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Controlled traffic farming benefits to soil physical properties and soil health on Granby loamy fine sands

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PROPOSAL
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Controlled traffic farming benefits to soil physical properties and soil health on Granby loamy fine sands

by

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Contents

I. Abstract

Typical Midwestern US agriculture requires the need for intensive machine traffic, causing soil compaction and over the long-term contributing to soil degradation and potential yield loss. Controlled traffic farming (CTF), which is restricting wheel traffic to a small repetitively tracked portion of the field while leaving the majority of the field untrafficked is a promising method to reduce farm machinery compaction. The idea is that CTF restricts compaction to a small area of the field – thus there may be some negative effects of concentrated traffic on the CTF zones, but comes at the benefit of the rest of the field. The overall objective of this study was to determine the effects of seven years of CTF on soil bulk density and aggregate stability across three 15-62 ha commercial fields in northwestern Indiana loamy fine sands. Due to CTF's redistribution of farm machine compaction we measured the effects within three traffic zones within each field: planter tracks, sprayer tracks, as well as non-tracked zones of the field. Bulk densities, on average were 1.30 g/cm^3 to 1.35 g/cm^3 in the CTF and conventional fields respectively. However, bulk density within non-tracked zones were 1.19 g/cm^3 and 1.32 g/cm^3 for CTF and conventional traffic (UTF) respectively. Soil aggregates under CTF lost less soil after slaking on average (-32%), compared to conventional traffic (-49%). Overall, CTF had positive effect on soil physical properties compared to conventionally trafficked treatments.

II. Background

CTF was developed in the 1850s and is commonly used in Australia and Europe while slowly becoming more popular in the United States. CTF involves syncing wheel traffic of all equipment to permeant traffic lanes by maintaining a common tramline or multiples of it so the lanes may be identified seasonally (Baker et al., 2007). The objective is to separate traffic zones from the cropping zones permanently in order to eliminate the negative impacts of compaction on cropped portions of the field (Chen et al., 2008; Y. X. Li, Tullberg, & Freebairn, 2007). While the trafficked zone is left unplanted generally, cropped portion of the field experiences benefits including better gain and retention of soil carbon, improved infiltration rates as well as potential water storage and better soil structure leading to more robust root development (Y. X. Li, Tullberg, Freebairn, & Li, 2009). This traffic pattern focuses on reducing field-level soil compaction by making 80%-90% of the field area non-trafficked resulting in more productivity in those areas while confining the soil compaction damage to 10%-20% of the field (Kingwell & Fuchsbichler, 2011). Any farming system using heavy equipment is subject to the negative consequences of compaction on soil health and land productivity. CTF helps to restore degradation of physical soil properties and limit future negative consequences from heavy equipment compaction while improving sustainability and productivity of farming systems (McHugh, Tullberg, & Freebairn, 2009). This practice is one tool in a farmers toolbox to contribute to soil health.

Soil health or soil quality is defined as the soils ability to operate as a living ecosystem to sustain humans, plants and animals in a continued capacity ("NRCS," n.d.). CTF is beneficial to soil health in many ways through reduced compaction (Vermeulen, Tullberg, & Chamen, 2010), increased soil porosity providing improved soil structure (Bethlenfalvay & Barea, 1994) increasing microbial activity (Wander, Traina, Stinner, & Peters, 1994) and allowing for increased water infiltration (Pierson, Blackburn, Van Vactor, & Wood, 1994). Many of these soil health improvements to contribute to the yield benefits often observed with CTF; such as improved plant growth, such as increased nutrient uptake from healthy rooting systems and improved soil aggregate structure (McHugh et al., 2009; Qingjie et al., 2009).

CTF combines management of soil health with field efficiency to reduce the impacts of heavy machinery on soil health resulting in reduced yields. Studies have shown an increase in yield by 11.2% on CTF fields when compared to conventionally trafficked fields on research plots in a 10 year study (Bai et al., 2009). Australian studies have shown a larger response to yield with a range of 10%-30% increase when using CTF practices on farm (Bowman, 2008). Soil compaction is a serious issue in agriculture with direct impacts on yield and long-term soil health. Yield losses due to compaction were studied in Rosemount Minnesota by applying axle loads of 4 tons in 1957 and 6 tons in 1958 to the surface of a silt loam prior to planting. The results showed an average of a 7.5 percent decrease in corn crop yields over this two-year study (Blake, Bofxter, Adams, & Aase, 1960). Plant responses to increased compaction vary and often depend on the hybrid, crop grown, soil, and climatic conditions. In drought years, when the crop is experiencing stress, CTF can make the most noticeable difference by providing increased infiltration rates and increasing water availability to the plant. (Pierson et al., 1994) With standard traffic patterns, subsurface compaction may restrict root growth and water infiltration leaving stressed plants with even less available water. In dry years, CTF has the most noticeable yield increase over UTF operations. Australian studies have shown as much as a 50% increase in yield during drought years when compared to traditional UTF operations (Bindi Isbister, Hall, Lemon, & Davies, 2017). Aeration issues can also arise from lower bulk density, and especially under saturated conditions, drainage slows, causing an anaerobic environment that limits microbial activity and plant nutrient uptake. Subsoil compaction affects many aspects such as water, nitrogen and phosphorus absorption, plant growth and yield as well as delay planting due to colder wetter soils (Dejong-Hughes, 2009).

Compaction also has a direct impact on soil porosity and aggregate stability. The ideal percentage of porosity is 45% mineral solids, 5% Organic solids, 25% air space and 25% water space. Solids will ideally occupy 50% of the volume and the other 50% is occupied by pore space (Brady, Weil, & Weil, 2008). Compaction increases bulk density and reduces total pore volume, which in turn also reduces water holding capacity (Field, Ecology, & Guide, 1998). Macro- and micro-pores are both affected by compaction in negative ways and result in a higher particle density creating many negative effects on soil health and crop yield. With poor infiltration rates and high runoff rates the soil plant relationship and crop success suffers. This can have a drastic impact on crop yield especially if the current crop year displays drought conditions. Compaction also causes difficulty both ways with water management in fields. Excess water that is ponding on compacted surfaces not only delays planting operations but may also reduce topsoil retention. If there is excess water present due to compaction, it is more susceptible to surface erosion, eventually draining into rivers and streams. Across the corn belt there is an average of 3.9 tons/ac lost per year due to erosion (Cox, Hug, & Bruzelius, 2011). Soil loss in the Midwest is a serious problem because the loss of one inch of topsoil takes approximately 500 years to replace (USDA, 2017).

