The Economic Benefit of Improving the Proximity of Tillage and Planting Operations in Cotton Production with Automatic Steering

J. S. Bergtold, R. L. Raper, E. B. Schwab

Abstract. *Producers in the Coastal Plain of the southeastern United States manage soil compaction in conservation tillage systems by in-row subsoiling prior to planting. However, planting directly over the loosened zone of soil can be difficult in high-residue conservation tillage systems where cover crop production is maximized. Tractors with automatic steering capability could assist with placement of deep tillage in close proximity to planting operations, but little is known about the accuracy necessary to maximize rooting development, reduce succeeding soil compaction, and optimize crop production. An experiment was conducted in south-central Alabama to evaluate the distance the cotton row can be from deep tillage and still affect cotton yield and economic performance. Results showed as distance between the planted row and tillage pass increased, seed cotton yields were reduced by as much as 24% to 52% and net revenues from cotton production by as much as 38% to 83%. An economic analysis of on-farm adoption showed that auto-guidance systems with accuracy of less than 2.5 cm may be the most profitable for larger farms, while systems with less than 10-cm accuracy may provide a better economic alternative for smaller farms.*

Keywords. *Cotton yield, Soil compaction, Subsoiling, Auto-guidance, Economics, GPS.*

Automatic steering (auto-guidance) systems for tractors with GPS-based guidance offers farmers the opportunity to reduce operating costs and improve profitability of cropping enterprises. The economic benefits of auto-guidance technology include: the reduction of overlap and skipping of fertilizer and pesticide applications, improved timeliness of operations (e.g. operating at night), accurate establishment of drip irrigation systems, and precision agricultural practices, such as variable rate application of inputs (Lewis, 2003). Gan-Mor and Clark (2001) suggest that using automatic steering systems with GPS guidance and centimeter accuracy to control traffic on farmers' fields can save farmers up to \$22.00 ha^{-1}. In addition, controlling vehicle traffic may reduce or eliminate the need for subsoiling on some soils by minimizing the re-compaction of soils from vehicles crossing the fields (Potter and Chichester, 1993; Raper et al., 2005b).

On the sandy Costal Plain soils of the southeastern United States, soils can compact naturally during the course of the year. Thus, in-row subsoiling or deep tillage may be required annually to alleviate recompaction in soils to avoid reductions in crop yields. Deep tillage disrupts compacted soil profiles in a narrow zone under the row, allowing roots to proliferate downward to obtain adequate soil moisture (Raper, 2005). While cost savings from controlled traffic are reduced with annual in-row subsoiling, passes through the field with farm machinery should be controlled to minimize recompaction of subsoiled areas. Failure to control traffic may cause subsoiled channels to recompact, reducing the effectiveness of subsoiling to protect from reductions in cash crop yields (Raper et al., 2000 and 2005b; Raper and Kirby, 2006). Thus, automatic steering systems with GPS-based guidance may provide the accuracy needed to control in-field operations to maximize the benefit of subsoiling operations (Raper et al., 2008).

High residue conservation tillage systems are becoming an important tool for farmers who want to conserve soil moisture, increase soil organic matter, and improve farm profitability across the southeastern United States. The presence of winter cover crops in these systems helps to alleviate some of the problems associated with soil compaction by improving soil organic matter and structure, as well as soil water infiltration and storage (Raper and Kirby, 2006). However, on sandy Costal Plain soils, annual subsoiling is still likely to be required. These deep tillage operations are commonly implemented between the termination of the cover crop and the planting of the cash crop. During planting, producers attempt to plant directly over the loosened zone created by deep tillage, to maximize crop production. Planting directly in the middle of the loosened zone can be difficult, especially with strip-tillage systems that do little surface disruption and high residue conservation systems that leave the soil surface virtually covered. Tractors with automatic steering capability can assist with the needed placement of deep tillage in close proximity to planting operations, but little is known about the

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accuracy necessary to maximize rooting development, reduce succeeding soil compaction, and maximize returns from crop production. In addition, the cost of auto-steer technology may be prohibitive and escalates rapidly with the increased precision of the auto-guidance system used. A farmer must weigh the benefits of improved accuracy using an auto-guidance system with GPS against the cost of the system in order to make an informed decision concerning the adoption of the technology.

The purpose of this article is to determine the effect on cotton yield and profitability as the proximity of planting operations to deep tillage operations changes. In addition, the economics of adopting alternative automatic steering systems with different levels of accuracy is examined. Experimental data were obtained from an experiment on a Coastal Plain soil with the objective of determining the distance between planted cotton rows to the center of deep tilled zones that would maximize crop production and minimize soil compaction for three tillage operations.

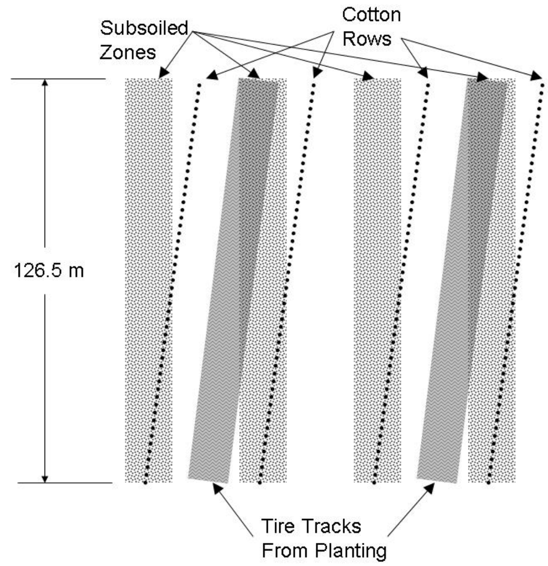

Figure 1. Experimental layout showing how cotton rows were directly on top of subsoiled zones at one end of field and deviated to the row middle at the other end of the field.

Data and Methods

The Experiment and Cotton Yield Data

Yield data were obtained from a three year experiment (2003-2005) initiated in the fall of 2002 at the E.V. Smith Research Station in Shorter, Alabama. The field selected had a pronounced soil hardpan. The soil type was a Compass loamy sand (Coarse-loamy, siliceous, subactive, thermic Plinthic Paleudults) with less than 2% slope. The field was planted with a rye (*Secale cereale* L.) cover crop in the fall of 2002 and all subsequent years. In the spring of each year, deep tillage was implemented after the termination of the cover crop with a John Deere® 8300 tractor (Moline, Ill.) equipped with a Trimble® AgGPS® Autopilot™ RTK system (Sunnyvale, Calif.)which has reported automatic steering accuracy of ±2.5 cm. The John Deere® 8300 tractor was then used to plant cotton (Stoneville 4892 BT/RR) at a slight angle to the deep tillage rows. At one end of the field, the cotton was planted directly over the deep tillage zone and at the other end of the field, the cotton was planted midway between the deep tillage zones (fig. 1).

