduction in draft force/fuel use from the entries above it.
[b] Economic estimates of fuel savings and costs are dependent on the assumptions made. Changes in tractor or implement used, row spacing, speed of operation and frequency will affect estimates. For example, an increase (decrease) in row spacing will decrease (increase) the estimated cost as less (more) passes over the field with a subsoiler are required.

mounted at an inclination to the vertical gave reduced draft measurements compared to a curved subsoiler.

One limitation that curved shanks have is that they are designed to operate at a single depth (fig. 7) while inclined shanks are equally effective at all depths (Gill and Vanden Berg, 1966). Considering the concept of site-specific subsoiling which may require subsoilers to operate at different depths, Raper (2005) conducted an experiment to compare straight and curved subsoilers operating at depths of 0.23, 0.30, and 0.38 m in a sandy loam soil and a clay loam soil in the soil bins of the NSDL. He determined that the angled shank took 7% to 16% less force in the sandy loam soil and 7% to 14% less force in the clay loam soil.

As a follow up experiment, Raper (2004) conducted an experiment in a loamy sand soil using three shanks: the Paratill™, the TerraMax™, and the KMC 45° subsoiler. Depths of subsoiling were 0.2, 0.3, and 0.4 m. The results from this experiment showed that near the soil surface, the KMC subsoiler reduced bulk density better than the other shanks while at deeper depths, the Paratill™ excelled in loosening the soil profile. Reduced subsoiling forces were found for reduced depths of subsoiling but no differences in draft were found for the different implements. Greater surface disruption was found for the KMC subsoiler. Increased belowground disruption was found with the Paratill™ than with the TerraMax™ or the KMC subsoiler.

Raper (2002) compared several shanks in the sandy loam soil and clay loam soil bins at the NSDL in Alabama to evaluate surface and belowground disturbance as well as differences in draft and vertical forces (fig. 8). Seven shanks were tested: (1) Deere & Co. straight shank (32 mm thick) and is currently used on the John Deere 955 Row Crop Ripper with a narrow point of 70 mm (SDN), (2) same Deere & Co. shank with a wide 178-mm point (SDW), (3) a KMC shank with an angle of 45° (SK45), (4) a KMC shank with a more passive angle of 15° and a flexible wing attached to the rear of the shank (SK15W), (5) a KMC shank with an angle of 45° and a flexible wing attached to the rear of the shank (SK45W), (6) a Paratill™ (BBP), (7) a Terratill™ (BBT), and (8) a Worksaver TerraMax™ (Litchfield, Ill.) (BWT). The first five shanks were straight but angled with the horizontal while the last three shanks were of bentleg design. The tillage depth was 0.33 m for all shanks. Contrary to popular opinion, the results showed that the bentleg shanks had the lowest draft requirements with the KMC shank at a 45° (SK45) also requiring minimal values of draft force (table 2). The largest belowground disruption was caused by the Deere shank with the wide point. The minimum aboveground disruption was caused by the Paratill™ and TerraMax™ shanks.

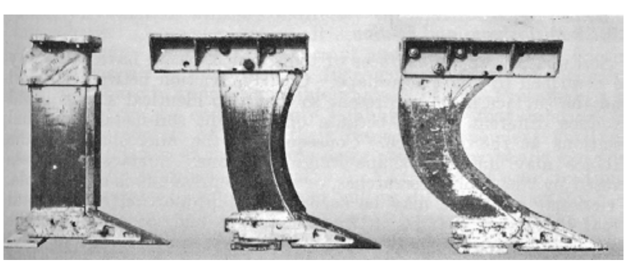

Figure 6. Subsoiler shanks used in studies to evaluate the effect of curvature on subsoiling forces (Nichols and Reaves, 1958).