Overall, CTF broadly has positive impacts on many aspects of soil health. These soil health benefits also often translate to economic benefits. Wheel slip is reduced (Hongwen & Xingxiang, 2000) so that fuel, herbicides, and fertilizer are saved by increased accuracy of trips across the field. On average fuel efficiency of controlled traffic operations is 30%-50% better than that of UTF operations (Bindi Isbister et al., 2017). There is also a minimum of a 15% return on capital with investment due to a reduction in inputs, more efficient fuel usage and increased yield (Bindi Isbister et al., 2017). There have also been opportunities of earlier planting dates due to quicker dry out time in the spring (Braunack, McPhee, & Reid, 1995), and minimized nitrogen losses due to less volatilization of gases out of soil. (Scott, Crichton, & Ball, 1999). Grain quality and crop yields also increase from reduced compaction while inputs go down due to decreased double application overlap (Kingwell & Fuchsbichler, 2011).

III. Introduction

CTF is one way to maximize the efficiency of heavy equipment and is beneficial for many reasons, but primarily it is thought to increase soil health mostly via reduced compaction (Soane, Dickson, & Campbell, 1982) and increasing soil porosity to favorable levels (Souza, Souza, Silva, Barbosa, & Araújo, 2014). Most research on CTF examines the effect of the practice on soil physical properties. Out of these studies, CTF has been shown to improves soil structure by 50% (McHugh et al., 2009), increases moisture by measurement of soil volumetric water potential by an average of 10%, reduces runoff by 38%, lower peak runoff rates (Hongwen & Xingxiang, 2000), increases soil water infiltration (Y. Li, Tullberg, & Freebairn, 2001), reduces herbicide losses by 47%-60% (Masters, Rohde, Gurner, & Reid, 2013), increases soil O_2 concentration by 10%, and slows down re-compaction rates of untrafficked soils (Busscher W.J. A4 - Bauer, P.J. A4 - Frederick, J.R., 2002).

Potential tradeoffs of CTF include the decreased success of crop yield directly next to traffic lanes, increased erosion in lanes when positioned downhill and poor nutrient distribution (B Isbister et al., 2013). Some other potential disadvantages include the need to increase planting populations closer to the lanes of compaction due to rooting issues as well as a high cost to change equipment over or modify to match permanent traffic lanes (Lamers, Perdok, Lumkes, & Klooster, 1986). While yield increases are possible from 0%-10% depending on the type of soil, crop grown, type of field traffic, weight of equipment and climatic factors, the overall gross farm income increases have been reported to be only 2% (Lamers et al., 1986), this on farm research study we are particularly interested in looking how the physical soil properties differ in a CTF vs. a UTF system.

Given the variable effectiveness of CTF and concerns with excess compaction in controlled zones, we designed a study to look at CTF effects on soil physical properties. Here I examined the effect of CTF versus UTF on Mollisol soils in northwest Indiana by examining soils under equipment tracks and those soils not under equipment tracks. In response to CTF and conventional traffic we focused on two soil health indicators to compare the physical properties of soil samples from CTF and UTF – bulk density and aggregate stability. I hypothesize that the CTF will decrease bulk density and increase aggregate stability in the non-compact zones of the field and increase bulk density and decrease aggregate stability directly under the wheel trafficked regions. This research study concentrates mainly on two methods for testing soil physical health indicators as well as considering peer-reviewed papers published on soil compaction and controlled traffic farming. Our goals for this research include providing adequate measurements of bulk density and soil aggregate stability testing in three zones of traffic between two different wheel traffic farming systems to see if any significant differences in soil physical properties occur. The two separate wheel traffic types will be represented by the three CTF farms and the three UTF farms which follow conventional traffic patterns not confined to tramlines. The three zones of traffic studied will be the planter, sprayer and non-compact zones in all farms examined. The objective is to see if the physical properties of bulk density and soil aggregate stability are affected significantly.

IV. Materials and Methods

Site Description and Experimental Design

The study took place in Newton county, Indiana and which has a mean annual precipitation of 947.9 mm and mean annual temperature of 10.8 ºC. Newton County is comprised of glaciofluvial deposits, glaciolacustrine deposits and glacial drift. The major physiographic areas include the Iroquois moraine, the Iroquois lacustrine plain, Kankakee outwash plain and the Tipton till plain. The soil types on these farm fields were all comprised of Granby mucky loamy fine sand. This soil type is very poorly drained and is found in depressional areas. The surface layer is black mucky loamy fine sand and the subsoil is comprised of very friable sand with the presence of mottling. There is a low available water holding capacity and high permeability present in these soils with very slow runoff due to being in a depression. They exist on outwash plains and lake plains. Newton County is made up of forty-nine percent Granby series soils (*Soil Survey of Newton County, Indiana*, 1988). Soil organic matter is also highly concentrated at the surface of these soils and ranges from 2-3%.

This experiment used a controlled-case, or paired-site, approach. Three pairs of farms located in close proximity and containing the same soil type, were chosen to receive CTF or UTF (Table 1). Thus making a total of six farms used in the study. All farms were maize (*Zea mays*) and soybean (*Glycine max.*) rotations and had similar management practices for several decades. The CTF fields have been trafficked on the same pattern for the past seven years. The UTF farm has used conventional traffic patterns since the farm was bought in 1985. A cereal rye (*Secale cereal*) cover crop mixture was used in field 1 on the CTF farm while no cover crop was used on the UTF conventional fields. The cover crop is used for grazing the farms newly acquired cattle in the winter months. The CTF farm uses a combination of strip tillage and no-till while the UTF farm uses conventional vertical tillage on the ground going to corn and no-till on the ground going to beans. A corn/soybean rotation is used on each of the farms. The UTF farm occasionally does a corn on corn rotation. Below is a table showing the crop that just came out of the field after sampling. The sampling was done in November of 2018 under average moisture conditions. The cover crop on the CTF farm was emerged on Kents place at the time of sampling. Within each field we used a stratified sampling protocol with random selection within that stratification. The fields were stratified into three zones: planter-traffic zone, sprayer-traffic zone, and non-compact no-traffic zones for soil sampling. Fields are paired below based on field similarities.

Table 1. Experimental Field pairs and characteristics.

