ASSESSMENT OF EQUIPMENT PERFORMANCE VARIABLES FOR IMPROVED MANAGEMENT DURING TILLAGE OPERATIONS

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ASSESSMENT OF EQUIPMENT PERFORMANCE VARIABLES FOR IMPROVED MANAGEMENT DURING TILLAGE OPERATIONS

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ASSESSMENT OF EQUIPMENT PERFORMANCE VARIABLES FOR IMPROVED MANAGEMENT DURING TILLAGE OPERATIONS

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Corey Mitchell Kichler, son of Walter and Evelyn Kichler, was born on September 2, 1983 in Elberta, AL. He was raised on a family farm with his brothers Jeremy and Benjamin. He graduated from Foley High School in May of 2001 and then attended Faulkner State Community College for 1 year. He began attending Auburn University in the fall of 2002 and graduated with a Bachelors of Science degree in Biosystems Engineering in May of 2005. He started graduate school in that same year in Civil Engineering working as a graduate research assistant in the Biosystems Engineering department.

THESIS ABSTRACT

ASSESSMENT OF EQUIPMENT PERFORMANCE VARIABLES FOR IMPROVED MANAGEMENT DURING TILLAGE OPERATIONS

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Deep tillage operations required to alleviate compaction layers in soils found especially in the southeast region of the United States remains to be one of the largest areas of energy and fuel expense for agricultural producers. Good farm managers look for more efficient fuel utilization techniques with improved productivity. The objectives of this research were to: 1) develop an in-field monitoring system to display and collect various real-time tractor and implement performance data; 2) collect and analyze tractor and implement performance data while varying different equipment operational variables during deep tillage operations; and 3) quantify fuel usage and cost savings for the implementation of site-specific equipment management strategies. Four different experiments were performed. A depth performance experiment investigated subsoiler draft and fuel consumption requirements for two different tillage depths (22.8 cm and 35.6 cm). The effects of tillage time rotation on energy requirements of three different subsoilers were also studied. The third experiment evaluated the effects of speed on equipment performance and energy requirements between two different subsoilers. The final experiment investigated the response of three different tire pressures on equipment performance and was used to highlight the value of spatially collected equipment data.

Results from the depth performance experiment indicated that a 130% and 23% increase in draft and fuel consumption, respectively, occurred between the shallow and deeper tillage depths. Draft more than doubled over a 12.7 cm depth difference indicating tillage at shallower depths can save energy and fuel costs. The tillage rotation experiment resulted in increases in fuel consumption, draft and axle torque in the triennial year rotation compared to annual and biennial rotations. The implement speed experiment showed that the Kelley Manufacturing Company (KMC) subsoiler had a 115.0%, 7.1%, and 37.3% increase in fuel consumption, axle torque, and implement draft respectively from a slow to fast speed. A 105.0%, 2.3%, and 27.8% increase in fuel consumption, axle torque, and implement draft, respectively, resulted between slow and fast speeds for the Paratill™. The data from the tire pressure experiment showed a 4.6%, 69.0%, and 17.1% increase in fuel consumption, tire slip, and axle torque, respectively, between the low and high air pressure treatments. Spatially, field variables effected equipment performance data with 17% to 23% increases in fuel consumption depending on travel direction and terrain differences. In conclusion, these experiments differentiated equipment performance between some of the available modern tillage implements and operational variables to quantify fuel usage and potential cost savings for alternative methods of performing tillage operations.

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CHAPTER ONE
INTRODUCTION

Problem Statement

In the Southeastern United States, soil compaction commonly occurs in agricultural fields. Soil compaction has been studied for decades and results from weather conditions, soil characteristics, and equipment traffic. Compaction layers commonly referred to as “hard pans” impede root growth causing adverse effects on crop yields. Soil properties including bulk density and cone index can indicate the severity of compaction throughout a field. However, over the years tillage has been the most effective way of managing this issue. New conservation tillage methods such as strip and site-specific tillage can decrease the energy requirements for such practices compared to conventional tillage methods while alleviating the existence of compaction.

Research has been limited to date on spatially monitoring equipment performance while performing subsoiling operations to assess how equipment performs across fields with inherent soil and terrain variability. Literature primarily concentrates on the effects tillage depth has on draft and fuel consumption within an assumed homogeneous study site. Since large amounts of energy is expended during deep tillage, the scope of this research covered different effects of speed, equipment setup, implement selection, and other factors that can lead to savings in the field during subsoiling operations. With the advent of the global positioning system (GPS), the capability exists of spatially documenting agricultural operations. Currently, spatial field documentation has been limited to precision agriculture technologies such as yield monitoring and spatially recording field activities such as planting and fertilizing. Equipment manufacturers are now using controller area networks (CAN) as the standard communication protocol on equipment. The use of CAN now permits equipment operators to document engine performance data such as fuel usage and load which can be tied back to geographic locations using GPS coordinates. This technology also enables equipment performance data to be monitored in real-time making it possible to modify operational performance on-the-go thus, optimizing fuel and energy usage. Spatially linking performance data can also provide the data necessary to analyze performance at a sub-field level.

Equipment performance monitoring has application in industries beyond agriculture. In construction, project management is essential in carrying out jobs in a timely and economical manner. Models have been developed to estimate the productivity and efficiency of earthmoving operations prior to construction. However, these models are complicated to operate and require specialized skills, not making them practical for implementation by construction companies. Research is limited on real-time performance monitoring of construction equipment during operation.

Objectives

The main goal of this experiment was to investigate relationships between equipment performance and various aspects of tillage operations to develop more efficient management methods to conserve energy and reduce costs. Therefore, the objectives of this research were to:

1. Develop an in-field monitoring system to display and collect various, real-time tractor and implement performance data,
2. Collect and analyze tractor and implement performance data while varying different equipment operational variables during deep tillage operations, and
3. Quantify fuel usage and cost savings for the implementation of site-specific equipment management strategies.

Thesis Organization

The *Introduction* chapter provides a brief overview of problems that are faced with tillage operations and the goals of this research. The *Literature Review* details previous research and other relevant information related to this project. The next Chapter, the *Methodology*, outlines the development of the performance monitoring system along with the equipment and experimental procedures used to conduct the four different tillage experiments. The *Results and Discussion* chapter summarizes collected data and supporting discussion on the relevance of the results. Finally, the last chapter summarizes the results for the different experiments conducted; presents final conclusions for this research; and suggests future work.

CHAPTER TWO
REVIEW OF LITERATURE

Introduction

Equipment performance has been a popular topic for researchers from past-to-present. This chapter presents previously performed research on general equipment performance and theory of equipment mechanics and management. Since the focus of this research is on tillage operations, research related to soil properties and the interaction between soil and implements is also discussed.

Off-Highway Vehicle Performance

Agricultural Applications

Over the years, the trend has been for farmers to upgrade to larger machinery for performing various field and farm tasks. The main reason has been the increase in acreages an individual farmer actually manages. In many cases, tractors will be overrated for the task at hand since smaller tractors have been replaced. However, the same task is completed without adopting different operating techniques to compensate for unused horsepower.