The field (126.5 m long) was divided perpendicular to the rows into 12 (9.1 m) plots with 11 (1.5 m) borders. This setup resulted in 12 plots with varying ranges of distances between the cotton row and the deep tillage area (row proximity distance) enabling the evaluation of row proximity (to tillage) on cotton yield and profitability. The midpoints (range) of the row proximity distances examined in each plot were 0.6 cm (-1.3 to 1.9 cm), 5.1 cm (3.2 to 6.4 cm), 9.5 cm (7.6 to 10.8 cm), 14.0 cm (12.1 to 15.2 cm), 18.4 cm (16.5 to 19.7 cm), 22.9 cm (21.0 to 24.1 cm), 27.3 cm (25.4 to 28.6 cm), 31.8 cm (29.8 to 33.0 cm), 36.2 cm (34.3 to 37.5 cm), 40.6 cm (38.7 to 41.9 cm), 45.1 cm (43.2 to 46.4 cm), and 49.5 cm (47.6 to 50.8 cm).

The study was designed to compare the effect of row proximity of the planted row to in-row subsoiling operations in conservation tillage systems using three deep tillage implements and no tillage as a control. The deep tillage implements used as treatments included a Kelley Manufacturing Company's (Tifton, Ga.) Rip/Strip in-row subsoiler (strip-till), a Bigham Brothers' (Lubbock, Tex.) Paratill® bentleg subsoiler (Paratill), and a Worksaver (Litchfield, Ill.) Terra-Max I® bentleg subsoiler (Terra-Max) (fig. 2). Each tillage treatment (×4) was replicated four times across each of the 12 plots with varying row proximity distances (192 plots). Each plot was four rows wide with 1-m row spacing. The experimental design was a randomized complete block with the four conservation tillage systems as treatments. Row proximity distance was not randomized across the 12 plots within each tillage treatment and replication. Therefore, this variable was treated as a covariate in all statistical analyses in order to capture the heterogeneity between plots with differing row proximity.

Seed cotton yield was collected for evaluation of each of the tillage systems. A John Deere® 9920 cotton picker was used to bag the center two rows of every plot. Relative change in seed cotton yield was calculated as the fractional change in cotton yield for each tillage treatment from the corresponding no-till treatment [i.e. $(Y_{\text{till}} - Y_{\text{no-till}})/(Y_{\text{no-till}})$]. This procedure allowed comparisons of the impact of alternative deep tillage treatments to be made between the various row proximities along the entire length of the field.

Seed cotton yields differed due to climatological differences. In 2003, weather delayed planting until 30 May, delaying harvest until 29 October, adversely affecting cotton boll development and seed cotton yields. Cotton was planted on 5 and 12 May and harvested on 22 September and 1 October for 2004 and 2005, respectively. Damaging rain and winds from Hurricane Ivan reduced seed cotton yields in 2004. Rainfall during the growing season (May to October) was 841 mm in 2003, 689 mm in 2004, and 571 mm in 2005.

Net Revenue Data

The net impact of row proximity and deep tillage on seed cotton yields was evaluated by examining the change in net revenues between the deep tillage and no tillage treatments. Changes in net revenues (*CNR*) were calculated for each deep

(a)

(b)

(c)

Figure 2. Deep tillage implements used in study: (a) Kelley Manufacturing Company's Rip/Strip in-row subsoiler (strip-till); (b) Bigham Brothers' Paratill® bentleg subsoiler (Paratill); and (c) Worksaver Terra-Max I® bentleg subsoiler (Terra-Max).

tillage treatment at the midpoint row proximity distance in each plot, using a partial budgeting equation of the form:

$$CNR = \left(\lambda P_{CL} + (1-\lambda) P_{CS}\right) \cdot \left(Y_{j,d}^{DT} - Y_{d}^{NT}\right) - DTC_{j} - HC \cdot \left(Y_{j,d}^{DT} - Y_{d}^{NT}\right) \quad (1)$$

where

CNR = change in net revenues (\$ ha^{-1});

λ = lint turnout (as a fraction) from harvested seed cotton;

P_{CL} = 2005 spot price for cotton lint in Alabama (\$ kg^{-1});

P_{CS} = 2005 spot price for cotton seed in Alabama (\$ kg^{-1});

$Y_{j,d}^{DT}$ = seed cotton yield for deep tillage treatment j with row proximity d (kg ha^{-1});

Y_{d}^{NT} = seed cotton yield for no tillage treatment with row proximity d (kg ha^{-1});

DTC_j = cost of machinery, fuel and labor for deep tillage treatment j (\$ ha^{-1}); and

HC = cost (savings) of harvesting and processing additional (less) seed cotton (\$ kg^{-1}).

Both variable and fixed costs were included in DTC_j. All prices and costs used for analyses are from 2005 so that production differences and heterogeneity can be examined across years, thereby avoiding differences due to changes in prices of inputs or outputs. Economic data and constants used are presented in table 1.

Statistical Analysis

Statistical analyses of seed cotton yield and change in net revenue data were performed using the mixed model procedure in SAS® (Littell et al., 2006). Mixed analysis of covariance (CANOVA) models were estimated for (i) the relative change in seed cotton yield above no-till (*RCY*) and (ii) the change in net revenues (*CNR*) above no till for each year of the study. Each model had deep tillage treatments as fixed effects and a random effect to capture variation across replications. The covariate in each model was a variable representing the row proximity distance (d) of the planted row to the center of the deep tilled zone. To capture potential nonlinearities, d^2 was included in the model as an additional covariate when found to be statistically significant. Given that the effect of d was assumed to vary across deep tillage treatments, the interaction terms between the fixed effects and covariates were included in the model, as well. Thus, the mixed CANOVA model estimated took the form:

$$Y_{j,k} = \alpha_j + \beta_j \cdot d + \delta_j \cdot d^2 + r_k + \varepsilon_{j,k} \quad (2)$$

where

$Y_{j,k}$ = dependent variable representing *RCY* (fractional change) or *CNR* (\$ ha^{-1});

α_j = intercept (fixed effect) for deep tillage treatment j;

β_j and δ_j = slope coefficients for the j^{th} deep tillage treatment;

d = row proximity distance (cm);

r_k = random effect of replication k, where $r_k \sim N(0, \sigma^2_r)$; and

$\varepsilon_{i,j}$ = independent and identically distributed error term, where $\varepsilon_{i,j} \sim N(0, \sigma^2)$.

Regression functions given by equation 2 were graphed with 95% confidence limits for each deep tillage treatment and year using MATLAB® (MATLAB, 2007).

Table 1. Economic parameters and assumptions.

