

## **IN-ROW SUBSOILING SOUTHEASTERN SOILS TO REDUCE COMPACTION AND IMPROVE CROP YIELDS**

Randy L. Raper<sup>1\*</sup>

<sup>1</sup>USDA-ARS, National Soil Dynamics Laboratory, 411 S. Donahue Dr. Auburn, AL 36832

\*Corresponding author's e-mail address: rlraper@ars.usda.gov

### **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 U.S. 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. These methods include: proper selection of subsoiler shanks, appropriate selection of subsoiler depth, appropriate selection of soil moisture for subsoiling, reducing frequency of subsoiling, and consideration of other methods of compaction reduction, including the use of a cover crop. Use of these methods should allow in-row subsoiling to continue to be a valuable part of conservation agricultural systems.

### **INTRODUCTION**

Soil compaction was only widely recognized as a possible limitation to crop yields in the early 1900's when large agricultural vehicles began to be used for agricultural production and compaction was more easily visualized due to vehicle rutting. Producers began to notice that reduced crop growth was sometimes found in the rutted areas of the field. 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 visualized 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 tending to completely 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 outweighed 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.

Subsoiling is defined as tillage below depths of 35 cm (ASAE Standards, 1999). Soils compacted from traffic or with naturally occurring soil compaction often benefit greatly from subsoiling with larger pores being created that increase rooting and infiltration. The ability of a soil to benefit from subsoiling depends upon many factors including soil type, soil management, vehicle management, etc. Much research has been conducted that has shown evidence about the overall benefit of subsoiling. However, some research has also been conducted that has shown no overall positive benefits to crop productivity. Reasons for discrepancies in these research results on subsoiling consist of differences in equipment, different climatic regions, cropping systems, 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. Conservation systems emphasize maximizing crop residue on the soil surface at the time after subsoiling has been conducted. Maximizing the amount of crop residue on the soil surface includes 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.

Therefore, the objective of this report is to examine the pertinent literature on subsoiling that has been conducted in the Southeastern U.S. and to point to opportunities to increase the effectiveness of subsoiling while minimizing the cost of the operation.

### **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 some soils in the Southeast that might contain toxic levels of soluble aluminum in the acid subsoils would not benefit from deep tillage as deeper rooting would not prove beneficial. 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 0.36-0.38 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 0.5-0.6 m. One year following subsoiling, the evidence of the previous year's tillage was found, but the soil strength had increased to levels of 1.5-2.5 MPa which were root-limiting. They advised that annual subsoiling was a mainstay of all cropping systems in the Southeastern Coastal Plain.

Touchoon 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 0.200-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.

In a later study, Busscher et al. (1988) studied in-row subsoiling on a loamy sand in South Carolina for two years. They used three subsoilers to unspecified depths: Brown-Harden Super Seeder<sup>1</sup> (Ozark, AL), Tye Paratill™ (currently manufactured by Bigham Brothers Inc., Lubbock, TX), 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 0.14-0.21-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, a sandy loam soil and a sandy clay loam 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 of the year in a clay soil in Mississippi. Subsoiling was conducted after harvest with a parabolic

---

<sup>1</sup>The use of company names or tradenames does not indicate endorsement by USDA-ARS.

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 of 73-132% as 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 a 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 evaluate 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, IL) 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. The advantages normally attributed to controlled traffic did not materialize due to the annual disruption of 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.

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 also found with these two subsoiling treatments thus contributing to the increased 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 hour time periods. They concluded that no-till /Paratill™/rye plots had 34% to tenfold less runoff than from other tillage systems, while conventional-till plots had 1.5 to 5.4-fold times more soil loss than from other tillage systems. Subsoiling as conducted with the Paratill™ had more influence on runoff and soil loss than did surface cover 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 and reduce 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, TX) 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 return to values similar to those measured prior to renovation treatments.

Baumhardt and Jones (2002) conducted a study on a semiarid 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 8-135% while subsoiling increased yield in only two years by 4-6%.

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 selection**

The shape and use of subsoiler shanks can vary greatly for conservation systems. Nichols and Reaves (Nichols and Reaves, 1958) studied several shapes of subsoilers in the soil bins of the USDA-ARS National Soil Dynamics Laboratory (NSDL) in Alabama. 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 (Upadhyaya et al., 1984) found that straight shanks 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 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 7-16% less force in the sandy loam soil and 7-14% less force in the clay loam soil.

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. Seven shanks were tested: (1) Deere and 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, (2) same Deere and Co. shank with a wide 178 mm point, (3) a KMC shank with an angle of 45°, (4) a KMC shank with a more passive angle of 15° degrees, (5) a KMC shank with an angle of 45° and a flexible wing attached to the rear of the shank, (6) a Paratill™, (7) a Terratill™, and (8) a Worksaver TerraMax™ (Litchfield, IL). 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. The results surprisingly showed that the bentleg shanks had the lowest draft requirements with the KMC shank at a 45° also performing quite well. 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.