Data acquisition systems on tractors have provided researchers with valuable information over the years. Schrock et al. (1982) devised a system to perform transmission gear recommendations for operating agricultural machinery. The purpose of this project was to maximize tractor efficiency using microcomputer technology to predict the most appropriate gear for the task being performed. The system used algorithms to analyze engine load, engine speed, and transmission speed to predict and display a gear and throttle setting in an attempt to maximize operating efficiency of the tractor. An equipment operating method known as "gear up, throttle down" was the basis for recommendations performed by the gear selection aid. While maintaining a predetermined speed, the operator "gears up" to a lower gear ratio and reduces engine speed, thus reducing overall engine load (Schrock et al., 1982 and Grisso et al., 2001).

Schrock et al. (1982) evaluated the system under four in-field operations. Two trials were performed operating a grain drill with and without the display active. The third operation was done pulling an anhydrous ammonia applicator and the fourth operated a chisel plow. Average fuel savings with the display active was 19.8% compared to use without the display. Using microcomputer technology, a gear selection aid proved to increase efficiency of agricultural processes.

Grisso et al. (2001) explained the "Gear Up and Throttle Down" concept, mentioned earlier, for saving fuel. Adjusting to a higher gear enables the operator to run at the same travel speed and reduce engine speed 70% to 80% of the rated engine speed. They showed that the most efficient operation occurred at less than 65% of rated maximum load. However, the engine can be overloaded by being expected to produce increased torque at higher speeds. They reported that a larger tractor pulling a light load using the geared up and throttled down concept will use the same or less fuel as a smaller tractor at full load. Guidelines for this technique included:

- Use on light loads only,
- Stay within working revolutions per minute (RPM) range of engine,
- Select a gear to sustain travel speed but decrease engine speed, and
- Do not overload engine.

In 1993, Turner devised a data acquisition system to determine an agricultural machine's tractive performance in the field. American Society of Agricultural Engineers (ASAE) standard S296.5 (2003) defines tractive efficiency as the ratio of output power to input power for a traction device. A traction device is defined as a powered device for propelling a vehicle using reaction forces from the supporting surface (ASAE S296.5, 2003). Tractive efficiency can also be described using the following relationship:

$$T.E. = \frac{(P \times V)}{(T \times \omega)} \tag{2.1}$$

where,

	T.E.	= tractive efficiency
	P	= vehicle tractive force (kN)
	V	= vehicle travel speed (m/s)
	T	= torque applied to tractive device (N-m)
	ω	= angular velocity (rad/s)

Turner (1993) pointed out that tractive efficiency serves as a good basis for improving traction. His particular system measured vehicle ground speed, traction surface speed, and draft force. Draft measurements were collected with a load cell for use with pull-type implements. Radar gun technology was utilized to collect ground speed as well as wheel speed. He used indirect methods to obtain power input to the tractive device so tractive efficiency (Eq. 2.1) could be derived.

Hansson et al. (2003) performed research on the effects of transient loads on fuel efficiency of agricultural tractors. Testing was executed under four different operations with various engine speeds. A 17,000 kg (37,479 lb) trailer was pulled for instrumentation calibration and some testing procedures. A steady state test was conducted with three different transmission gear settings and two engine speeds, 2,100 rpm and 1,700 rpm. An acceleration test was performed by accelerating to the maximum velocity attainable while towing the trailer. The third test was done with no load under normal on-farm driving conditions including acceleration, deceleration, and turning. The last test involved moving 15 buckets of material with a front-end loader from one location to another. Tractor fuel efficiency was decreased under transient loading caused mainly by non-optimal air/fuel ratio, meaning there was inadequate air intake for proper fuel-air ratio causing the engine to run rich (Hansson et al., 2003). Non-optimum air/fuel ratios resulted in increased fuel consumption and increased emissions due to incomplete fuel combustion. A decrease in fuel efficiency indicated that more fuel was used to accomplish the same amount of work. The researchers concluded that the front-end loading resulted in a 13% decrease in fuel efficiency compared to the steady-state test. The normal farm driving under no load experienced a 7% decrease compared to steady-state operations.

Draft measuring devices can be important tools for fully understanding the impact of draft on equipment energy requirements. Three point hitch mounted implements can be difficult to collect accurate draft measurements because of complex geometry. Al-Janobi (2000) researched a data acquisition system to monitor the performance of three-point hitch mounted implements. Two draft dynamometer designs were developed: 1) frame type and 2) integrated type. The first group consists of an independent frame with transducers that mount between the tractor and the implement. Integrated dynamometers have transducers built into the stock lift system. The advantage of the integrated system was the ability to maintain the geometry of the lift system (Al-Janobi, 2000). He chose to utilize an integral system that measured forces in the longitudinal and vertical planes for use with category II and III implements. A 100 kN tension/compression load cell was integrated in the existing top link of the tractor. The lower links of the 3-point hitch were implemented with an extended octagonal ring transducer (EORT) developed by R.J. Godwin in 1975 (Al-Janobi, 2000). This particular transducer measured vertical and horizontal forces simultaneously at the ball end of the lower link. The implement depth and angular position of the dynamometer were measured with a rotary position transducer connected to the rockshaft of the tractor lift system. The transducer signals were linked to a datalogger that was connected to an activity unit. The activity unit was responsible for providing an excitation to the transducers and identified the test being performed by the tractor. Testing was conducted using a 2.10 m chisel plow at tillage depths of 7 cm, 12 cm, and 0.15 cm. He concluded that the integral draft system performed well during field testing.

Construction Applications

Construction site preparation often requires earth and materials to be relocated to different locations at the site or transported to another location. Earthmoving operations usually involve a loading unit that loads a hauling unit with material. The hauling unit then transports the load to another location such as an area needing to be filled or a disposal area (Martinez, 1998). For large projects, large fleets of equipment are used to increase productivity. Prior to starting the project, operations must be planned out logistically so that the operation can be completed under the time allotted for the phase.

Estimating productivity of these operations prior to beginning is necessary for project planning and budget management. Minor improvements in logistics and equipment selection for these operations can result in considerable time and money savings.

Several simulation models have been developed to analyze earthmoving operations prior to project commencement (Smith, 1999). Complex simulation models that have been developed are highly advanced and require extensive training and programming knowledge. Navon (2005a; 2005b) indicated the need for autonomous project performance control. Data collected autonomously would present the tools to compare expected with actual performance. Real-time control using this type of data would aid in keeping projects on track, thus meeting specified objectives and deadlines. Monitoring positions of equipment with GPS would be beneficial in analyzing operation efficiencies. Currently, the literature is limited on real-time monitoring of construction equipment.