Output prices	
Cotton lint[a]	$1.09 kg^{-1}
Cotton seed[a]	$0.09 kg^{-1}
Variable costs	
Deep tillage treatments[b]	
Terra-Max	$13.10 ha^{-1}
Paratill	$14.16 ha^{-1}
Strip-Till	$13.94 ha^{-1}
Harvesting/processing seed cotton[c]	$0.22 kg^{-1}
Fixed costs	
Deep tillage treatments[d]	
Terra-Max	$10.11 ha^{-1}
Paratill	$10.55 ha^{-1}
Strip-Till	$10.15 ha^{-1}
Total annualized cost for auto guidance system with GPS[e]	
Trimble- AgGPS- Autopilot™ DGPS	$5090 year^{-1}
Trimble- AgGPS- Autopilot™ HP	$5790 year^{-1}
Trimble- AgGPS- Autopilot™ RTK	$9858 year^{-1}
Economic constants	
Average lint turnout (λ)[f]	0.41
Life span of deep tillage implements[g]	12 years
Life span of auto-guidance systems[h]	5 years
Interest Rate	0.065

[a] Cotton prices are the marketing year average prices received in Alabama in 2005 as reported by the USDA National Agricultural Statistics Service (Agricultural Statistics Board, 2006).

[b] Total variable costs for deep tillage treatments include machinery, fuel and labor costs for the tractor and implement. Costs were estimated from Mississippi cotton budgets (Mississippi State University, 2006). Machinery estimates assumed a six shank implement with 1-m spacing. Labor costs include operator labor, as well as unallocated (and hand) labor estimates. Unallocated labor was determined by multiplying an unallocated labor to machine ratio of 1.25 times machine hours per hectare for each deep tillage implement. Cost estimates differed due to performance rates and repair and maintenance costs.

[c] Harvesting and processing costs include the cost of hauling and ginning of seed cotton (Mississippi State University, 2006).

[d] Total fixed costs were estimated by computing the annual capital recovery charge per hectare (Mississippi State University, 2006). Fixed costs varied due to differences in the purchase price of implements.

[e] The total cost of each auto-guidance system was assumed to include fixed costs, such as the cost of equipment and software ($14,000 for the DGPS and HP; $37,300 for the RTK), auto-steer system equipment for a John Deere 8320 tractor ($3948), and variable costs, such as a yearly service subscription fee ($800 for DGPS, $1500 for HP, and $0 for RTK). Pricing for the auto-guidance systems was obtained from Ag Technologies (Cordele, Ga.) and for the auto-steer system equipment from John Deere (www.deere.com/en_US/deerecom/usa_canada.html) in 2006. It was assumed that the systems have no salvage value. In addition, it was assumed that farmers can purchase the equipment with a simple interest five year loan at a 6.5% interest rate.

[f] The lint parameter, λ, was based on average lint turnout from cotton variety trials from 2003 to 2005 in Shorter, Ala. near the experimental site (Glass et al., 2004, 2005, 2006).

[g] Based on Mississippi estimates (Mississippi State University, 2006).

[h] This time span was used due to potential computer compatibility issues.

The joint significance of the β_j and δ_j terms across deep tillage treatments was tested using a Type III *F* test statistic in SAS® at a significance level of $P \leq 0.10$. The δ_j terms were only found to be statistically significant for the *RCY* mixed CANOVA models in 2003 and all *CNR* mixed CANOVA models. Thus, δ_j was set equal to zero in the *RCY* models estimated using data in 2004 and 2005. The statistical significance of all remaining fixed effects and covariate terms in each regression were tested using t-tests with associated p-values being reported. In addition, model fit was assessed by calculating pseudo R^2 statistics following Magee (1990)using the likelihood ratio. To examine differences across tillage treatments, mean separation comparisons were evaluated using one-way t-tests. Each t-test examined if the least squares mean for treatment *a* was statistically larger than the least squares mean for treatment *b*. All possible combinations of deep tillage treatments were tested for each level of *d* in the model at a significance level of $P \leq 0.10$. All tests were conducted using SAS®.

Economic Analysis

An economic analysis was conducted based on the framework presented by Lewis (2003) to examine if investing in an auto-guidance system with GPS for subsoiling would be profitable. Lewis (2003) mentions that not all producers will benefit from adopting auto-guidance systems, but lower variable costs and higher revenue from additional output from use of the system may exceed the increase in fixed costs from purchasing the system for farms of sufficient size. Thus, there may be a minimum cost-effective acreage at which the auto-guidance system becomes profitable. As the cost and accuracy of auto-guidance systems with GPS change, this base acreage will differ, as well. For the purpose of this study, the minimum cost-effective acreage will be substituted with the minimum cost-effective area of land in hectares (MCEH)

The MCEH is determined at the point where the cost per hectare of the auto-guidance system is equal to the gain in revenue (plus cost reductions) per hectare from using the system. Using a partial budgeting approach:

$$MCEH_{s,k} = \frac{TC_s}{CNR^{\rho}_{s,k}} \tag{3}$$

where

$MCEH_{s,k}$ = minimum cost-effective area of land for auto-guidance system with accuracy *s* and deep tillage treatment *k* (ha);

TC_s = total cost of auto-guidance system with accuracy *s* (variable plus fixed costs) in a given year ($); and

$CNR^{\rho}_{s,k}$ = additional revenue gained by using auto-guidance system with accuracy *s* and deep tillage treatment *k* ($ ha^{-1}).

$CNR^{\rho}_{s,k}$ and in turn $MCEH_{s,k}$ are functions of ρ, the difference in row proximity distance between the accuracy of the tillage operation using the auto-guidance system and that from human error. That is, $CNR^{\rho}_{s,k} = \left[\left(\lambda P_{CL} + (1-\lambda)P_{CS}\right) - HC\right]\cdot\left(Y^k_{j,s} - Y^k_{j,d}\right)$ for $d > s$, where $\rho = d - s$. If a driver is as accurate as the auto-guidance system used (i.e. ρ = 0), then it is assumed that MCEH will be equal to zero. This assumption may not hold in practice, but data limitations restrict comparisons to values of ρ greater than zero. MATLAB® was used to generate graphs to examine MCEH for auto-guidance systems with different levels of accuracy and deep tillage practices. In addition, a sensitivity analysis was conducted examining changes in MCEH by varying both TC_s and $CNR^{\rho}_{s,k}$ and graphing the contours of the function surface using MATLAB®. The objective of this analysis was to examine the ability of different size farms to adopt auto guidance systems with accuracy of at least 2.5 cm.