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.

### **Reducing energy 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 covering excessive amounts of crop residue remaining on the soil surface. Also, loosening the soil to greater depths than necessary can promote future deeper compaction resulting from vehicle traffic.

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 0.1-0.15 m. Therefore, shallow subsoiling was conducted just below the root-impeding layer with an experimental Yetter (Colchester, IL) 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. Half of the plots also were planted in a rye cover crop with the main cash crop being 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. 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; 0.15-0.25 m, 0.25-0.35 m, and 0.35-0.45 m. Subsoiling 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. 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. Site-specific subsoiling also reduced estimated fuel use by 43% for the 0.25-m hardpan depth plots and 24% for the 0.35-m hardpan depth plots.

### **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 in Alabama. Subsoiling was conducted with two different shanks: a Deere and 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. Results from this experiment showed that the draft and vertical subsoiling forces obtained from the 'very dry' soil condition were the largest. 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 but was not hygroscopic in nature. At the 'dry' soil moisture level, the draft forces were reduced by 25-32% which were not statistically different than any of the other soil moisture levels except for the 'very dry' soil moisture condition. The 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%.

### **Reducing energy through reduced frequency of use**

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.

Raper et al. (2005b) compared 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, TX). 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 showed that annual subsoiling reduced bulk density and draft force as compared to all other treatments. The KMC subsoiler required the minimum draft force, followed by the Paratill™ and the Terratill™. The KMC subsoiler also maintained the loosest soil environment for the longest period of time with the Paratill™ reconsolidating within 3 years to bulk density values similar to no-till. Cotton yields did not show any improvement from any of the three subsoiling treatments with optimum yields being produced with no subsoiling and a rye cover crop.

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. However, using a cover crop may replace the need for in-row subsoiling on a silt loam soil if compaction is effectively managed.

### **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, 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:



- 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.
- Only subsoil to the depth necessary to remove soil compaction. Subsoiling deeper than necessary wastes energy while potentially reducing your crop's yield.
- Adjusting subsoiling depth based on the soil's needs. 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.
- Consider whether subsoiling can be totally eliminated due to the use of a cover crop which can increase soil moisture to the point that excessive soil strength is not a problem.
- Subsoil only when the soil is not in an extremely dry state. This prevents excessive energy requirements and surface soil disruption.
- Reduce frequency of subsoiling in soils where annual subsoiling is not required. Adoption of other conservation strategies can assist with increasing the length of time between subsoiling.

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.

## REFERENCES

- ASAE Standards, 45th Edition. 1999. EP291.2: Terminology and definitions for soil tillage and soil-tool relationships. St. Joseph, Mich.: ASAE.
- Baumhardt, R.L., and O.R. Jones. 2002. Residue management and paratillage effects on some soil properties and rain infiltration. *Soil Till. Res.* 65(1-2):19-27.
- Blackwell, P.S., N.S. Jayawardane, J. Blackwell, R. White, and R. Horn. 1989. Evaluation of soil recompaction by transverse wheeling of tillage slots. *Soil Sci. Soc. Am. J.* 53(1):11-15.
- Box, J., and G.W. Langdale. 1984. The effects of in-row subsoil tillage and soil water on corn yields in the Southeastern coastal plain of the United States. *Soil Till. Res.* 4(1):67-78.
- Busscher, W.J., and P.J. Bauer. 2003. Soil strength, cotton root growth, and lint yield in a southeastern USA coastal loam sand. *Soil Till. Res.* 74(2):151-159.
- Busscher, W.J., D.L. Karlen, R.E. Sojka, and K.P. Burnham. 1988. Soil and plant response to three subsoiling implements. *Soil Sci. Soc. Am. J.* 52:804-809.
- Busscher, W.J., R.E. Sojka, and C.W. Doty. 1986. Residual effects of tillage on Coastal Plain soil strength. *Soil Sci.* 141:144-148.
- Camp, C.R., and E.J. Sadler. 2002. Irrigation, deep tillage, and nitrogen management for a corn-soybean rotation. *Trans. ASAE* 45(3):601-608.
- Campbell, R.B., D.C. Reicosky, and C.W. Doty. 1974. Physical properties and tillage of Paleudults in the southeastern Coastal Plains. *J. Soil Water Cons.* 29(5):220-224.
- Clark, R.L., D.E. Radcliffe, G.W. Langdale, and R.R. Bruce. 1993. Soil strength and water infiltration as affected by paratillage frequency. *Trans. ASAE* 36(5):1301-1305.
- Coates, W. 1997. Minimum tillage systems for irrigated cotton: is subsoiling necessary? *Applied Eng. Agric.* 13(2):175-179.