Forestry Applications

Veal et al. (2005) investigated the tillage energy requirements needed for forest site preparation. Similar to agricultural soils, compaction also occurs in forestry sites due to heavy equipment traversing throughout the site during harvest. Costly tillage processes for forestry applications can cost up to $250 per hectare. The goal of this research was to quantify the power requirements needed to perform conventional forestry site tillage to develop methods for improving equipment efficiency and lower costs. The implement used for experimentation was a single shank trailing subsoil plow that was configured with a vertical coulter in the front of the ripping shank and discs in the rear of the implement. The experiment design was five treatments with five different implement configurations. The implement depth and tractor travel speed were constant for each treatment. Implement draft force was measured with a load cell and equipment position monitored by GPS. Veal et al. (2005) reported a 34% decrease in draft force with the ripping shank alone compared to the coulter and the ripping shank. This reduction was the most noticeable draft difference among the implement setup combinations. They also mentioned the need for further research to include different implements and configurations to better understand the power requirements of different operations. Research pertaining to forestry tillage operations and equipment performance was limited.

Spatial Equipment Management

Measuring equipment operating characteristics and associating them to field variables can be used to improved efficiencies and lower operating costs. Yule et al. (1999) evaluated a real-time GPS data acquisition system on a Zetor agricultural tractor implemented with a tine cultivator outfitted with a consolidation roller. Variables monitored directly included fuel consumption, fuel temperature, engine speed, draft force, pitch and roll angles, GPS position, wheel speed, and ground speed. Engine performance maps described with equations were used to extract torque values. They created general performance maps of field slope, slip, and operating costs. Operating costs, excluding fuel costs, were calculated according to work rates collected with the tractor performance system. Areas of high slip were identified and field remediation was suggested so that operating costs could be decreased. They concluded that operating costs increased in areas of high slope causing increased wheel slip, thus decreasing work rate.

Adamchuk et al. (2004) used the GPS position of a tractor to assess performance and estimate operational costs. The main goal of their research was to investigate the possibilities of using geographic position records to assess the spatial performance of agricultural machinery. The three main variables identified to quantify spatial performance were speed, swath width, and the traffic pattern. Experiments were performed with a grain combine equipped with two individual GPS devices. One GPS device collected data only while the combine was harvesting and the other collected data the entire time in the field. Adamchuk et al. (2004) developed an algorithm to post-process collected traffic patterns. They identified two characteristics of interest to be obtained from this data, field capacity and field efficiency. Field capacity is defined by ASAE standard S495.1 (2005) to be the ratio of effective field capacity to theoretical field capacity. Effective field capacity is defined as the actual rate of land or crop processed in a known amount of time. Theoretical field capacity is defined as the rate of performance obtained if a machine performs its function 100% of the time at a given operating speed using 100% of its theoretical width (Adamchuk et al., 2004). Maps were created to spatially analyze the performance of the combine. Adamchuk et al. (2004) concluded that areas of low field efficiency were associated with unnecessary turns, field obstacles, and overlapping paths.

Demmel et al. (2002) configured a system to collect geo-referenced data in order to improve farm management and equipment traceability. The system was installed on five test tractors on a test farm in Germany which acquired data such as: GPS coordinates, engine speed, power-take-off (P.T.O) speed, draft forces, and others values depending upon the implement and process being done. The basis of their work was to obtain an autonomous data acquisition system that collects data without operator interaction. The system had three basic components: an agricultural CAN bus system, GPS, and implement identifiers (Demmel et al., 2002). The task controller determined if the tractor was actually performing or not performing in the field. This assessment was accomplished by comparing field position data to the actual data being acquired from the GPS during field operation.

An overwhelming amount of data was collected with the system, so algorithms were developed to compute and collect valuable data (Demmel et al., 2002). The data collected autonomously with the system helped quantify how efficiently the farm equipment was working in the field. They used the programs IMI_{lyzer} along with the database program Microsoft Access® to post-process the data. The data provided the total hours spent in the field and percentages of time working, turning, and standing idle. Averages and totals were also easily computed after data was post processed. Collecting draft forces along with GPS data enabled the researchers to create maps of estimated soil resistance for each field which could be used for site-specific management. Demmel et al. (2002) concluded that these types of GPS based systems are a valuable way to improve in-field efficiency of farm equipment. However, the system did not provide a real-time display permitting the operator to make machine operating adjustments in the field.

Off-Highway Vehicle Management

Traction

Traction describes the effectiveness of power transfer between a tractive device and another surface. Tractive efficiency can be improved by adjusting operating technique and equipment setup. Tractive efficiency is defined as the ratio of drawbar power to axle power. Travel reduction is defined as the reduction in forward speed that occurs when a tractor pulls a load. Slip is a term often interchanged with travel reduction. However, slip can occur without pulling a load. Adjusting the amount of slip the tractor is having can improve tractive efficiency. Optimum slip ranges according to ASAE standard EP496.2 (2003) are as follows:

- 4% to 8% for concrete,
- 8% to 10% for firm soil,
- 11% to13 % for tilled soil, and
- 14% to 16 % for soft soils and sands.

The tractive performance of the tractor can be calculated by analyzing the performance of each individual drive tire. The motion resistance of the front wheels subtracted from the net pulls of the drive wheels is how to calculate the drawbar pull of a two wheel drive tractor.

A draft equation (ASAE Standard EP496.2, 2003) for a certain implement that incorporates field conditions is as follows:

$$D = R_{sc} + MR \tag{2.1}$$

where,
D = draft, N
R_{sc} = soil and crop resistance, N
MR = total implement motion resistance, N

Soil and crop resistance is defined by the ASAE standard EP496.2 (2003) as the force parallel to the direction of travel resulting from the contact between the soil or crop and the working components of the implement. An equation for soil and crop resistance is as follows:

$$R_{sc} = nr_{sc} \tag{2.3}$$

where,
R_{sc} = soil and crop resistance, N
n = implement numeric including total width, number of shanks, cross-sectional area, number of rows
r_{sc} = unit soil and crop resistance specific to the implement: ASAE D497, clause 4
(ASAE EP496.2, 2003)

Motion resistance for the entire implement is calculated as follows:

$$MR = \Sigma R_M \tag{2.4}$$

where,
MR = total implement motion resistance, N
R_M = motion resistance of each wheel supporting the implement, N
(ASAE EP496.2, 2003)

Calculating drawbar power for tractor powered implements and propulsion power for self propelled implements is calculated as follows:

$$P_{db} = \frac{Ds}{const.} \tag{2.5}$$

where,
P_{db} = drawbar power required for the implement, kW
D = implement draft, kN
s = travel speed, km/h
$const.$ = 3.6 metric units
(ASAE EP496.2, 2003)

Jenane et al. (1996) investigated the relationship between tractive performance and specific fuel consumption of agricultural tractors over a range of field conditions.

They indicated that the main variable that restricts higher drawbar pulling efficiency was excessive wheel slippage. Further, they also reported that soil type, soil condition, tractor configuration, and hitch type effect slip. A microcomputer based data acquisition system was developed to monitor drawbar load, engine speed, forward speed, torque, transmission output torque, and fuel consumption. Data was recorded to a magnetic tape for later interpretation. Specific variables calculated during testing included slip, dynamic traction ratio, axle torque, and tractive efficiency (Jenane et al., 1996). Slip was calculated with the following formula:

$$s = 100 \times \left(1 - \left(\frac{v_1}{v_2}\right)\right) \tag{2.6}$$

where, s = slip, %
v_1 = forward speed under load, km/h
v_2 = theoretical speed under no load, km/h

Dynamic traction ratio is defined as ratio of drawbar load to tractor weight.

$$D_{tr} = \frac{d_p}{W} \tag{2.7}$$

where, D_{tr} = Dynamic traction ratio, dimensionless
d_p = drawbar pull, N
W = tractor weight, N

Three field conditions were tested that included crop stubble, a chisel plowed field, and a moldboard field (Jenane et al., 1996). They concluded that fuel consumption was maximized when the tractor operated near maximum tractive performance. Increased fuel efficiency was found to be within a slip range of 10% to 30%.