Auto-guidance systems with GPS were analyzed with differing levels of accuracy. The systems considered were: (1) Trimble® *Ag*GPS® Autopilot™ DGPS (DGPS) with at least 30-cm accuracy, (2) Trimble® *Ag*GPS® Autopilot™ HP (HP) with at least 10-cm accuracy, and (3) Trimble® *Ag*GPS® Autopilot™ RTK (RTK) with at least 2.5-cm accuracy. To provide conservative estimates, it was assumed that the accuracy of the auto-guidance systems used were equal to the minimum row accuracy provided by the system (e.g. for the Trimble® *Ag*GPS® Autopilot™ RTK system this would be 2.5 cm). The total annualized cost for each system is provided in table 1. It is assumed that the systems have no salvage value, making the economic analyses performed more conservative.

Results and Discussion

Seed Cotton Yield

The effect on the relative change in seed cotton yield of the proximity of planting operations to the center of deep tilled zones is presented in table 2 and illustrated in figure 3. Seed cotton yields, in general, differed across years due to climatological differences as discussed in the previous section. In addition, results in table 2 strongly suggest the need for deep tillage operations, as the relative change in seed cotton yield above no tillage is statistically significant for all the deep tillage treatment fixed effects in 2003 and 2004, and for strip-till in 2005. Thus, not performing any tillage may be very detrimental to seed cotton yields in central Alabama.

The effect of row proximity distance of planting operations to deep tilled zones is highly significant for all deep tillage implements and most years. As row proximity distance increases, the relative change in seed cotton yield

Table 2. Mixed CANOVA estimation results for relative change in seed cotton yield above no-till and least square means of the relative change in seed cotton yield above no tillage for alternative row proximity distances of the planted row to deep tillage operations.

	Estimation Results[a]		
	2003	2004	2005
Test statistics of fixed effects			
Terra-Max	6.72 (0.00)	5.23 (0.00)	1.14 (0.32)
Paratill	5.84 (0.00)	7.61 (0.00)	1.53 (0.21)
Strip-Till	6.14 (0.00)	7.68 (0.00)	2.85 (0.05)
Terra-Max * distance	-3.80 (0.00)	-2.90 (0.00)	-0.03 (0.98)
Paratill * distance	-2.36 (0.02)	-4.57 (0.00)	-2.48 (0.01)
Strip-Till * distance	-2.38 (0.02)	-3.84 (0.00)	-2.60 (0.01)
Terra-Max * distance^2	2.94 (0.00)	---	---
Paratill * distance^2	1.35 (0.18)	---	---
Strip-Till * distance^2	1.58 (0.12)	---	---
Fit statistics			
Pseudo R^2	0.34	0.50	0.56

	Least Square Means[b]											
	Row Proximity of Tillage (cm)											
Tillage	0.6	5.1	9.5	14.0	18.4	22.9	27.3	31.8	36.2	40.6	45.1	49.5
						2003						
Terra-Max	0.644	0.512	0.398	0.304	0.229^a	0.173^a	0.137^a	0.119^a	0.121^a	0.141	0.181	0.240
Paratill	0.565	0.480	0.405	0.338	0.280^{ab}	0.231^{ab}	0.191^{ab}	0.160^{ab}	0.137^{ab}	0.123	0.119	0.123
Strip-Till (KMC)	0.595	0.511	0.437	0.373	0.319^b	0.276^b	0.243^b	0.221^b	0.209^b	0.207	0.215	0.234
						2004						
Terra-Max	0.378^a	0.348^a	0.319^a	0.290^a	0.260^a	0.231^a	0.201^a	0.172^a	0.142^a	0.113^a	0.083	0.054
Paratill	0.549^b	0.503^b	0.456^b	0.410^b	0.363^b	0.317^b	0.270^b	0.224^{ab}	0.177^{ab}	0.131^{ab}	0.084	0.038
Strip-Till (KMC)	0.555^b	0.516^b	0.477^b	0.438^b	0.399^b	0.360^b	0.321^b	0.282^b	0.243^b	0.204^b	0.164	0.125
						2005						
Terra-Max	0.133^a	0.133^a	0.133^a	0.133^a	0.133^a	0.133^a	0.132^b	0.132^b	0.132^b	0.132^b	0.132^b	0.131^b
Paratill	0.177^a	0.160^a	0.143^a	0.126^a	0.109^a	0.092^a	0.075^a	0.058^a	0.041^a	0.024^a	0.007^a	-0.009^a
Strip-Till (KMC)	0.332^b	0.314^b	0.297^b	0.279^b	0.261^b	0.243^b	0.225^c	0.208^c	0.190^b	0.172^b	0.154^b	0.137^b

[a] Statistical tests involving fixed effects, covariate and interaction terms were conducted with t-tests using the proc mixed procedure in SAS. The p-value for each test is provided in parentheses after the test-statistic. The pseudo R^2 values were calculated following the procedure discussed in Magee (1990) using the likelihood ratio.

[b] Across treatments within years least square means followed by the same letter are not statistically different at a 0.10 level of significance. If two means have different letters then the mean with the higher letter (e.g., c > b > a) has a mean statistically greater than the mean it is compared to at a 0.10 level of significance (using a one-sided t-test). No letters indicate none of the means where statistically different from each other.