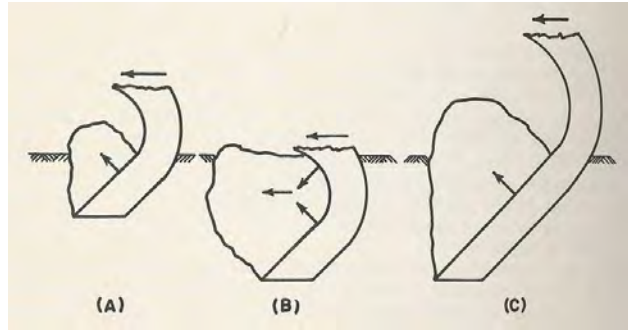

Figure 7. Subsoiling depth effect on soil disruption caused by curved subsoilers. Shallow subsoiling with appropriate curvature (A), deep subsoiling with curvature too depth to reduce forces (B), and deep subsoiling with appropriate curvature (C) (Gill and Vanden Berg, 1966).

Based on the soil bin experiments, savings in draft force between 27% and 37% can be achieved by appropriate selection of subsoiler (Raper, 2005). If we assume an average savings value of 32%, estimations can be made using previously discussed procedures that indicate an additional reduction in 15% in fuel usage for proper moisture content and for a cumulative total of 40% savings in fuel usage using all previously suggested fuel saving strategies (table 1). The total cost of subsoiling would be further reduced to $30.53/ha based on the additional fuel savings of $0.99/ha.

Reducing Draft Force through Reducing Tillage Depth

Another aspect of subsoiling is to target the depth of subsoiling to the depth of compaction. Subsoiling at depths greater than necessary requires significant additional tillage energy and may reduce crop yields while disrupting exces-

Figure 8. Bentleg shanks (lower) and angled shanks (upper two rows) that were used in soil bin experiment at NSDL in Auburn, Ala. (Raper, 2002).

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

	Draft Force (kN)[a]	Aboveground Disruption Cross-sectional Area ($m^2 \times 10^{-3}$)	Belowground Disruption Cross-sectional Area ($m^2 \times 10^{-3}$)
Norfolk sandy loam soil			
SDW	8.72 ac[b]	43.5 a	105.7 a
SDN	9.25 a	35.9 b	74.8 b
SK45W	7.77 cd	32.4 bc	74.6 b
SK15W	8.99 a	33.3 bc	88.5 b
SK45	8.02 bc	36.0 b	82.4 b
BBP	5.85 f	30.0 c	88.0 b
BBT	7.22 de	34.8 b	88.1 b
BWT	6.72 e	28.8 c	80.3 b
Decatur clay loam soil			
SDW	13.14 a	53.1 a	127.8 a
SDN	11.58 abc	46.7 b	112.2 b
SK45W	12.79 ab	45.0 bc	110.9 bc
SK15W	12.29 ab	42.7 bcd	92.5 d
SK45	10.20 cd	39.9 de	94.6 d
BBP	10.15 cd	36.3 e	102.8 bcd
BBT	11.08 bcd	41.6 cd	95.8 cd
BWT	9.65 d	39.7 de	107.5 bcd

[a] Shaded zones indicate the statistically best shanks for each parameter (from Raper, 2002).
[b] Letters indicate LSD statistical differences at the 0.10 level.

sive amounts of crop residue remaining on the soil surface. Also, loosening the soil to greater depths than necessary can promote deeper compaction from vehicle traffic in future years.

Raper et al. (2000a) conducted an experiment that examined subsoiling depth, when subsoiling was conducted, and the use of a cover crop to combat compaction in a silt loam soil in Alabama. Preliminary soil strength measurements determined that the depth of the root-impeding layer was found at depths of 0.1 to 0.15 m. Therefore, shallow subsoiling was conducted just below the root-impeding layer with an experimental Yetter (Colchester, Ill.) implement to a depth of 0.18 m. A deeper subsoiling depth was also conducted to a depth of 0.33 m. Subsoiling treatments were conducted either in autumn after harvest or in the spring prior to planting. In addition, half of the plots were planted in a rye cover crop and the main cash crop was cotton. Results from this experiment showed that soil strength was reduced by the subsoiling treatments to their depth of operation. Spring subsoiling was most effective in reducing soil compaction throughout the growing season as compared to subsoiling conducted almost 12 months earlier. They found that subsoiling conducted to a depth of 0.18 m took 50% less energy than subsoiling conducted to a depth of 0.33 m. They also found that in 3 of the 4 years of the experiment, the highest yields in the plots were found with the shallow subsoiling treatment combined with the use of a cover crop. The concept of only supplying the necessary depth of subsoiling to the depth of compaction proved to be the best solution for obtaining maximum yields in this soil type.