Equipment Management

Many methods of managing and selecting the proper equipment to perform a specified job have been developed. Srivastava et al. (1993) discussed several concepts for estimating in-field productivity for agricultural machinery. Field capacity is a measure of equipment productivity in the field and is described as the amount of area a machine can process over a period of time illustrated in equation 2.8 below:

$$C_a = \frac{vw\eta_f}{10} \tag{2.8}$$

where,
C_a = theoretical field capacity (hectares/hour)
v = travel speed (km/h)
w = machine working width (m)
η_f = field efficiency (decimal)

Due to non-productive activities like turning, overlap, and material fill-up, field efficiency cannot be 100%. Field efficiency is defined as the ratio of theoretical time to perform a task to the time loses associated to the performed operation shown in equation 2.9:

$$\eta_f = \frac{\tau_t}{\tau_e + \tau_h + \tau_a} \tag{2.9}$$

where,
η_f = field efficiency (dimensionless)
τ_t = theoretical time required to perform operation (h)
τ_e = τ_t / K_w, (h)
K_w = fraction of implement actually utilized
τ_a = time losses proportional to area, (h)
τ_h = time loses not proportional to area, (h)

Srivastava et al. (1993) include a table available that shows field efficiencies, speed ranges, and estimated maintenance costs of many different field operations as they pertain to agricultural operations.

Estimated draft requirements are important for choosing the proper tractor to operate an implement. Srivastava et al. (1993) provided formulas for estimating the implement draft requirement and the drawbar power required to pull the implement under field conditions. The draft requirement for implements was estimated using the following formula:

$$D_I = F_i \left(A + Bv + Cv^2\right) wd \tag{2.10}$$

where,

D_I	= implement draft (kN)
F_i	= texture adjustment factor
i	= 1 for fine soils, 2 for medium soils, or 3 for coarse textured soils
A, B, C	= implement adjustment factors
w	= implement working width (m)
v	= travel speed
d	= tillage depth (cm)

The draft equation above is prelude to estimating drawbar power requirements (2.11).

$$P_{db} = \frac{D_I\ v}{3.6} \tag{2.11}$$

where,

P_{db}	= drawbar power (kW)
D_I	= implement draft (kN)
v	= travel speed (km/h)

In-field management of machinery is important for performing tasks in a timely manner. Economic machinery management is an important aspect of farming that needs attention. Ownership costs include depreciation, interest, taxes, insurance, and sheltering the machinery. Depreciation is the value reduction of a machine over time. Estimating machinery depreciation can be a key factor in determining economic management strategies (Srivastava et al., 1993).

Bryant (2004) described some methods the J.G. Boswell Company used to manage equipment. This company or farm row crops about 140,000 acres which requires hundreds of different tractors and implements. A farm of this scale tries to run efficiently as possible by effectively managing their equipment. The management philosophy is to operate as fast as possible using the least number of people. With this philosophy in mind, they have adopted the use of tracked tractors to minimize soil compaction and disturbance by reducing tractor weight and increasing available horsepower. They have been successful at accomplishing a weight to power ratio of 1 horsepower to 100 pounds of tractor weight.

Ballasting

Zoz et al. (1995) performed research on a methodology for estimating proper tractor ballasting. Previous methods of choosing proper ballasting for agricultural operations were based general field observations and not technical calculations as they reported. The traditional idea was that the amount of slip governs equipment ballasting. However, ballasting varies with soil types and cannot be solely estimated from slip. They suggested that gross traction ratio was the best variable to base ballasting recommendations. Gross traction ratio (2.12) is defined as the input to the tractive device.

$$GTR = \frac{P}{(W \times V_t)} \tag{2.12}$$

where,
GTR = Gross traction ratio (fraction)
P = Tractor power, kW
W = Tractor weight, kg
V_t = Theoretical travel speed, m/s

Net traction ratio can be a good indicator of proper ballasting if the drawbar force is known. This variable also changes with soil strength and tire size, which makes it difficult to accurately calculate. The main objective of proper tractor ballasting was to maximize the time spent at maximum tractive efficiency, and to minimize fuel consumption (Zoz et al., 1995). They suggested that gross traction ratio was the best estimate of proper ballasting for agricultural tractors because of its independence of soil strength and traction devices. Unfortunately, many operators ballast their equipment according to the worst case scenario that the tractor will encounter and never alter this configuration. They suggested a gross traction ratio of around 0.50 was required for maximum tractive efficiency. In order to spend the most time at maximum tractive efficiency, the ballast will have to be lighter than the ballasting required for the worst cases of operation. They concluded that gross traction ratio of 0.54 to 0.60 supplied good traction efficiency for most operations.

Equations have been developed to estimate equipment performance data without direct measurement. Goering et al. (2004) discussed equations to estimate equipment variables. A definition of linear power (2.13) was defined:

$$P = \frac{(F \times S)}{3.6} \tag{2.13}$$

where,
P = linear power (kW)
F = force (kN)
S = speed (km/h)

If fuel consumption is known then fuel equivalent power can be calculated. Fuel equivalent power (2.14) is defined as the amount of power that can be obtained by burning fuel.

$$P_{fe} = \frac{\lfloor (HV) \times (M_f) \rfloor}{3600} \tag{2.14}$$

where,
P_{fe} = fuel equivalent power (kW)
HV = heating value of fuel (kJ/kg)
M_f = mass fuel consumption rate (kg/h)

The mass fuel consumption rate (2.15) is a function of the volumetric flow rate and the density of the fuel at time of consumption.

$$M_f = Q_f \times P_f \tag{2.15}$$

where, M_f = mass fuel consumption rate (kg/h)
Q_f = volumetric fuel consumption rate (L/h)
P_f = fuel density (kg/L)

Tire Pressure

Adjustments made to tire pressure can improve traction and operational efficiency. Lancas et al. (1996) performed research on the effect of tire pressure on equipment productivity. There are two types of tires used in agriculture, bias-ply and radial. A radial tire is constructed with the reinforcing belts, usually steel belts, sideways under the tread rather than lengthwise and a bias-ply tire has crossed layers of ply cord running diagonally to the tread. Radial tires perform better because the belts stiffen the tire which reduces lug deflection which decreases performance (Lancas et al., 1996). These tires have increased side wall deflection which increases the contact area, thus increasing traction. Power-hop is a problem encountered when using radial tires and is defined as a combination of vibration and bounce that causes a vertical jumping effect seen on mechanical front wheel drive (MFWD) and four-wheel-drive tractors (4WD) (Lancas et al., 1996). Advantages to lower tire pressures include higher tractive efficiency, increased fuel efficiency, lower soil compaction, and power-hop control.