Pair	Treatment	Field Nickname	Size (ha)	Previous Crop	Tillage Practices	Cover crop Usage	Predominant soil types (% coverage of each soil type per field)
1	CTF	Kent's Place	31	Beans	Strip till	Yes: cereal rye	Gt: Granby LFS (91.5%) ObB: Oakville FS (5.6%) BmB: Brems LS (1.8%) MuA: Morocco LS (1.1%)
1	UTF	ML	15	Beans	VT spring	No	Gt: Granby LFS (96%) WeA: Watseka LS (3.9%)
2	CTF	Ingles	62	Beans	Strip till	No	Gt: Granby LFS (61.4%) Mk: Maumee mucky LFS (16.9%) Ad: Adrian muck (11.7%) OaB: Oakville FS (1.5%) MuA: morocco LS (0.5%)
2	UTF	011B/011C	26	Beans	VT spring	No	Gt: Granby LFS (73.2%) To: Toto muck (10%) Gn: Granby mucky LFS (10.7%) Ad: Adrian muck (2.9%) Gf: Gilford FSL (2.6%)
3	CTF	The 120	43	Beans	Strip till	No	Gt: Granby LFS (50.6%) Mk: Maumee mucky LFS (31.8%) Ad: Adrian muck (8.3%) OaC: Oakville FS (6.6%) To: Toto muck (1.6%) WeA: Watseka LS (.6%) OaB: Oakville FS (.3%)
3	UTF	012	20	Corn	No-till	No	Gt: Granby LFS (79.2%)

							Mk: Maumee mucky LFS (12%) Ad: Adrian muck (7.7%) OaB: Oakville FS (1.2%)

Soil Sampling and Analyses

Soils were sampled November 14-17, 2018. For the bulk density portion of sampling, three soil cores were collected randomly one within each of the three stratified trafficked zones with a 7.62 cm diameter soil core to a depth of 7.5 cm. Cores were retained separately as samples for each traffic zone within each field which was repeated at a total of five random locations throughout the field. For bulk density, a 7.5 cm diameter ring is driven into the soil (7.5 cm depth) with a hammer and block of wood as seen below in figure 1. ("Bulk density and soil aeration", n.d.).

Figure 1. Ring used to take bulk density core samples which was driven in with a hammer and wood plank.

The outer edges of the core are removed with a knife. With a clean plastic bag, the sample core is measured and recorded. A 1/2 cup subsample is then taken of the core after mixing the soil uniformly. The wet weight of the sample is recorded, and the sample is dried in the microwave for 2 ×15 minute defrost cycles until no weight change is seen. The dry weight is then recorded, and the bulk density of the soil is calculated as g of soil per cubic cm^3 and reported in table 4.

Soil aggregate stability is a general, integrative soil health measure (Arshad, Lowery, & Grossman, 1996; Karlen & Stott, 1994), and can be quantified using a number of techniques but one of the simplest methods is measuring the ability for a soil aggregate to maintain structure, or resist disaggregation, upon multiple rewetting events (Herrick et al., 2001). An undisturbed surface sample of soil aggregates for each sample site and zone was also collected from the upper 3.25 cm of soil, left in bulk form and dried in a warm, dry room for 40 d. before aggregate stability was conducted. After the drying process was complete and no weight change was detected, four 18-22 mm diameter aggregates from each zone and field was weighed for initial weight. Each aggregate was first submersed for 8 min, and then 5 s submersion cycles with 5 s breaks between the cycle. After the final submersion cycle, the remaining aggregates are placed into a muffin tin and dried for 8 h at 66 °C (*sensu* Herrick, 1992). Final dry weight of the aggregate was recorded and the difference in aggregate weight is calculated for stability in terms of net grams lost. The weights were taken via an American Weight Scale AMW-2000 scale model on the dry aggregate and recorded followed again by the dry weight after the dunking cycles and the drying process were completed. Net mass lost was calculated as original minus slaked divided by the original weight (Table 5).

Statistical Analyses

The statistics utilized will be through Statistical Analysis Software (SAS) programming. The LSMEANS procedure will be used with a p value of .05 in order to look at the significance of mean comparisons. The other procedure used is the GLM procedure which will be used to understand more about the analysis of variance in both sets of data. The ANOVA outputs will be available in the appendix of the document for reference as well as the raw data from both bulk density and soil aggregate results. Each replicate of the bulk density and soil aggregate stability measurements will have a mean value calculated. An analysis of variance was used in order to draw conclusions about the F value, probability, sum of squares, variance as well as understanding the comparison of means. We will also draw observational analyses from the raw data as well to draw conclusions.

Table 2. ANOVA table for both Bulk Density and Soil Aggregate stability showing Sources of variation, Df, MS, F and Pr>F using the LSMEANS function in SAS.

Variable	Source of variation	Df	Type 1 SS	MS	F	Pr>F
Bulk Density	Traffic	1	.05695771	.05695771	2.33	.1303
	Zone	2	.24221512	.12110756	4.96	.0092
	Traffic x Zone	2	.07442200	.0372110	1.53	.2235
Soil Aggregate Stability	Traffic	1	.622175504	.62175504	19.87	<.001
	Zone	2	.00081791	.00040896	.01	.9870
	Traffic x Zone	2	.01305519	.00652760	.21	.8121

V. Results and Discussion

Bulk density

The mean bulk density for both the CTF and the UTF operations differed depending on location of the zone. Statistically speaking bulk density results demonstrated a zone effect but no significant treatment effect. Bulk density values were calculated for each treatment and ranged on average from 1.27 g/cm^3 to 1.43 g/cm^3 in the CTF treatment and 1.12 g/cm^3 to 1.46 g/cm^3 in the UTF treatment when looking at all pairs. If we are to break it down further by zone of traffic, the non-compact zone of the CTF operation showed an average of 1.19 g/ cm^3 while the UTF operation showed a higher average of 1.28 g/ cm^3. The results show a 7% reduction in the seven-year CTF operation as compared to the traditional UTF operation on Granby LFS in the non-trafficked zones. Other zones such as the planter zones between the two treatments showed slight differences but not as drastic as the non-compact zones. Planter and sprayer zones for field location 1 both showed to be higher on average for CTF zones, which is to be expected due to higher intensity of travel across these tramlines. This field was also recently grid tiled 2 years prior. Field locations 2 and 3 however did not display the same observation. Interestingly, the UTF treatment for these sites were both lower in planter and sprayer zones than that of the CTF treatment. Neither planter nor sprayer zones between the two operations showed significant differences statistically between bulk density on the farms in this experiment, however the non-compact zone did demonstrate significance (p= .05). The sprayer zones between the two treatments across all field replications averaged around the same value of 1.34 g/cm^3 which was unexpected due to the higher concentration of wheel traffic in the CTF zone. It was hypothesized that there would be a higher bulk density on the tramlines of the CTF operation due to consistent traffic over the seven-year period. My hypothesis on higher tramline compaction rates was drawn from a study done on sugar beets that concluded that repetitive heavy traffic loads leads to higher bulk density and aggregate density values while porosity and air filled permeability decreased (Schäfer-Landefeld, Brandhuber, Fenner, Koch, & Stockfisch, 2004). Overall, the CTF operation averaged lower bulk densities in sprayer and non-compact zones across field replications when compared to the UTF traffic pattern as seen below in Figure 1. The bulk density results concluded that there is a positive impact on compaction reduction with the implementation of controlled traffic management practices. CTF fields examined and tested demonstrated lower bulk densities leading us to infer better porosity ratios on a field wide basis when compared to traditional traffic patterns.