In some cases, totally eliminating the use of a subsoiler may prove to be the best option. In the same experiment as previously discussed, Raper et al. (2000b) found that one of the most significant results of this experiment was that the use of a cover crop almost eliminated excessive soil strength in the soil profile during the growing season and increased cotton yields compared to no-tillage (fig. 9). Increased soil moisture was found in the plots with cover crops due to increased infiltration and proper termination of cover crop growth in the spring prior to planting. Even though significant soil compaction was measured prior to starting the study, the use of a subsoiler proved to not significantly increase yields over the use of a cover crop.

In a different soil type with an extremely variable soil, Raper et al. (2005a) conducted an experiment in a field located in southern Alabama over four years to evaluate whether the concept of site-specific subsoiling (tilling just deep enough to eliminate the hardpan layer) would reduce tillage draft and energy requirements and/or reduce crop yields. An initial set of soil strength measurements indicated that the depth of hardpan present in this field was extremely variable, but could be split into three distinct depth ranges; 0.15 to 0.25 m, 0.25 to 0.35 m, and 0.35 to 0.45 m. Subsoiling

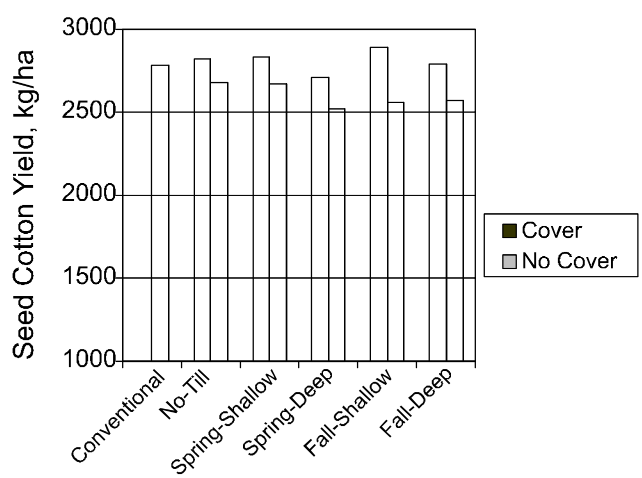

Figure 9. Seed cotton yields showing the benefits afforded by the use of cover crops (Raper et al., 2000b).

treatments were conducted using a John Deere 955 Row Crop Ripper equipped with 7-cm wide LASERRIP™ Ripper Points. A cover crop was also used to determine if similar benefits found in the silt loam soil in north Alabama would also be found in central Alabama on the Coastal Plains soil. Results from this study showed that similar corn yields were produced by site-specific subsoiling and by uniform deep subsoiling (fig. 10). Both of these subsoiling treatments yielded greater than the no subsoiling treatment. The cover crop did not affect corn yield. In the shallow (0.25 m) and medium (0.35 m) hardpan soil condition, draft force was reduced by 55% and 28%, respectively, using site-specific subsoiling compared to uniform deep subsoiling at 0.45 m. In the shallow (0.25 m) and medium (0.35 m) hardpan soil condition, drawbar power was reduced by 47% and 17%, respectively, by site-specific subsoiling as compared to uniform deep subsoiling at 0.45 m.