Lancas et al. (1996) performed a series of tests in California in both spring and summer of 1994. Spring testing consisted of disking a wet, Capay clay with two tire inflation pressures. A high tire pressure of 165 KPa and a low/correct pressure of 76 KPa for the rear tires and 90 KPa in the front tires were chosen for these tests. Over the summer, a Rincon silt clay/Yolo silt loam soil was tilled with a 9 shank subsoiler using two tire inflation pressures. Inflation pressures for summer consisted of a high pressure of 165 KPa and low/correct pressures of 97 KPa for the rear and 90 KPa in the front for summer testing. A John Deere 8870 4WD agricultural tractor was used for testing. Soil data collected included moisture content, bulk density, and cone index. They concluded that a tractor with lower tire pressures used 20% less fuel and achieved a 5.7% increase in productivity.

Soil Compaction

The impact of soil compaction on agricultural soils has been studied and documented for well over 50 years. Farmers, foresters and others who cultivate land have found the existence of soil compaction to be a cumbersome problem. As with many problems, compaction can have a wide range of influence on plants. Plants may be influenced minimally, causing a slight decrease in growth and yield, or compaction can totally impede crop growth by limiting seedling emergence resulting in little or no yield.

Solids, liquids, and gas are three main components constituting soil. Mineral and organic particles make up the solid portion while liquid and gas parts occupy pore space or porosity. All three components are important when defining soil compaction. Compaction involves the reduction of the porosity of the soil matrix caused by an external factor. Soil compaction has been defined as the process by which the macro-pore structure of soil collapses and soil particles are rearranged (Reaves and Nichols, 1955).

Soil pores are important to plant growth. They permit water and air movements through soil along with letting roots penetrate and explore the soil medium to collect nutrients and moisture. As porosity is reduced, plant growth is directly affected. Soil compaction involves both internal and external variables, which determine its magnitude and extent. Natural soil characteristics determine the internal factors such as soil texture and structure. External factors exert pressure on the soil matrix and generally are induced by surface traffic and cultivation practices. As machinery and other equipment traverses a soil, pressure is applied that tends to push soil particles closer together creating less space for the gas-liquid components of the soil. Moisture and other variables such as soil texture can also effect soil compaction.

Soil moisture content is the factor having the greatest influence on the degree of compaction generated by external pressure (Weaver and Jamison, 1951; Amir et al., 1976; Cooper and Nichols, 1959; and Hampton and Selig, 1965). Throughout the year, moisture fluctuates with rain and snow accumulation, and the drying effects caused by nature. Moisture held between soil particles acts as a lubricant (Harris, 1971). The presence of moisture allows particles to be more easily rearranged and to be packed together much tighter than in dry conditions. The bulk density of soil increases with increasing moisture content, but only to an optimum moisture content for compaction, at a given pressure. Most soils are compactable when the moisture content reaches field capacity (Akram and Kemper, 1979). Field capacity is defined as the moisture content of a soil after it has drained from saturation for approximately 24 hours. Soils with water contents above field capacity do not compact as easily because water occupies some or all of the macropore space.

Dry soils have more resistance to compaction. More pressure is required to compress a dry soil to a given porosity than is required for a moist soil. In return, more power is required for tillage and similar operations at lower moisture contents. Soil moisture conditions during field operations play a significant role in managing compaction due to the pressure exerted by large equipment.

Both texture and structure determine the ability of soil to supply nutrients, water and air to plants (Grandt, 1988). Soil texture is the distribution of the size of soil particles expressed in percent of sand, silt, and clay. Soil structure is the connection of various sizes of soil particles into secondary particles or aggregates. Raghaven et al. (1976) reported that, for a given external pressure, soil of any texture will be compacted to some degree. Clay soils at high moisture contents are susceptible to compaction (Eriksson et al., 1974). Of the three soil particle size categories, sand will compact to a denser state than silt or clay (Larson et al., 1980). A soil having a wide range of particle sizes is more compactable than one with a uniform particle size because smaller particles can move into the voids between larger particles.

Plant roots have a harder time penetrating a compacted clayey soil than a compacted sandy soil. Veihmeyer and Hendrickson (1948) showed that plant roots could grow well in a sandy soil at 1.6 g/cm^3, but experienced an effective barrier in clay soil at the same density with growth factors kept equal between both textures. A poorly structured soil is susceptible to compaction, notably those with low organic matter contents (Larney and Fortune, 1986).

Literature has indicated that an increase in soil organic matter results in a decrease in compatibility (Larson and Allmaras, 1971; Howard et al., 1981; and Free et al., 1947).

The existence of organic matter within soil horizons helps reduce both bulk density and penetration resistance, and increases the ability of soil to retain and transport water (Ohu et al., 1994). Most farmers depend on crop residue left after harvest to add to the organic matter content of soils within their fields. The residue is considered important and most farmers benefit by managing residue to preserve an optimum level.

Wheeled vehicles are the most predominant types of transport elements used in off-road applications. Wheeled machinery is faster and less damaging to paved roadways than tracked vehicles. However, these machines are the most common source of machine-induced soil compaction (Reed, 1940). The first pass of a wheel induces about 80% of the total compaction on a loose soil. As with agricultural soils, forested soils are also sensitive to compaction. A conventional forest harvesting operation can cause 20% to 40% soil disruption and compacting (Brady et al., 2002). The highest impacts are along the skidder trails were machines skid logs to the landing decks.

Rubber tires tend to concentrate a load in a relatively small contact area between the ground and tire. This leads to high contact pressures on equipment with large axle loads. Agricultural tractor tires inflated to nominal pressures of 69 to 103 KPa commonly apply pressures of 138 to 345 KPa to the soil (Cohron, 1971).

Several advancements that reduce the tendency of pneumatic tires to compact soils are: wider tires (Taylor, 1980), larger diameter tires, and lower inflation pressures (Abu-Hamdeh et al., 1995). Robertson and Erickson (1978) showed that dual tires and flotation tires could decrease compaction. These advancements increase the contact area at the tire-soil interface reducing the exerted pressure by distributing the weight of the machine over a larger area.

The adverse effects of soil compaction on crop growth have been recognized for years. Bulk density and soil strength are two physical properties which quantify soil compaction. The level of compaction which requires amelioration for a given soil type is not well understood. No generally accepted rule of thumb exists.

Soil bulk density is defined as the weight of oven dry soil divided by its volume. Therefore, bulk density provides a measurement for the compactness of soils. Many methods have been devised to determine the bulk density of soil. Special coring devices have been developed to extract soil of know volume while minimizing disruption of its natural state (Brady et al., 2002). Devices have a cylinder that has a series of inner cylinders of a known volume that are filled with soil when driven into the ground. First the samples must be dried in the over at 105ºC for 72 hrs. The samples are weighed and the bulk density is calculated.