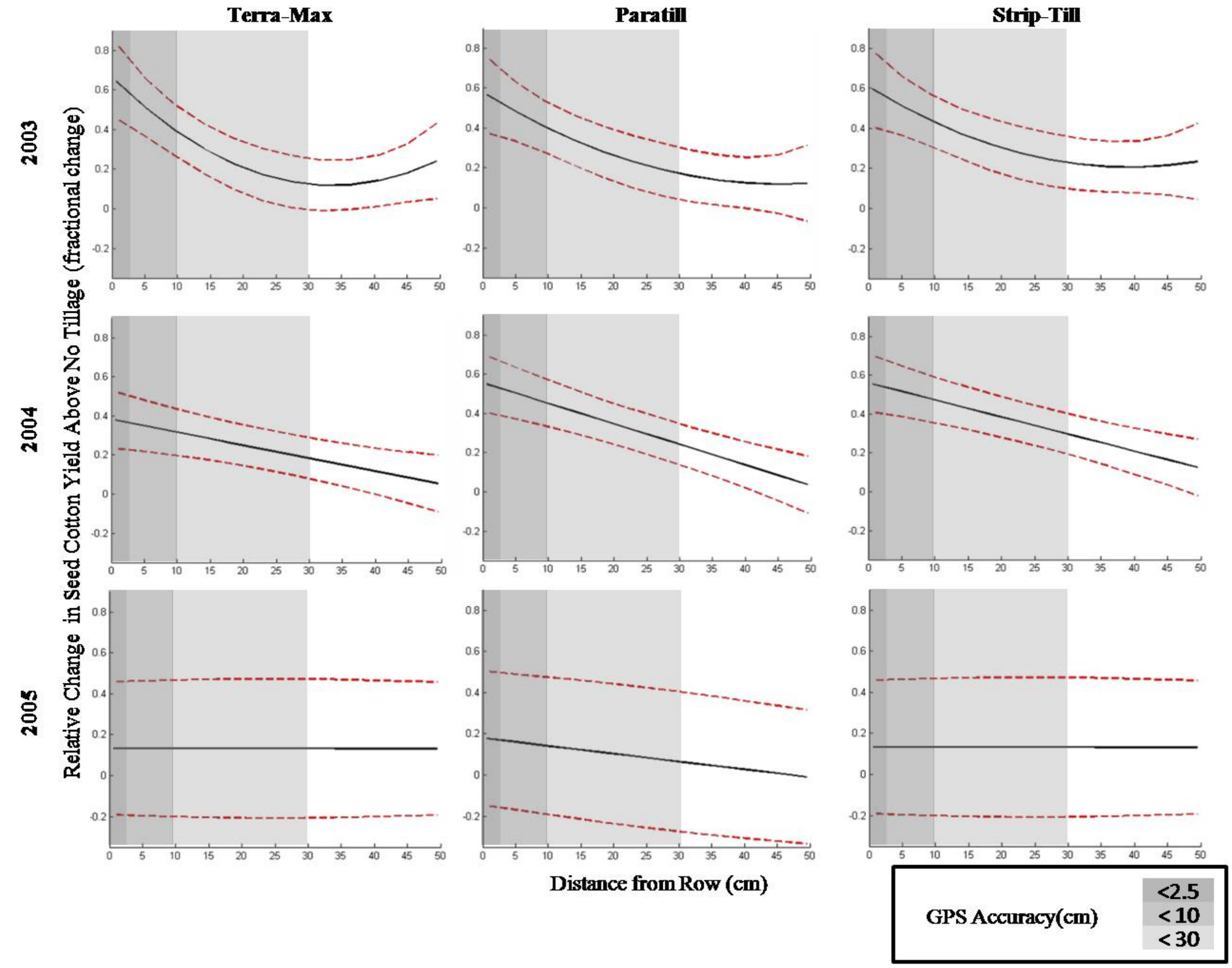

Figure 3. Relative change in seed cotton yield above no tillage as row proximity distance between planting and tillage operations increase for three deep tillage methods. Effect of using auto-guidance GPS systems to control traffic is captured in the shaded areas for <2.5, <10, and <30 cm. Dashed lines on either side of the regression line represent the estimated upper and lower 95% confidence limits.

declines (fig. 3). Depending on the year, seed cotton yields would have fallen by as much as 64% in 2003, 55% in 2004, and 33% in 2005 without subsoiling. When planting operations deviated over 49.5 cm from the center of deep tilled zones, depending on climatological differences, relative changes in seed cotton yield above no-tillage ranged from 0.0 to 0.24, depending on the deep tillage implement used. In contrast, if planting operations were within 0.64 cm of the center of deep tilled zones, then relative changes in seed cotton yields above no tillage ranged from 0.13 to 0.64. That is, seed cotton yields were greater with deep tillage than yields with no tillage, and more so when the planted row was in close proximity to the center of deep tilled zones. Given that planting was delayed in 2003 due to inclement weather, results suggest that the impact of not subsoiling under these conditions would have an additional significant effect on seed cotton yields. Negative changes in seed cotton yield in 2004 were not expected, and given the impact of climate, are potentially due to random variation.

In all of the years, relative change in seed cotton yields from plots using strip-till were significantly greater than or equivalent to the other two deep tillage treatments (table 2). The differences found between strip-till and the other two deep tillage treatments, Terra-Max and Paratill, is likely due to the orientation of the subsoiling shanks. The strip-till implement (Kelley Manufacturing Company's Rip/Strip in-row subsoiler, Tifton, Ga.) has straight shanks, while the Terra-Max (Terra-Max I® bentleg subsoiler,Litchfield, Ill.) and Paratill (Bigham Brothers' Paratill® bentleg subsoiler, Lubbock, Tex.) have bentleg shanks, that bend toward the center of the implement to provide a wider path of disruption under the planted row (fig. 2). This modification affects the below surface disruption depending on the direction the subsoiled zone is moving away from the planted row. Viewing the tillage from above, as the Terra-Max or Paratill implements move to the right (left) away from the planted row, the shanks on the right (left) of the implement begin to disturb the soil away from the planted row, leaving the soil under the planted row more heavily compacted. On the left (right), as the subsoiler moves away from the planted row, the soil under the planted row is still disturbed, but the planted row is no longer at the center of the path of disruption, potentially decreasing seed cotton yields.

The decreases in seed cotton yield as the path of disruption of the subsoiler moves away from the planted row, emphasizes the potential for controlled traffic to minimize yield reductions. Thus, the use of automatic steering becomes an enticing option to improve the accuracy of planting operations to tilled areas. Automatic guidance systems with GPS with accuracy within a couple of centimeters can provide the highest protection against yield reductions, but with a significant capital investment. Less accurate systems, with less than 10 to 30 cm of accuracy, provide some protection, as well. These alternatives require less investment in capital, but reduce gains in yield under the most accurate systems by as much as 13% and 52%, respectively. These differences are highlighted in figure 3. While the reduction in yield benefit can be significant from reducing accuracy, the farmer must weigh the economic benefit of the automatic guidance system against the cost of the system.

Changes in Net Revenues

The effect on net revenues from cotton production as the row proximity of planting operations to the center of deep tilled zones increases is provided in table 3 and illustrated in figure 4. As with seed cotton yields, the differences across years are due to climatological changes that affected crop yield directly or timeliness of operations. When considering whether to subsoil or not each year, the economic impact of not subsoiling annually may be significant. Depending on the accuracy of subsoiling, losses in revenue from not subsoiling could be as high as \$236 ha^{-1}. The largest reductions from not subsoiling would have occurred in 2004, when Hurricane Ivan damaged crops across the state of Alabama.

As with seed cotton yields, changes in net revenues from cotton production above no tillage when using strip-till was statistically larger or at least equivalent to changes in net revenues from using Terra-Max or Paratill (table 3). This finding is likely due to the orientation of the shanks on the Terra-Max and Paratill subsoilers (see previous subsection). For all the subsoiling implements, changes in net revenues decreased as row proximity distance increased (fig. 4). This decline in net revenues could be partially or mostly averted by investment in an auto-guidance system with GPS. Such a system could help to control additional traffic and recompaction of soils, as well as reduce losses in revenues from human error, by improving accuracy of subsoiling operations. This becomes especially important in conservation tillage systems where residue on the soil surface may obscure the line of sight of the driver to the planted row, further increasing the risk of reduction in crop yields and profits (Raper et al., 2008).