Draft force was reduced by an average of 41% in the shallow and medium hardpan soil conditions which were the predominant soil conditions in the 8-ha field that was investigated by Raper et al. (2005a). Using the same assumptions and procedures as were previously used to estimate fuel savings from proper in-row subsoiler shank selection, an additional 14% savings in fuel usage could be realized by the use of site-specific subsoiling for a cumulative total of 54% savings in fuel usage (table 1). The total cost of subsoiling would be further reduced to $29.79/ha based on the additional fuel savings of $0.74/ha.

Summary

The literature is replete with studies that indicate that in-row subsoiling is a valuable production practice that can loosen compacted soil profiles, increase infiltration, reduce runoff, and in most cases also increase crop yield. However,

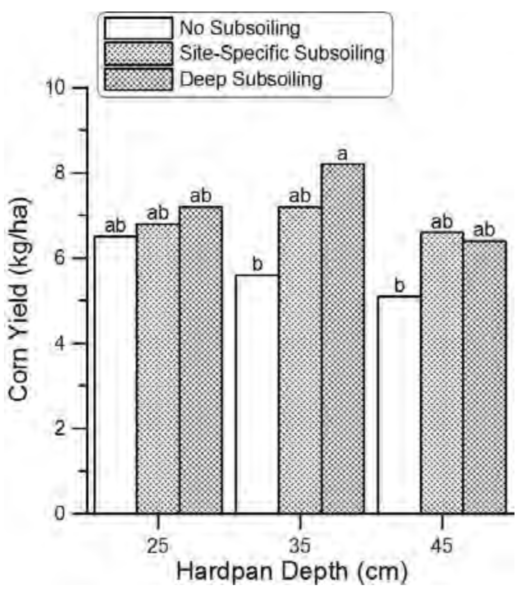

Figure 10. Corn yield from site-specific subsoiling experiment conducted in Alabama on Coastal Plains soil. Letters were used to indicate statistical differences ($LSD_{0.1}$) (Raper et al., 2005a).

subsoiling does require a significant amount of energy to disrupt compacted soil profiles. Every opportunity should be used to examine where savings can be found during the subsoiling operation. Several methods can be employed to reduce the amount of energy required to subsoil in conservation systems. These include the following:

- Use controlled traffic concepts to ensure alignment of rows and subsoiled zones. It is estimated that draft savings of 9% and fuel savings of 6% can be achieved with this suggestion.
- Subsoil only when the soil is not in an extremely dry state. This prevents excessive energy requirements and surface soil disruption. It is estimated that draft savings of 28% and fuel savings of 19% can be achieved with this suggestion.
- Selecting inclined shanks or bentleg shanks that minimize energy requirements while minimally disturbing the soil surface and are equally efficient at various depths of operation. It is estimated that draft savings of 32% and fuel savings of 15% can be achieved with this suggestion.
- Only subsoil to the depth necessary to remove soil compaction. Subsoiling deeper than necessary wastes energy while potentially reducing crop yield. Southeastern U.S. fields are especially variable and knowledge about the field's variability can allow shallower subsoiling depths to be used in certain areas of the field. It is estimated that draft savings of 41% and fuel savings of 14% can be achieved with this suggestion.
- The four energy and fuel saving strategies suggested by the authors can assist with reducing the fuel necessary for subsoiling by as much as 54% using cost information from 2005. The fuel portion of the cost of subsoiling is approximately 25% without energy-saving strategies but can be reduced to approximately 16% of the total cost of subsoiling. The estimated cost of in-row subsoiling can be reduced from $33.52/ha to $29.79/ha which is a savings of $3.73/ha.

Even though it is possible to subsoil a field to remove compaction, care should be exercised before this potentially expensive operation is performed. Once soil is subsoiled, it easily recompacts if traffic is applied in the same area. Research indicates that two passes of a tractor in the subsoiled area will cause the soil to return to its previous state prior to subsoiling (Blackwell et al., 1989). If traffic is controlled, however, the benefits of subsoiling can be long-lasting and beneficial to crops and soil.

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