Figure 2. Bulk Density results bar chart for UTF and CTF on each traffic zone.

Soil Aggregate Stability

Soil aggregate stability is a measurement of the susceptibility of aggregates to external destructive forces. The aggregate stability results of the CTF treatment showed lower soil mass lost versus that of the UTF and was significant overall treatment effect across all zones. Soil aggregates of the CTF ultimately held together better during the dunking cycles leading to a lower number of net grams lost. Across all farms, the average mass lost was much lower on the CTF operations (23%) versus the UTF (48%) (Fig. 2). Even the compacted zones lost less soil under CTF than UTF – 33% and 29% less loss in planter and sprayer zones respectively. When looking at the non-compact zone, there was an average net loss of 28% less in the CTF treatment.

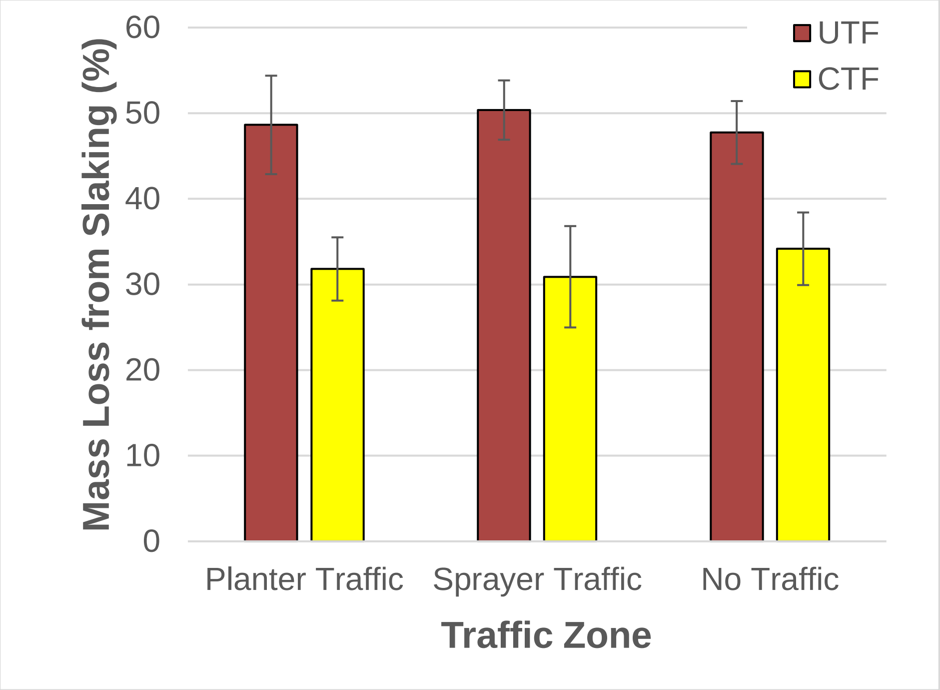

Figure 3. Soil Aggregate Stability percent mass lost from slaking for both UTF and CTF in all zones.

This commercial farm research clearly demonstrated the positive effects of CTF on soil physical properties of Northwestern Indiana Granby loamy fine sands. In the non-compact zones, the CTF showed an improvement in soil aggregate stability and reduced bulk density ratings over that of the UTF treatment. Despite results not always being statistically significant in all zones, the CTF treatment did show a general pattern of better stability and lower bulk density ratings in the CTF treatment. Concerning soil aggregate stability, all three zones averages concluded that the CTF operation lost less mass overall than that of the UTF operation. Statistical differences occurred in the sprayer zone (P=.01) and in the planter and non-compact zones (P=.05). My measurements are also proxies for other important soil health properties. In other words, this reduced bulk density and more stable aggregates also reflect better porosity, infiltration rates (Y. X. Li et al., 2007), and improved root growth in corn and soybean crops (Y. X. Li et al., 2009).

I expected that CTF might actually result in higher compaction in trafficked zones (like sprayer and planter), since machinery is restricted to these zones concentrating overall time that force is applied to these soils. However, it is interesting to note, that these ‘trafficked’ zones were not all that more compacted than the conventional, UTF. Observationally, platy soil structure was found in many of the planter and sprayer zones on the CTF operation as well as in some portions of the UTF field as seen in figure 4 below.

Figure 4. Platy structure in CTF sprayer zone in field 1.

Visually we might be led to believe that there is overall better field health through less compaction, increased aggregate stability and better porosity ratios in the CTF operation. In the CTF system percentages for aggregate stability ranged on average from 23% to 48% mass lost while the UTF system ranged on average from 34% to 65% of mass lost. The UTF system demonstrated a wider range of soil loss over the CTF perhaps leading us to believe there is a difference in the consistency of soil aggregate stability in the overall field between the two treatments.

Soil aggregate stability may be more consistent in the CTF system due to better soil health, porosity ratios and more glomalin holding these aggregates together while the UTF treatment may experience a broad range of physical properties affecting soil health. In a study done on aggregate stability there is shown to be a direct relationship between the stability of an aggregate and glomalin (produced by arbuscular mycorrhizal fungi) which both increased as a result of reduced traffic practices which is the goal with the CTF system (Wright, Starr, & Paltineanu, 1999). We might infer that there would be a direct relationship between increased glomalin and better soil health due to the reduced amount of traffic contributing to compaction. The CTF treatment also presented an average of 28% less mass lost in the non-compact zone of travel. Based on the better soil aggregate stability results of the CTF farms might lead us to infer that these soils have better water holding and movement capacity, protection of soil organic matter, increased aeration, improved root development, higher favorability to a positive microbial environment and facilitate better root development (Arias, González-Pérez, González-Vila, & Ball, 2005). Soil aggregate health is related to several ecosystem functionalities which include the resistance to erosion (Blackburn & Pierson, 1994), the makeup and quality of organic matter (Tisdall, 1996), soil biotic activity (Wander et al., 1994), infiltration capacity of water (Pierson et al., 1994) as well as the composition stability of macroaggregates (Bethlenfalvay & Barea, 1994).