The tradeoffs in accuracy between different auto-guidance systems are illustrated in figure 4. By going from a system that can provide accuracy within 2.5 cm to a system that can provide accuracy within 10 cm, a farmer could potentially reduce net revenues by as much as 38% for Terra-Max, 25% for Paratill, and 17% for strip-till. Moving from a system that can provide accuracy within 2.5 cm to a system that can provide accuracy within 30 cm, the potential reduction in net revenues could be as high as 83% for

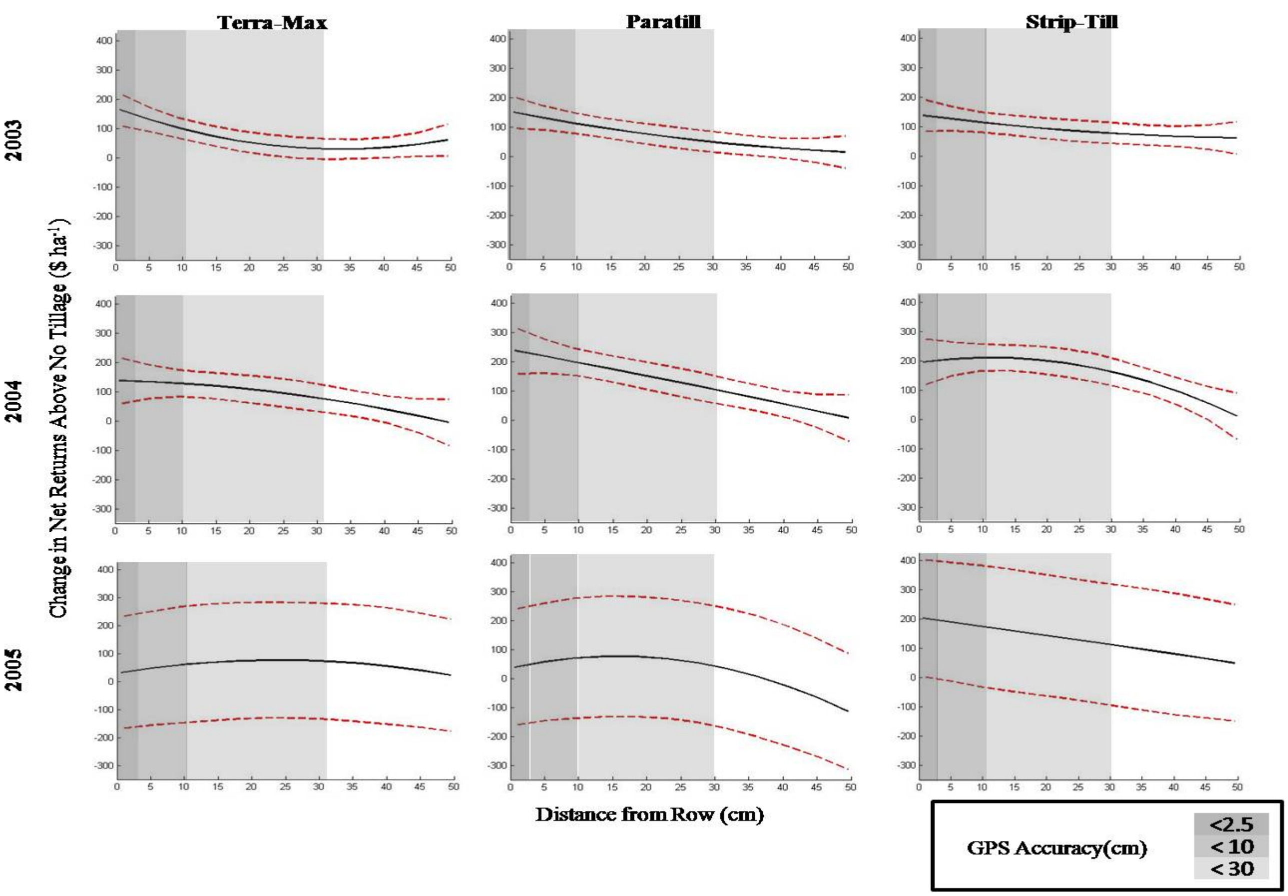

Figure 4. Changes in net returns for cotton production above no tillage as row proximity distance between tillage and planting operations increase for three deep tillage methods over time. Effect of using auto-guidance GPS systems to control traffic is captured in the shaded areas for <2.5, <10, and <30 cm. Dashed lines on either side of the regression line represent the estimated upper and lower 95% confidence limits.

Table 3. Mixed CANOVA estimation results for change in net returns ($ ha^{-1}) from cotton production above no-tillage and least square means of the change in net returns from cotton production above no tillage for alternative row proximity distances of the planted row to deep tillage operations.

	Estimation Results[a]		
	2003	2004	2005
Test statistics of fixed effects			
Terra-Max	0.35 (0.74)	3.27 (0.00)	5.91 (0.00)
Paratill	0.42 (0.69)	5.70 (0.00)	5.32 (0.00)
Strip-Till	2.45 (0.05)	4.61 (0.00)	4.87 (0.00)
Terra-Max * distance	0.89 (0.38)	-0.13 (0.90)	-3.29 (0.00)
Paratill * distance	1.18 (0.24)	-1.11 (0.27)	-1.76 (0.08)
Strip-Till * distance	-0.68 (0.50)	0.78 (0.43)	-1.12 (0.27)
Terra-Max * distance^2	-0.96 (0.34)	-0.65 (0.52)	2.54 (0.01)
Paratill * distance^2	-1.94 (0.05)	-0.11 (0.91)	0.70 (0.48)
Strip-Till * distance^2	-0.03 (0.98)	-1.83 (0.07)	0.53 (0.60)
Fit statistics			
Pseudo R^2	0.63	0.68	0.63

Least Square Means[b]

	Row Proximity of Tillage (cm)											
Tillage	0.6	5.1	9.5	14.0	18.4	22.9	27.3	31.8	36.2	40.6	45.1	49.5
						2003						
Terra-Max	163	129	100	76 [a]	57 [a]	42 [a]	32 [a]	28 [a]	29 [a]	34 [a]	44 [ab]	59 [ab]
Paratill	149	130	112	96 [ab]	81 [ab]	67 [ab]	55 [ab]	44 [a]	35 [a]	27 [a]	20 [a]	14 [a]
Strip-Till (KMC)	137	125	114	104 [b]	95 [b]	87 [b]	80 [b]	75 [b]	70 [b]	66 [b]	63 [b]	61 [b]
						2004						
Terra-Max	137 [a]	133 [a]	123 [a]	121 [a]	111 [a]	100 [a]	87 [a]	73 [a]	56 [a]	37 [a]	17	-5
Paratill	236 [b]	217 [b]	198 [b]	178 [b]	158 [b]	137 [a]	116 [a]	95 [a]	73 [a]	52 [a]	30	7
Strip-Till (KMC)	195 [ab]	205 [b]	210 [b]	209 [b]	203 [c]	192 [b]	175 [b]	153 [b]	125 [b]	92 [b]	54	11
						2005						
Terra-Max	31 [a]	47 [a]	59 [a]	68 [a]	73 [a]	76 [a]	75 [ab]	71 [ab]	64 [b]	53 [b]	39 [b]	22 [b]
Paratill	38 [a]	57 [a]	70 [a]	76 [a]	75 [a]	68 [a]	54 [a]	34 [a]	7 [a]	-27 [a]	-67 [a]	-113 [a]
Strip-Till (KMC)	202 [b]	188 [b]	175 [b]	161 [b]	148 [b]	134 [b]	120 [b]	106 [b]	92 [b]	77 [b]	63 [b]	49 [b]