Bowen (1981) suggested a general rule (with many exceptions) that bulk densities of 1.55, 1.65, 1.80 and 1.85 Mg/m^3 can impede root growth and thus will reduce crop yields in clay loams, silt loams, fine sandy loams, and loamy fine sands, respectively. Bulk density greater than 1.2 Mg/m^3 for clay soil, 1.6 Mg/m^3 for loam soil, and 1.8 Mg/m^3 for sandy loam adversely affected the root growth of rice (Kar et al., 1976). Singh et al. (1992) proposed a bulk density less than or equal to 1.3 Mg/m^3 as non-limiting to crop growth, in any soil type. However, due to the lack of research literature, they suggested that a maximum bulk density of 2.1 Mg/m^3 in any type of soil is unusable by plants. Within the range of 1.6 to 2.0 Mg/m^3, some type of tillage or other physical manipulation should be applied. Around 2.0 Mg/m^3, a critical bulk density for soils, exists at which roots are unable to penetrate and develop.

Soil strength or mechanical impedance is also an indicator of how easily roots can penetrate soil and provides a measurement of the physical resistance of a soil to deform under pressure. Cone index is measure of soil strength that is measured with an instrument called a soil cone penetrometer. ASAE S313.3 (2004) describes the cone penetrometer as a driving shaft with a 30 degree circular stainless steel cone (or cone base) at one end. Recommendations for cone base sizes are: 323 mm^2 with 15.88 mm diameter shaft for soft soils and 130 mm^2 with a 9.53 mm diameter shaft for hard soils. For accurate cone index readings, the cone should be inserted into the ground at a rate of 30 mm/s. Readings should be taken at least every 50 mm of depth (ASAE EP542, 1999).

Manual penetrometers can be difficult to operate and pose inaccuracies if insertion is paused to take readings. Raper et al. (1999) developed a tractor mounted soil cone penetrometer with an on-board instrumentation system for increased measurements. The penetrometer was hydraulically inserted in the ground and a SOMAT® instrumentation system collected cone index readings at rates between 5 to 10 Hz. This system was effective for applications that require higher sampling rate such as soil compaction profiling.

Penetrometer resistance limiting root growth depends upon the soil conditions and characteristics and the crop of interest. Ehlers et al. (1983) stated that the penetrometer resistance limiting growth of oats was 3.6 MPa in tilled Ap horizon, but 4.6 to 5.1 MPa in untilled Ap horizon and subsoil. Cone index became less dependent on dry density at higher moisture contents. Sojka et al. (1990) studied the effect of penetrometer resistance on sunflowers. A penetrometer measurement of 2 MPa produced some restriction to root growth and a resistance of 3 MPa created a total barrier to root elongation. A maximum root growth index for citrus is 1.5 MPa (Lutz et al., 1986). Taylor et al. (1964) found that cotton roots are unable to penetrate soil strength above 3.0 MPa in an Amarillo fine sandy loam. Murdock et al. (1995) suggested a penetrometer reading of 2.07 MPa as indicative of severe compaction for Kentucky soils. The literature suggests that penetrometer values measured with a 13-mm, 30-degree cone tip above 2.5 to 3.0 MPa limits root growth in most soils (Busscher and Sojka, 1987).

Philips and Kirkland (1962) and Morris (1975) reported corn yield reductions of 10 to 22 % due to compaction. Canarache et al. (1984) reported that each 0.1 Mg/m^3 increase in bulk density created an 18% decrease in maize grain yields compared to the yield on a non-compacted plot. Increased soil compaction can reduce yields in potatoes up to 22% (Saini and Lantagne, 1974) and decrease wheat growth (Feldman and Domier, 1970). These results illustrated the potential for compaction to reduce crop yields.

Gaultney et al. (1980) studied the effect of bulk density on corn (*Zea mays* L.) yields over two years. They compacted a silt loam soil to densities between 1.71 to 1.82 Mg/m^3. A layer of the compressed soil, 0.04 to 0.05 m thick was placed at 0.20 to 0.23 m depths within in the soil. Yields were reduced by 45% to 50% over the study. Similarly, Pollard and Elliott (1978) found barley (*Hordeum vulgare* L.) yields were reduced by 38% due to a sandy loam soil compacted to range of 1.89 to 2.07 Mg/m^3 at 0.15 to 0.20 m depth as compared to compaction levels between 1.52 to 1.56 Mg/m^3 at the same depth. Unger and Kasper (1994) reported that natural amelioration of compaction can result from freezing/thawing and wetting/drying cycles in some soil types.

Methods to Reduce Compaction

Current cropping practices produce a cycle between soil compaction produced by off-road equipment and the alleviation of this condition by means of tillage or natural processes such as freezing and thawing. Nature tends to reduce soil compaction over several years, but most stewards of the land require a quicker cure for compaction problems. Tillage is the main process used in agriculture to break up compacted layers.

Controlled Traffic

Considerable research has shown controlled traffic to be an effective means of reducing compaction in agricultural operations (Buckingham, 1975; and Dumas et al., 1973). Equipment is confined to predetermined paths to decrease the area of soil affected and traffic is restricted to dry soils. Real time kinematic (RTK) technology is being used to guide equipment with centimeter accuracy. Manufacturers including John Deere and Trimble have agricultural guidance systems on the market that automatically steer the tractor along a predetermined path. These systems are often used for installation of in-furrow irrigation systems were accuracy is crucial. Guidance systems would allow for easy implementation of controlled traffic. Gan-Mor and Clark (2001) indicated that controlled traffic can lessen and in some cases eliminate the need for deep tillage operations. Raper and Bergtold (2007) reports a 6% fuel savings and 9% draft force reduction could be achieved with controlled traffic subsoiling.

Tillage

"Tillage may be defined as the mechanical manipulation of soil for the purpose of enhancing the growth of crops" (Wells, 1994). Tillage processes are used to reduce bulk density and lower soil strength to facilitate root development. Deep tillage, sometimes called subsoiling, provides a method to alleviate poor physical properties caused by soil compaction. The presence of hardpans and other restrictive layers requires deep tillage to break up these layers and permit roots to reach the B-horizon early in the growing season to access valuable nutrients and moisture. The U.S. southeastern coastal plains contain sandy loam soils, which are highly compatible. Many researchers have studied the effects of deep tillage on these soils and have often reported yield increases for crops (Chancy and Kamprath, 1982; Box and Langdale, 1984; Reeves and Touchton, 1986; Sene et al., 1985; Wagger et al., 1992; and Busscher et al., 1988). Kamprath et al. (1979) showed that subsoiling increased the utilization of subsoil moisture in soils with root limiting layers.

Deep tillage can result in benefits for short periods of time or create adverse effects. Gaultney et al. (1982) found subsoiling was ineffective in reducing the effects of compaction on a silt loam soil in Indiana. Barnhisel (1988) reported that there was a tendency for bulk density to increase over a period of two years in both ripped and non-ripped areas. Elkins et al. (1983) also noted that subsoiling has short-term beneficial effects but undesirably mixes soil horizons. Subsequent cultivation operations requiring machinery traffic, along with the natural settling of the soil particles, can lead to a reduction on pore space that was created by deep tillage (Larney and Fortune, 1986; and Kouwenhoven, 1985). Therefore, some soils may require yearly subsoiling to help reduce soil strength and bulk density and enhance plant growth. However, deep tillage requires large amounts of power and can become costly if required annually. Raper and Bergtold (2007) recommended subsoiling when soil has adequate moisture so that surface soil disruption and energy requirement can be minimized. They reported a 19% fuel savings and a 28% draft reduction by avoiding tillage in dry conditions.