Observationally when looking at the raw data for the soil aggregate stability procedure, we can say that there was a difference between the two compared treatments. The higher the net gram value, the better the soil aggregate held together leading us to believe that there are more natural glues holding that aggregate together thus in turn healthier soil structure. How well soil aggregates hold together is a function of how well they can hold up to disruptive forces (Kemper & Rosenau, 1986). The CTF treatment showed to have more natural glues holding the soil together. This research leads us to believe that through better soil aggregate stability soils present more long-term stability and resistance strength than those not on a tramline.

Soil aggregate stability testing can sometimes be variable in success according to the percent organic matter content in the soil you are working with. Organic matter additions increase the soil structural stability and in higher OM soils this can often times influence outcomes when dealing with these soils in aggregate stability testing (Ditzler & Tugel, 2002). Our series the Granby loamy fine sand (LFS) only has an average of 2%-3% organic matter so skewed aggregate stability outcomes from high organic matter was not a worry when working with this soil type. One pertinent thing to consider is that LFS textures have been found to either be extremely durable or sometimes easily crushed when undergoing stability testing depending on what crops have been grown previously and tillage practices implemented. Course textured soils on the other hand showed less variability in field trials (Skidmore & Layton, 1992). Since our Granby loamy fine sand is a of a fine grained particle size, this could have led to some variability in the field trials. It is also possible that damage from heavy equipment passes in the UTF treatment have damaged the loamy fine sand soil structure in the UTF treatment leading to a poor aggregate stability outcome.

When looking at bulk density values the contrast was less drastic but still significant (P= .05) in the non-compact zone which is the focus zone of our study. Overall, the non-compact zone showed a 10% improvement in bulk density ratings in the CTF treatment. When looking at the combined field improvements again the planter zone showed an average of a 2% increase while the sprayer showed no benefit to CTF. As stated, we would have expected higher bulk density values in the CTF treatment zones of the planter and sprayer, however that only occurred in the field 1 pairing. Fields 2 and 3 interestingly demonstrated higher bulk density readings for these zones in the UTF system. Some possible explanations for this could be compaction from using heavy equipment by operating in less than optimal moisture conditions or long-term damage sustained to the loamy fine sand soil structure from random traffic patterns. The soils in each pairing both demonstrated similar climatic, drainage and topography in relation to one another so differences in these factors leading to higher compaction ratings is likely ruled out.

Overall this experiment has shown the differences originally hypothesized; however, they were not as significant as expected for seven years of CTF practice. It is possible that CTFs effects on soil physical properties take longer than seven years to have noticeable changes. Despite changes being small, there were differences in the physical properties that could eventually lead to a substantial increase in yield, infiltration, better rooting development and a healthier soil microbial population but further study is needed on this topic to explore those outcomes.

VI. Conclusions

In this on-farm research study we compared traditional long term UTF to a seven-year CTF operation to see if there were noticeable differences in physical soil properties on northwestern Indiana Granby loamy fine sands. CTF had a slight positive impact on soil physical properties, more dramatically in soil aggregate stability but also in the case of bulk density. Despite the use of long term CTF, the differences in soil properties were relatively small but did present positive improvements to physical soil attributes. Traffic lines that have been intensively driven on show symptoms of compaction damage to physical properties while areas not trafficked of the CTF showed improvements even when compared to the entire UTF operation.

To further understand the implications of CTF on soil physical properties there may be some considerations for further testing. I would consider looking at a 10 year and 15 year CTF practice to perform further testing. It would also be valuable to have more robust and widely tested treatments across various states and soil types could also provide more information on if CTF can be more beneficial to soil physical properties on certain soil types under certain conditions. Additional testing procedures on these farms could include carbon burst procedures to determine yet another indicator of soil health. Carbon burst testing uses the amount of CO2 released to understand the soils maximum biological activity. Water infiltration testing may also be another useful insight to understand more quantitatively about how soil porosity is affected. Yield testing in the form of a strip trial would also be an interesting way to mix farm economics to quantify how valuable CTF is to an operation.

In conclusion, there are differences between the two traffic systems (mostly aggregate stability) indicating there are benefits to soil physical properties by operating a CTF tramline system. The non-compact zones of each field comparison are the most important comparison to be made because 80%-90% of the CTF field is non-compact while 10%-20% is compacted tracks. Comparably, 100% of the UTF field has been crossed with traffic at some point being impacted by damage to physical properties. By the CTF treatment presenting better bulk density and soil aggregate stability ratings, we can see there are differences among the physical soil properties between the two systems that could lead to other positive effects which could lead to a future of more sustainable farming practices. With the overall decreased level of compaction in the field, there is potential to also adopt less tillage practices as a result, further helping reduce time and money put into the operation. Long term CTF practices such as this seven-year study display the benefits of itself by helping to regenerate damaged soils as well as reduce the negative impacts of intensive wheel traffic. With further study on the subject, the potential of CTF in the United States presents an exciting future for these sustainable farming systems.