[a] Statistical tests involving fixed effects, covariate and interaction terms were conducted with t-tests using the proc mixed procedure in SAS. The p-value for each test is provided in parentheses after the test-statistic. The pseudo R^2 values were calculated following the procedure discussed in Magee (1990) using the likelihood ratio.

[b] Across treatments within years least square means followed by the same letter are not statistically different at a 0.10 level of significance. If two means have different letters then the mean with the higher letter (e.g., c > b > a) has a mean statistically greater than the mean it is compared to at a 0.10 level of significance (using a one-sided t-test). No letters indicate none of the means where statistically different from each other.

Terra-Max, 70% for Paratill, and 48% for strip-till. Based on results in table 3, these numbers will change depending on climatological conditions and farming practices.

It should be noted, in absolute terms, strip-till provided the greatest change in net revenues (and relative change in seed cotton yields for the most part) when the row proximity distance between the planting and tillage operations was greater than 5.1 cm. When the proximity of these operations was less than 5.1 cm, results in tables 2 and 3 suggest that strip-till may provide the most consistent results, but Paratill may provide a significant boost in yields and net revenue as well. The results for Terra-Max are mixed, and while providing a boost in yields and net returns when the planted row is in close proximity to the tilled zone, results seem more variable than the other two deep tillage treatments as weather conditions affect crop growth and management of the crop.

Minimum Cost-Effective Area of Land for Adopting Auto-Guidance with GPS

The profitability of using an auto-guidance system with GPS for subsoiling is dependent on how accurate the driver of the tractor would have been if they did not have the system. With high residue cover crops that produce a large amount of biomass left on the soil surface, the chance for human error to deviate significantly off the row is increased. The economics of adopting different auto-guidance systems with GPS is presented for strip-till in figure 5. Given seed cotton yields and changes in net revenues for strip-till were statistically greater or at least equal to those for the other two deep tillage treatments, the analysis in this section focuses on using auto-guidance systems for strip-till operations. The different graphs represent the three auto-guidance systems (DPGS, HP, and RTK) examined and present data for each year of the study. Furthermore, in analyzing the economic problem faced by a farmer deciding to adopt this technology,

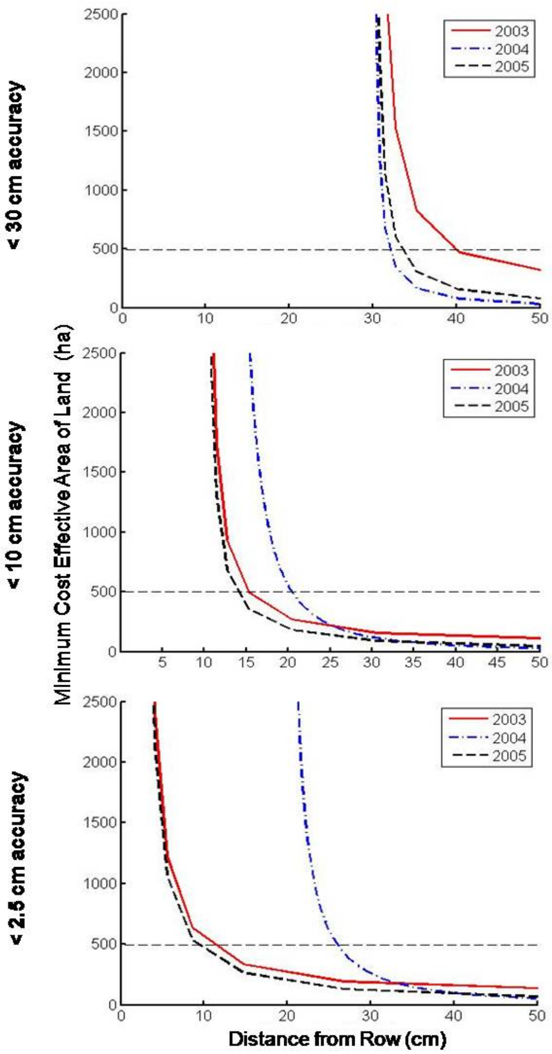

Figure 5. Minimum cost-effective area of land (ha) for adoption of auto-guidance with GPS when human error would result in planting operations being farther from the strip-tilled zone than if auto-guidance systems were used.

it was assumed that when the driver could be as accurate as the minimum accuracy of the GPS system, then that system would provide no additional benefit for subsoiling operations. Taking this into account, the MCEH curves in the graphs slope upward at 30, 10, and 2.5 cm for the DGPS, HP, and RTK systems, respectively.

The potential for a certain size farm to benefit from adopting automatic steering technology can be analyzed using figure 5. The dotted line on each graph in figure 5 at 500 ha represents a 500-ha farm, and where it intersects each of the MCEH curves indicates an upper bound on how much a diver could error without auto-guidance before investing in an automatic steering system becomes profitable. The general rule is that for a given base area of land, a particular auto-guidance system is profitable when the MCEH curve lies below that base. For the 500-ha farm: the DGPS system is profitable when human error results in planting operations greater than 32 to 40 cm from the tilled zone; the HP system is profitable when human error results in planting operations greater than 14 to 21 cm from the tilled zone; and the RTK system is profitable when human error results in planting operations greater than 10 to 26 cm from the tilled zone. As shown, results will vary due to climatological differences. As seen in this example, depending on the accuracy of the driver and the size of the farming operation, different auto-guidance systems may or may not be profitable to adopt. Figure 5 suggests that RTK systems, which have less than 2.5 cm of accuracy, are profitable for very large farms (greater than 1000 ha), large farms (around 500 ha), mid-size farms (around 250 ha) and small farms (less than 100 ha) when the driver is off more than 5, 10, 15, and 30 cm from the planted row, respectively.