Site-Specific Tillage

Rising fuel costs are influencing producers to consider alternative tillage methods to reduce input costs. Most crop producers subsoil at a constant depth usually limited by the moisture content of the soil and/or the size of the tractor and implement being used (Raper et al., 2005a). However, soil compaction occurs at variable depths throughout a field and many producers subsoil deeper than required.

A method known as site-specific tillage reduces energy requirement and saves fuel cost by tilling only to the depth required to destruct compaction layers. Knowing where the hardpan is located throughout the field and performing tillage site-specifically can decrease energy requirements and optimize crop yields (Raper et al., 2005a). First, the compaction layer is located throughout the field and tillage zones are assigned according to depth layers. Methods of locating the compaction layers include bulk density, cone index, and electrical conductivity. Fulton et al. (1996) investigated using the physical soil properties bulk density and cone index to determine the depth of the hardpan. He reported that little correlation existed between dry bulk density and cone index for the particular soil type being examined. According to the selected dry bulk density threshold of 1.6 Mg/m^3, no portion of the field exceeded this value. However, portions of the field exceeded the cone index threshold of 2.0 MPa. Fuel consumption estimations yielded a 50% reduction in fuel usage could be achieved with subsoiling the portions of field exceeding the 2.0 MPa cone index value compared to uniform deep subsoiling the entire field.

Raper et al. (2005a) investigated the idea of using site-specific tillage techniques in order to save energy and maximize corn yields. Tests were carried out using three tillage patterns. Site-specific tillage was carried out at three depths: 25 cm, 35 cm, or 45 cm. The second treatment was to simulate uniform depth subsoiling at 45 cm and the third treatment was no subsoiling. The results show that site-specific subsoiling had similar affects compared to deep subsoiling, but both methods had better results than no tillage. Various treatments of cover crops were also planted and tested but did not have a significant effect on corn yields. Subsoiling at the shallower depths of 25 cm and 35 cm required less draft force compared to deep subsoiling (45cm), thus saving time and energy. Referring to Table 2.1, shallower subsoiling also reduced the amount of fuel used during the operation with fuel savings of 45% for 25 cm subsoiling and 27% for 35 cm subsoiling depth compared to deep subsoiling.

Raper et al. (2005b) performed a similar experiment to investigate subsoiling benefits on cotton production. The results showed slightly higher savings with a 59% and 35% decrease in draft forces with the 25 cm and 35 cm tillage depths respectively compared to uniform deep depth tillage at 45 cm. Reductions in power requirements reached 52% with the 25 cm depth compared to deep tillage and 26 % less power required at the 35 cm tillage depth. Estimations of fuel savings ranged from 43% with the 25 cm depth and 27% less fuel required for the 35cm tillage depth.

Abbaspour-Gilandeh et al. (2005) also investigated the energy and fuel savings for variable-depth tillage operation for three different soil types. Soil electrical conductivity and penetrometer readings were also used to assign appropriate tillage depths needed to correctly eliminate the existing compacted layer. In order to determine the effects of the variable-depth tillage methods, a tractor was implemented with a data acquisition system that monitored and recorded draft forces, fuel flow, engine speed, GPS coordinates, and ground speed. Uniform and site-specific tillage were conducted in three different soil types, three tractor speeds, and two soil moisture levels. The three different soil types encountered were Faceville loamy sand, Fuquay sandy loam, and Lakeland sand. Compared to uniform depth tillage (45.72 cm), site-specific tillage yielded a 50% energy savings and 30% fuel savings in the Faceville loamy sand (Table 2.1). The Fuquay sandy loam soil yielded 21% and 8% energy and fuel savings, respectively, along with 26.1% and 8.5% energy and fuel savings, respectively, for the Lakeland sand soil (Table 2.1).

Gorucu et al. (2001) researched variable depth tillage based on geo-referenced soil compaction data in South Carolina. Penetrometer, electrical conductivity, and yield maps were created to access soil variability throughout a 4.9 ha field. A relationship between electrical conductivity and corn yield existed. The field was divided into four management zones according to soil electrical conductivity and penetrometer data. According to predicted tillage depths, 75% of the field could be tilled shallower than the conventional tillage depth. Each zone was subjected to 5 replications of 3 treatments: no tillage, uniform depth tillage, and variable depth tillage. Variable depth tillage was carried out at 25 cm, 33 cm, and 38 cm. Deep tillage was performed at a depth of 41 cm. A tractor was implemented with a data acquisition system that collected fuel consumption, engine speed, ground speed, slip, and draft forces. Results indicated a 42.8% energy savings and a 28.4% fuel savings with variable depth tillage compared to constant depth tillage (Table 2.1).

Table 2.1. Summary of results on site-specific tillage research.

Authors	Year	Soil type	Uniform tillage depth Range	Site-specific depth range	-------Energy savings------- Draft	Fuel	Power
Fulton et. al	1996	Maury silt-loam	45.7 cm	0.0 - 40.6 cm	N/A	50%	NA
Gorucu, et al.	2001	Dothan Loamy sand	43.2 - 45.7 cm	25.4 - 40.6 cm	N/A	28.4%	42.80%
Gilandeh et al.	2005	Faceville	45.7 cm	20.3 - 35.6 cm	N/A	30%	50%
Gilandeh et al.	2005	Fuquay	45.7 cm	27.9 - 45.7 cm	N/A	8%	21%
Gilandeh et al.	2005	Lakeland	45.7 cm	27.9 - 45.7 cm	N/A	8.50%	26.10%
Raper et al.	2005a	Dystrudepts - Hapludults	45.0 cm	24.9 - 35.0 cm	28-55%	27-45%	17-47%
Raper et al.	2005b	Toccoa fine sandy loam	45.0 cm	24.9 - 35.0 cm	35-59%	27-43%	26-52%

In-Row Subsoiling Performance

Raper et al. (2005c) performed experiments regarding the effects of tillage frequency on soil compaction and cotton yield in southeast silt load soils. Three different subsoilers were chosen for comparison: Kelley Manufacturing Company (KMC) in-row subsoiler, and Bigham Brothers Paratill™, and a Bigham Brothers TerraTill™. The Paratill™ and TerraTill™ are of a bent shank design often used by southeast regional farmers. Three tillage frequencies were analyzed: annual, biennial, and triennial. Cone-index measurements were used to determine the depth of the compaction layer throughout the field which was at 30 cm. With that information, the tillage depth was set at 33 cm so the compaction layer would be disrupted. A John Deere 8300 tractor equipped with a data acquisition system collected speed, and implement draft. Data for 2002 and 2003 were collected. For 2002, results for the annual subsoiling frequency were reduced compared to the biennial and triennial subsoiling frequencies. The KMC subsoiler exhibited the lowest draft forces compared to the TerraTill™ or the Paratill™. The TerraTill™ had the highest draft forces for 2002. The 2003 results yielded no differences in draft forces between the three implements. Results showed that the annual frequency had lower draft forces compared to the biennial and triennial tillage frequencies. However, the magnitudes of differences between the frequencies were not as great in 2003 compared to 2002.