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Appendix

Field Maps of Location and Sample spots

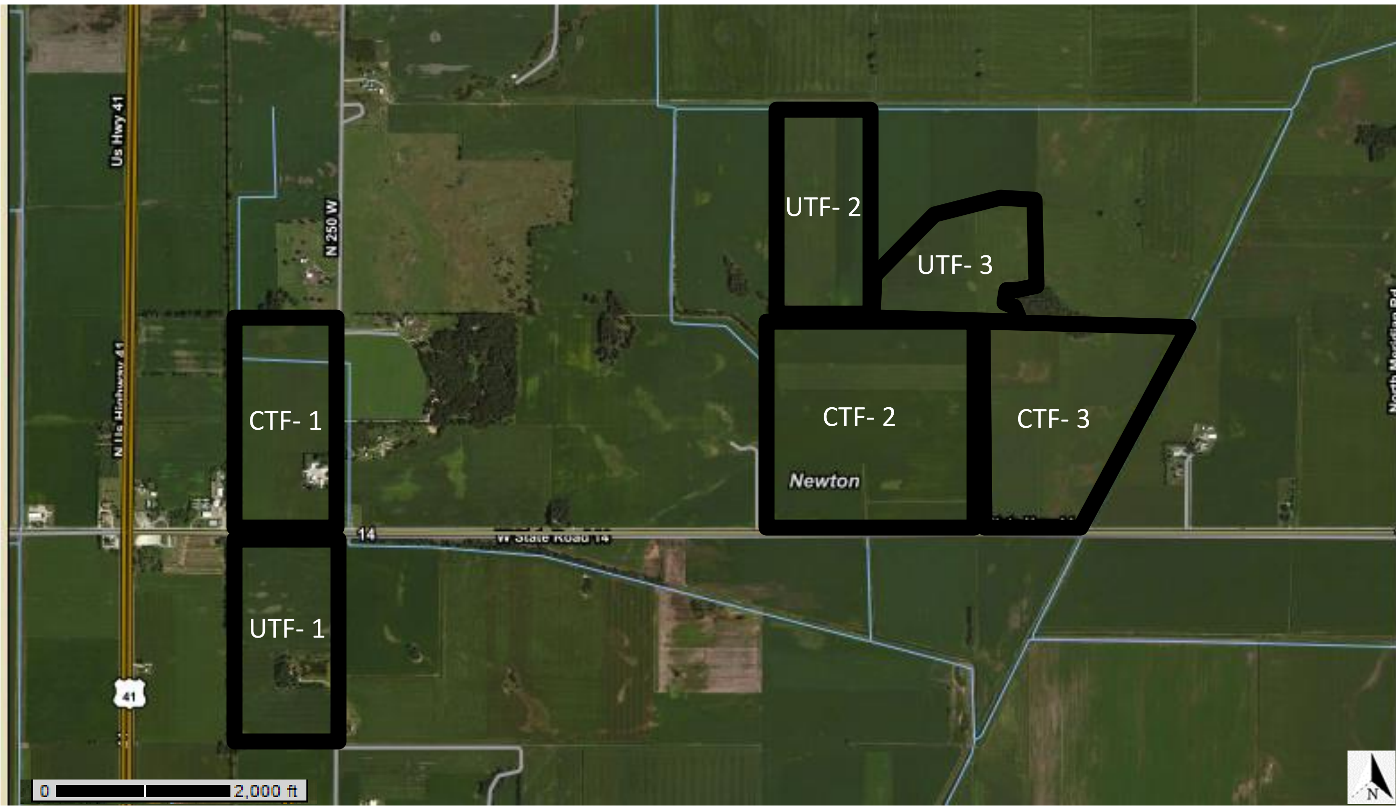

Figure 5. CTF and UTF Field locations in proximity to one another. They are located 6 miles northeast of the nearest city Morocco, Indiana.

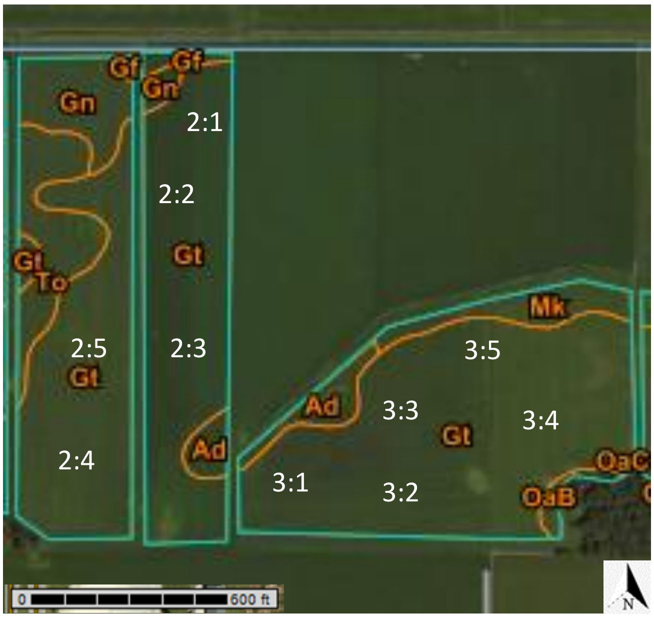

Figure 6. UTF Fields 2 and 3 with sample locations which are located north of state road 14.

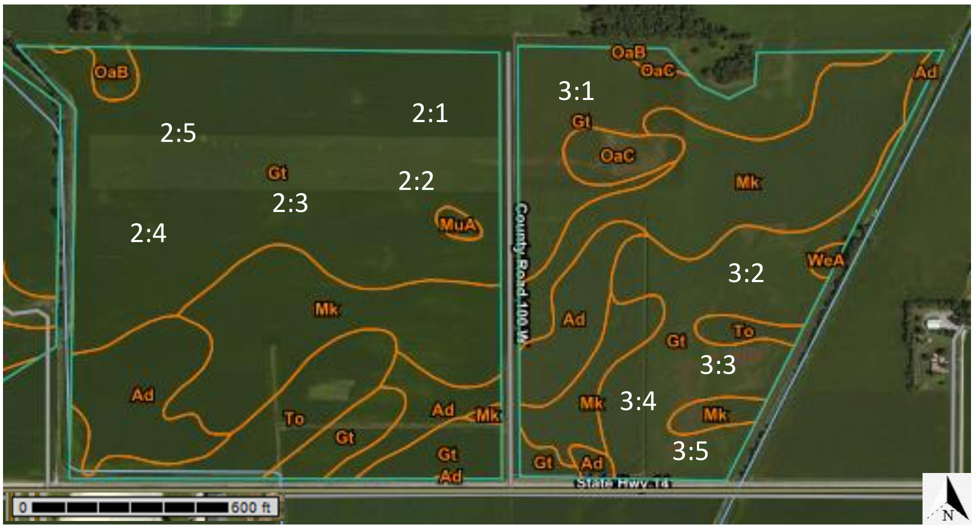

Figure 7. CTF Fields 2 and 3 with sample locations which are located north of state road 14.