The previous analysis in figure 5 assumes that the total annualized cost for each of the auto-guidance systems was fixed (see table 1). In figure 6, this assumption is relaxed, so that MCEH can be examined by varying both total annualized cost and row proximity of planting operations to the tilled zone. Each graph in figure 6 shows the contours of the MCEH function for each year of the study for the RTK auto-guidance system. The contours represent different size farms, with the solid black lines representing specific farm sizes of 100, 250, 500, 750, 1000, and 2500 ha, respectively. Using figure 6, in 2003 and 2005, if the total annualized cost for the RTK system was $5000, then it would be profitable for farms greater than 250 ha in size to invest in the RTK technology if their drivers on average could not plant cotton within 10 cm of the center of the tilled zone without an auto-guidance system. In contrast, at the current total annualized cost for the RTK system, $9858 (table 1), under the same situation, it is only profitable for farms of greater than 500 ha to invest in the RTK system. In 2004, Hurricane Ivan significantly reduced cotton yields across Alabama. Events such as this one do not make it economical for even very large farms to invest in an RTK guidance system, unless drivers are significantly inaccurate, consistently planting cotton greater than 22 cm from the center of deep tilled zones. In general, Figure 6 shows that as farm size grows, a farm can absorb more of the cost of an auto-guidance system and worry less about the accuracy of their drivers.

The MCEH provides the minimum amount of land an auto-guidance system must be used on to recover the cost of the system. As a driver becomes more accurate, the additional gain in revenue of using an automatic steering system for subsoiling declines, increasing the minimum cost-effective area of land needed to cover the cost of the system. Thus, larger farmers are more likely to benefit from auto-guidance system with GPS. For both the RTK and HP systems, drivers would have to consistently be off the planted row by 20 to 25 cm with tillage operations to make an auto-guidance system profitable for smaller farming operations (less than 200 ha). For this farmer group it may be cheaper to replace an inaccurate driver, with a driver who requires a higher wage rate. Another possibility is combining planting and tillage operations, but the effect on re-compaction of soils from the use of a heavier tractor with more horsepower and the bulk of the equipment is unknown. In addition, this analysis does not take account of other economic benefits of using an auto-guidance system with GPS, such as timeliness of operations and reductions in input costs. These will likely further enhance the benefit of using automatic steering systems on-farm and reduce MCEHs required for adoption. Thus, the analysis provided here gives conservative estimates of the MCEH required for adoption for different size farms for subsoiling purposes.

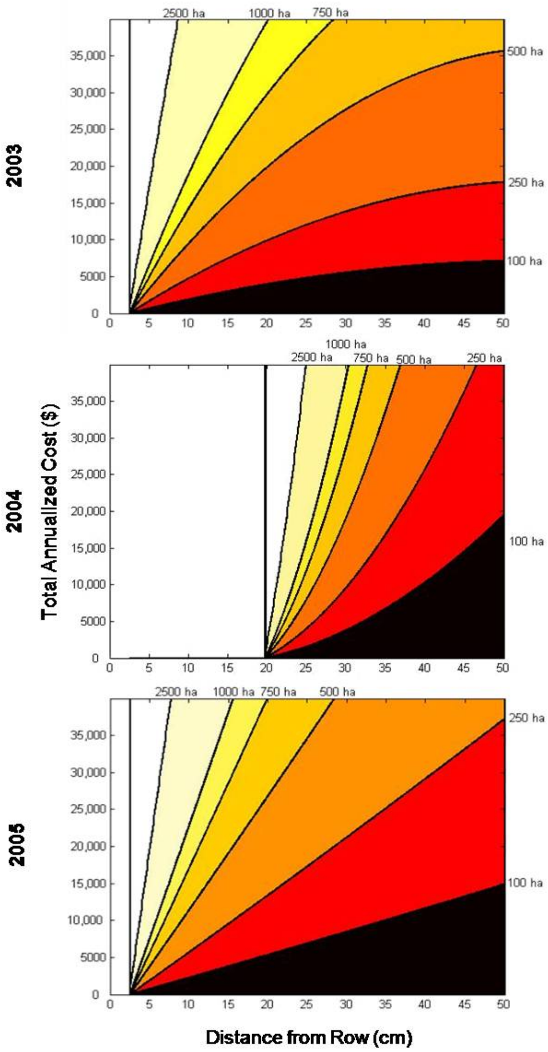

Figure 6. Total annualized cost for RTK auto-guidance systems (<2.5-cm accuracy) for different size farms as the difference between RTK auto-guidance systems and human error results in strip-tillage operations being farther from the planted row. The graph represents the contours of the minimum cost-effective area of land function as a function of total annualized cost and distance of planting operations from the tilled zone.

CONCLUSIONS

Soils that naturally recompact may require annual subsoiling to alleviate potential cash crop yield reductions from inhibited root growth and decreased water infiltration into the soil as a result of soil compaction. The proximity of planting operations to the center of deep tillage zones will determine how effective subsoiling is for promoting crop growth, in turn impacting the economic performance of the crop (Raper et al., 2008). Using an auto-guidance system may ensure that crop yields and revenues can be maximized for a moderate capital investment. Results of an experiment examining row proximity of deep tillage operations showed that the distance between the planted row and tillage pass can significantly affect the performance of a cotton crop. As distance between the planted row and tillage pass increased from 0.6 cm to 10, 20 and 30 cm seed cotton yields above no tillage were reduced by as much as 24%, 47%, and 52%, respectively. In the same regard, as distance increased from 0.6 cm to 10, 20 and 30 cm, net revenues from cotton production above no tillage were reduced by as much as 38%, 74%, and 83%, respectively. Of three deep tillage implements examined, conservation tillage systems using strip-till had seed cotton yields and changes in net revenues that where statistically larger or at least equivalent to yields and net revenues from systems with Paratill and Terra-Max. Thus, auto-guidance systems with GPS could benefit subsoiling operations by improving accuracy, avoiding cash crop yield reductions, and improving profitability. An economic analysis of the potential for adoption showed that as farm size increased potential for auto-guidance systems increased. In addition, auto-guidance systems with accuracy of less than 2.5 cm may be the most profitable for larger farms, while systems with less than 10-cm accuracy may provide a better economic alternative for smaller farms.

In addition to the direct benefits auto-guidance systems with GPS can provide for subsoiling operations, integrating other practices with the system can further improve the profitability and adoptability of automatic steering systems. Such practices include precision agricultural or site-specific practices (Gan Mor and Clark, 2001). Auto-guidance is a turn-key technology that many other precision farming technologies rely upon (Batte and Eshani, 2005). Based on this area of application and using the results of this study, precision subsoiling, that is varying the depth and placement of deep tillage across the field, may be a practice that could be utilized to further reduce energy and input costs, as well as improve farm profitability, building off the use of automatic steering systems for subsoiling operations (Raper et al., 2005a; Wells et al., 2005). This is an area for future research.

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