- Gill, W.R., and G.E. Vanden Berg. 1966. Design of tillage tools. In *Soil dynamics in tillage and traction*, pp. 211-297. W. R. Gill, and G.E. Vanden Berg, ed. Auburn, AL.: USDA.
- Mullins, G.L., C.H. Burmester, and D.W. Reeves. 1997. Cotton response to in-row subsoiling and potassium fertilizer placement in Alabama. *Soil Till. Res.* 40(3-4):145-154.
- Nichols, M.L., and C.A. Reaves. 1958. Soil reaction: to subsoiling equipment. *Agr. Eng.* 39(6):340-343.
- Raper, R.L. 2002. Force requirements and soil disruption of straight and bentleg subsoilers for conservation tillage systems. ASAE Paper No. 02-1139. St. Joseph, Mich.: ASAE.
- Raper, R.L. 2004. Selecting subsoilers to reduce soil compaction and minimize residue burial. In *Proc. Session IV of 2004-CIGR International Conference*, 135-143. Beijing, China.
- Raper, R.L. 2005. Subsoiler shapes for site-specific tillage. *Applied Eng. Agric.* 21(1):25-30.
- Raper, R.L., D.W. Reeves, C.H. Burmester, and E.B. Schwab. 2000a. Tillage depth, tillage timing, and cover crop effects on cotton yield, soil strength, and tillage energy requirements. *Applied Eng. Agric.* 16(4):379-385.
- Raper, R.L., D.W. Reeves, and E. Burt. 1998. Using in-row subsoiling to minimize soil compaction caused by traffic. *J. Cotton Sci.* 2(3):130-135.
- Raper, R.L., D.W. Reeves, E. Burt, and H.A. Torbert. 1994. Conservation tillage and traffic effects on soil condition. *Trans. ASAE* 37(3):763-768.
- Raper, R.L., D.W. Reeves, E.B. Schwab, and C.H. Burmester. 2000b. Reducing soil compaction of Tennessee Valley soils in conservation tillage systems. *J. Cotton Sci.* 4(2):84-90.
- Raper, R.L., D.W. Reeves, J.N. Shaw, E. vanSanten, and P.L. Mask. 2005a. Using site-specific subsoiling to minimize draft and optimize corn yields. *Trans. ASAE* 48(6):2047-2052.
- Raper, R.L., E.B. Schwab, K.S. Balkcom, C.H. Burmester, and D.W. Reeves. 2005b. Effect of annual, biennial, and triennial in-row subsoiling on soil compaction and cotton yield in Southeastern U.S. silt loam soils. *Applied Eng. Agric.* 21(3):337-343.
- Raper, R.L., and A.K. Sharma. 2004. Soil moisture effects on energy requirements and soil disruption of subsoiling a coastal plains soil. *Trans. ASAE* 47(6):1899-1905.
- Reicosky, D.C., D.K. Cassel, R.L. Blevins, W.R. Gill, and G.C. Naderman. 1977. Conservation tillage in the Southeast. *J. Soil Water Cons.* 32(1):13-19.
- Schwab, E.B., D.W. Reeves, C.H. Burmester, and R.L. Raper. 2002. Conservation tillage systems for cotton in the Tennessee Valley. *Soil Sci. Soc. Am. J.* 66(2):569-577.
- Self-Davis, M.L., M.S. Miller, R.L. Raper, and D.W. Reeves. 1996. Pasture soil and vegetation response to renovation tillage. In *Proc. 19th Annual Southern Conservation Tillage Conference on Sustainable Agriculture*, 131-136. Jackson, TN.
- Smith, L.A. 1995. Cotton response to deep tillage with controlled traffic on clay. *Trans. ASAE* 38(1):45-50.
- Threadgill, E.D. 1982. Residual tillage effects as determined by cone index. *Trans. ASAE* :859-867.
- Touchton, J.T., D.H. Rickerl, C.H. Burmester, and D.W. Reeves. 1986. Starter fertilizer combinations and placement for conventional and no-tillage cotton. *J. Fert. Issues* 3:91-98.
- Truman, C., W. Reeves, J. Shaw, A. Motta, C. Burmester, R.L. Raper, and E. Schwab. 2003. Tillage impacts on soil property, runoff, and soil loss variations from a Rhodic Paleudult under simulated rainfall. *J. Soil Water Cons.* 58(5):258-267.
- Tupper, G.R. and H.C. Pringle, III. 1986. New equipment for deep banking dry lime into acid subsoils. In *Proc. Beltwide Cotton Production Research Conf.*, 456-457. Memphis, TN: National Cotton Council of America.
- Upadhyaya, S.K., T.H. Williams, L.J. Kemble, and N.E. Collins. 1984. Energy requirements for chiseling in coastal plain soils. *Trans. ASAE* 27(6):1643-1649.
- Wesley, R.A., and L.A. Smith. 1991. Response of soybean to deep tillage with controlled traffic on clay soil. *Trans. ASAE* 34(1):113-119.