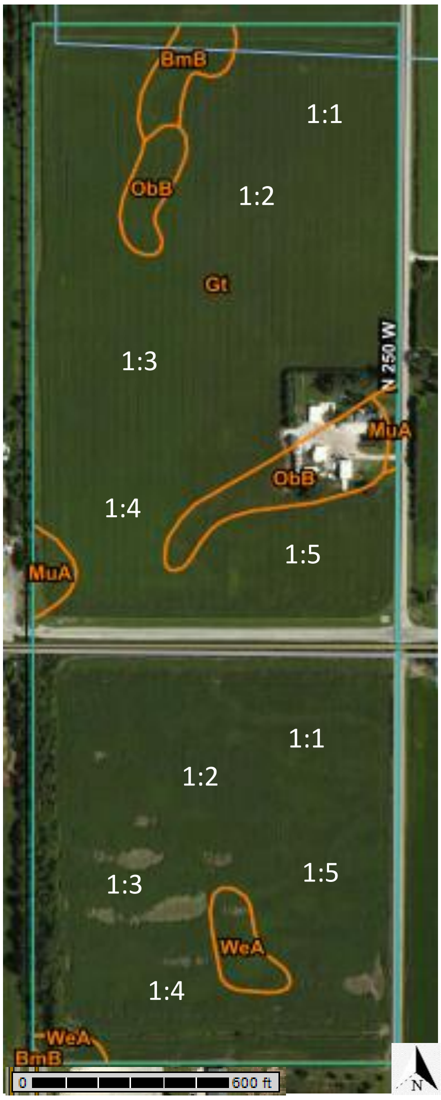

Figure 8. Field 1 for CTF (Top) and UTF (Bottom) and sample spots which are located south of state road 14.

Bulk density information and Calculations

Table 3. Bulk Density Information and calculations used.

Bulk density Information and Calculations
Volume used in experiment: πr^2x Height 3.14 x $(3.66\ \text{cm})^2$x(7.62 cm) = 321 cm^3
Dry weight of soil bulk sample= {Weight of field moist soil + bag (grams)- Weight of bag (grams)]/ [1+ Soil Water content g/g)
BD= Dry weight of bulk sample/volume of soil core

Bulk Density Data

Table 4. CTF and UTF Bulk Density results reported in g/cm^3.

Farm	Field	Spot	Zone	Bulk Density	Farm	Field	Spot	Zone	Bulk Density
CTF	1	1	Non-Comp	1.34	UTF	1	1	Non-Comp	1.53
CTF	1	1	Planter	1.49	UTF	1	1	Planter	1.39
CTF	1	1	Sprayer	1.44	UTF	1	1	Sprayer	1.35
CTF	1	2	Non-Comp	1.45	UTF	1	2	Non-Comp	1.35
CTF	1	2	Planter	1.53	UTF	1	2	Planter	1.50
CTF	1	2	Sprayer	1.42	UTF	1	2	Sprayer	1.34
CTF	1	3	Non-Comp	1.40	UTF	1	3	Non-Comp	1.44
CTF	1	3	Planter	1.40	UTF	1	3	Planter	1.38
CTF	1	3	Sprayer	1.52	UTF	1	3	Sprayer	1.40
CTF	1	4	Non-Comp	1.37	UTF	1	4	Non-Comp	1.30
CTF	1	4	Planter	1.60	UTF	1	4	Planter	1.27
CTF	1	4	Sprayer	1.50	UTF	1	4	Sprayer	1.30
CTF	1	5	Non-Comp	1.43	UTF	1	5	Non-Comp	1.42
CTF	1	5	Planter	1.53	UTF	1	5	Planter	1.57
CTF	1	5	Sprayer	1.51	UTF	1	5	Sprayer	1.48
CTF	2	1	Non-Comp	1.12	UTF	2	1	Non-Comp	1.35
CTF	2	1	Planter	1.43	UTF	2	1	Planter	1.33
CTF	2	1	Sprayer	1.34	UTF	2	1	Sprayer	1.30
CTF	2	2	Non-Comp	1.04	UTF	2	2	Non-Comp	1.37
CTF	2	2	Planter	1.41	UTF	2	2	Planter	1.41
CTF	2	2	Sprayer	1.27	UTF	2	2	Sprayer	1.44
CTF	2	3	Non-Comp	1.17	UTF	2	3	Non-Comp	1.29
CTF	2	3	Planter	1.41	UTF	2	3	Planter	1.44
CTF	2	3	Sprayer	1.33	UTF	2	3	Sprayer	1.38

CTF	2	4	Non-Comp	1.19	UTF	2	4	Non-Comp	1.22
CTF	2	4	Planter	1.31	UTF	2	4	Planter	1.37
CTF	2	4	Sprayer	1.25	UTF	2	4	Sprayer	1.24
CTF	2	5	Non-Comp	1.05	UTF	2	5	Non-Comp	1.13
CTF	2	5	Planter	1.25	UTF	2	5	Planter	1.31
CTF	2	5	Sprayer	1.14	UTF	2	5	Sprayer	1.35
CTF	3	1	Non-Comp	0.86	UTF	3	1	Non-Comp	1.48
CTF	3	1	Planter	1.00	UTF	3	1	Planter	1.50
CTF	3	1	Sprayer	0.99	UTF	3	1	Sprayer	1.44
CTF	3	2	Non-Comp	1.15	UTF	3	2	Non-Comp	1.25
CTF	3	2	Planter	1.23	UTF	3	2	Planter	1.31
CTF	3	2	Sprayer	1.45	UTF	3	2	Sprayer	1.27
CTF	3	3	Non-Comp	0.93	UTF	3	3	Non-Comp	1.25
CTF	3	3	Planter	0.92	UTF	3	3	Planter	1.37
CTF	3	3	Sprayer	0.92	UTF	3	3	Sprayer	1.35
CTF	3	4	Non-Comp	1.18	UTF	3	4	Non-Comp	1.12
CTF	3	4	Planter	1.55	UTF	3	4	Planter	1.41
CTF	3	4	Sprayer	1.69	UTF	3	4	Sprayer	1.38
CTF	3	5	Non-Comp	1.21	UTF	3	5	Non-Comp	1.33
CTF	3	5	Planter	1.51	UTF	3	5	Planter	1.38
CTF	3	5	Sprayer	1.34	UTF	3	5	Sprayer	1.01

Soil Aggregate Data

Table 5. CTF and UTF raw data of soil aggregate stability results reported as a percent net weight of grams lost.

Farm	Field	Spot	Zone	Before Weight	After Weight	Net Weight Loss (%)	Farm	Field	Spot	Zone	Before Weight	After Weight	Net Weight Loss (%)
CTF	1	1	Non-comp	17	14	-17.6	UTF	1	1	Sprayer	20	13	-35.0
CTF	1	1	Planter	22	20	-9.1	UTF	1	1	Planter	23	14	-39.1
CTF	1	1	Sprayer	14	10	-28.6	UTF	1	1	Non-comp	22	16	-27.3
CTF	1	2	Non-comp	24	11	-54.2	UTF	1	2	Sprayer	22	16	-27.3
CTF	1	2	Planter	20	5	-75.0	UTF	1	2	Non-comp	21	12	-42.9
CTF	1	2	Sprayer	16	13	-18.8	UTF	1	2	Planter	16	10	-37.5
CTF	1	3	Non-comp	22	21	-4.5	UTF	1	4	Non-comp	21	8	-61.9
CTF	1	3	Planter	20	11	-45.0	UTF	1	4	Sprayer	24	8	-66.7
CTF	1	3	Sprayer	20	15	-25.0	UTF	1	4	Planter	22	8	-63.6
CTF	1	4	Non-comp	21	13	-38.1	UTF	1	5	Sprayer	22	15	-31.8
CTF	1	4	Planter	20	17	-15.0	UTF	1	5	Planter	21	15	-28.6
CTF	1	4	Sprayer	20	12	-40.0	UTF	1	5	Non-comp	23	15	-34.8
CTF	1	5	Non-comp	21	15	-28.6	UTF	2	1	Non-comp	22	14	-36.4
CTF	1	5	Planter	22	14	-36.4	UTF	2	1	Sprayer	23	16	-30.4
CTF	1	5	Sprayer	19	10	-47.4	UTF	2	1	Planter	22	7	-68.2
CTF	2	1	Non-comp	22	16	-27.3	UTF	2	2	Non-comp	22	7	-68.2
CTF	2	1	Planter	20	15	-25.0	UTF	2	2	Sprayer	24	14	-41.7
CTF	2	1	Sprayer	19	12	-36.8	UTF	2	2	Planter	22	8	-63.6
CTF	2	2	Non-comp	21	12	-42.9	UTF	2	3	Non-comp	21	7	-66.7
CTF	2	2	Planter	22	14	-36.4	UTF	2	3	Sprayer	23	17	-26.1
CTF	2	2	Sprayer	23	17	-26.1	UTF	2	3	Planter	22	14	-36.4
CTF	2	3	Non-comp	22	15	-31.8	UTF	2	4	Planter	23	16	-30.4
CTF	2	3	Planter	20	4	-80.0	UTF	2	4	Non-comp	23	12	-47.8
CTF	2	3	Sprayer	23	11	-52.2	UTF	2	4	Sprayer	23	17	-26.1
CTF	2	4	Non-comp	19	15	-21.1	UTF	2	5	Sprayer	21	9	-57.1
CTF	2	4	Planter	20	17	-15.0	UTF	2	5	Non-comp	22	14	-36.4
CTF	2	4	Sprayer	18	14	-22.2	UTF	2	5	Planter	20	10	-50.0
CTF	2	5	Non-comp	22	14	-36.4	UTF	3	1	Planter	22	13	-40.9
CTF	2	5	Planter	21	18	-14.3	UTF	3	1	Non-comp	20	5	-75.0
CTF	2	5	Sprayer	21	14	-33.3	UTF	3	1	Sprayer	21	5	-76.2

CTF	3	1	Non-comp	23	14	-39.1	UTF	3	2	Planter	22	9	-59.1
CTF	3	1	Planter	22	20	-9.1	UTF	3	2	Non-comp	22	9	-59.1
CTF	3	1	Sprayer	21	18	-14.3	UTF	3	2	Sprayer	22	6	-72.7
CTF	3	2	Non-comp	20	12	-40.0	UTF	3	3	Sprayer	22	4	-81.8
CTF	3	2	Planter	22	16	-27.3	UTF	3	3	Non-comp	23	16	-30.4
CTF	3	2	Sprayer	17	16	-5.9	UTF	3	3	Planter	23	11	-52.2
CTF	3	3	Non-comp	21	16	-23.8	UTF	3	4	Planter	23	6	-73.9
CTF	3	3	Planter	21	18	-14.3	UTF	3	4	Non-comp	22	9	-59.1
CTF	3	3	Sprayer	21	16	-23.8	UTF	3	4	Sprayer	24	2	-91.7
CTF	3	4	Non-comp	20	9	-55.0	UTF	3	5	Non-comp	21	11	-47.6
CTF	3	4	Planter	19	10	-47.4	UTF	3	5	Planter	21	13	-38.1
CTF	3	4	Sprayer	23	14	-39.1	UTF	3	5	Sprayer	22	9	-59.1
CTF	3	5	Non-comp	23	11	-52.2	UTF	1	3	Planter	23	12	-47.8
CTF	3	5	Planter	25	18	-28.0	UTF	1	3	Sprayer	22	15	-31.8
CTF	3	5	Sprayer	20	10	-50.0	UTF	1	3	Non-comp	22	17	-22.7

Overall ANOVA (SAS) outputs

Table 6. SAS ANOVA output for Bulk Density on UTF and CTF across all zones showing significant differences between UTF and CTF farms.

Source	DF	Sum of Squares	Mean Square	F Value	Pr>F
Model	5	.37359483	.07471897	3.06	.0137
Error	84	2.04923250	.02439562		
Corrected Total	89	2.42282732			

Table 7. SAS ANOVA output for Soil Aggregate Stability on UTF and CTF across all zones showing significant differences between UTF and CTF farms.

Source	DF	Sum of Squares	Mean Square	F Value	Pr>F
Model	5	6351.98267	1270.39653	4.06	.0024
Error	84	26284.31333	312.90849		
Corrected Total	89	32636.29600			

Bulk Density Results (SAS) across zones of travel

Table 8. SAS ANOVA output for Bulk Density on UTF and CTF on Non-compact zones showing significant differences in both UTF and CTF.

Source	DF	Sum of Squares	Mean Square	F Value	Pr>F
Model	1	.12644079	.12644079	5.49	.0264
Error	28	.64457777	.02302063		
Corrected Total	29	.771010856			

Table 9. SAS ANOVA output for Bulk Density on UTF and CTF on Sprayer zones showing non-significant differences in both UTF and CTF.

Source	DF	Sum of Squares	Mean Square	F Value	Pr>F
Model	1	.00013318	.00013318	0.00	.9446
Error	28	.75941865	.02712209		
Corrected Total	29	.75955183			

Table 10. SAS ANOVA output for Bulk Density on UTF and CTF on Planter zones showing non-significant differences in both UTF and CTF.

Source	DF	Sum of Squares	Mean Square	F Value	Pr>F
Model	1	.00480574	.00480574	.21	.6514
Error	28	.64523608	.02304415		
Corrected Total	29	.66004182			