Raper (2005d) looked at straight and bentleg subsoilers and their force requirements and soil disruption on two different soil types. Ideally for conservation tillage systems, tillage should maintain minimum aboveground soil disruption while still having adequate belowground soil disruption to alleviate hardpan conditions. Eight different subsoiler shanks were compared for the experiment with five being straightleg and three bentleg shank designs. Testing was carried out in the indoor soil bins located at the USDA-ARS National Soil Dynamics Laboratory in Auburn, AL. Artificial hardpan conditions were simulated and tests consisted of four replications for each shank in a randomized block. Cone index readings were obtained before and after tillage. Result indicated that the straight shanks required increased amounts of draft forces than the bentleg shanks for the Norfolk sandy loam soil (Raper, 2005d). Overall, the Decatur clay loam required more draft than the Norfolk sandy loam however, only one statistically significant difference between shanks existed. The bentleg shanks generated increased side force compared to the straight shank designs. Raper and Bergtold (2007) reported that the use of bentleg or inclined subsoiler shanks can save up to 15% in fuel and 32% in draft.

Summary

Researchers have developed and tested various data acquisition systems and measurement devices to monitor and collect equipment performance data (Schrock et al., 1982; Turner, 1993; Hansson et al., 2003; and Al-Janobi, 2000). Schrock et al. (1982) reports a 19.8% saving in fuel when using his gear selection aid. GPS technology enables the collection of performance data joined to spatial coordinates for site specific management of equipment (Adamchuk et al., 2004; Demmel et al., 2002; Veal et al., 2005; Yule et al., 1999).

Many agricultural machinery operators often neglect altering equipment setup for different processes. Tire air pressure and ballast are two straightforward adjustments that can improve traction and save valuable fuel during operation. Slip, tractive efficiency, and dynamic traction ratio are all variables used to help describe how efficiently power is transferred from the traction device to the traction surface. Various equations are used to estimate equipment performance such as draft and implement motion resistance for proper equipment selection.

Soil properties have been thoroughly studied for decades and have a substantial effect on equipment behavior during tillage. The majority of energy and time is expended during subsoiling operations in order to control soil compaction. Tillage research revealed that tilling at shallower depths can save fuel and reduce draft forces. Implement design has evolved to more effectively conform to conservation tillage and tractor performance. Two prominent implement shank designs include straightleg and bentleg. Depending on the soil type and conditions, each design has advantages and disadvantages. Referring to equipment performance, implement research is limited to basic fuel consumption and draft data, some of which is based on formulated estimates and not real-time in-field monitoring.

CHAPTER THREE
RESEARCH METHODS

Introduction

This chapter describes the data acquisition system components and sensors used to measure equipment performance during four different tillage experiments. Several variables were analyzed in order to compare performance differences within each experiment. Experimental methods used to conduct the different experiments along with the statistical analysis methods performed on the data will also be presented in this chapter.

Data Acquisition System Development

A data acquisition system was developed to monitor and collect various equipment performance data. The system was capable of accommodating several sensor types including analog, digital, temperature, and transistor-transistor logic (TTL) signals. An important system characteristic was its ability to be transferred from vehicle-to-vehicle without major modifications to the vehicles. Components needed to sustain the harsh operating environments encountered during field operation which primarily consisted of dust, moisture, vibration, and physical abuse.

Transducers

Several variables were measured to assess equipment performance. The following provides a list of directly measured variables seen as major components to measure equipment performance:

1. Fuel Consumption,
2. Torque,
3. Exhaust Gas Temperature (EGT),
4. Wheel Speed,
5. Ground Speed,
6. Engine Speed, and
7. GPS position.

Accurately measuring fuel consumption for a diesel engine can be challenging. The fuel supplied by the fuel tank, referred to as supply fuel, is delivered by the injector pump to the injectors at high pressure. Once the fuel is delivered to the injectors, only the necessary amount of fuel is injected based on engine speed and load while the rest is bypassed back to the tank. The bypassed fuel is commonly referred to as return fuel. At this point, the fuel return has been heated causing its gravimetric properties to differ from fuel at ambient temperatures or temperature within the fuel tank. To accurately measure fuel consumption, the return fuel must be cooled, volume measured and that amount subtracted from the supply fuel to accurately compute the actual injected fuel. Corrsys Datron Systems manufactured the fuel sensor (model number CDS-DFL3) used in this research to measure the fuel consumption of diesel engines (Figure 3.1; Appendix F.3) described above about measuring return fuel.

The fuel sensor has an integrated reservoir that supplies the engine with fuel. The return fuel is cooled through an internal heat exchanger and is routed to the transducer reservoir instead of the tractor fuel tank. The transducer works on the concept of maintaining a fixed volume in this reservoir at all times. In order to sustain this fixed volume, fuel is delivered from the tractor fuel tank to the reservoir. This amount represents the quantity of fuel added to maintain the reservoir at a fixed volume and is the consumption amount (Corrsys Datron, 2007). Measurement is performed by a counter in which four pistons are connected to a crankshaft. Fuel is forced through the crankshaft cavity into the piston cylinders thus rotating the crankshaft. Crankshaft rotation is measured by two Hall Effect sensors which produce twelve pulses per revolution. Each pulse is equal to approximately 0.333 cm^3. Digital pulse multiplication yields a final output signal of 500 pulses/cm^3 (Corrsys Datron, 2007).

Figure 3.1. Corrsys Datron DFL-3 fuel consumption transducer.

A torque transducer was needed to measure rear drive axle torque. Several types of transducers exist differing in power and signal transmission options while ranging from slip ring couplers to radio frequency (RF) signal transmission for rotating shafts or in this case an axle. For the application at hand, a compact and rugged system was needed to monitor torque on a rotating tractor axle shaft. A Binsfeld Engineering® (Appendix F.6) product was chosen that measures strain on a round shaft. The system uses a 4-arm Wheatstone bridge strain gage that is adhered to the shaft. The strain gage is wired to a transmitter that broadcasts the signal using radio frequency to a receiver. The signal processing system then interprets the signal and outputs an analog voltage signal (+/-10 V) based on the amount of torque being applied to the axle. The full scale torque was calculated according to the diameter of the shaft and then divided by 10 to determine the amount of torque per volt. The signal is then directed into the digital/analog module of the data acquisition system.

Pre-strain often happens when mounting strain gages. This is caused when the strain gage measures strain but under a no-load condition which commonly occurs when adhering the gage to the specimen of interest. In order to compensate for pre-strain, an AutoZero feature located on the telemetry receiver subtracts the measured no-load strain from the full scale range. Larger no-load strains reduce the measurement range of the system. For example, if the initial imbalance was +2.5 V, the AutoZero function would subtract that amount from the positive range of the system resulting in a full scale range of +7.5 V compared to the potential full scale range of +10 V.

Exhaust gas temperature (EGT) was measured using a K-type thermocouple produced by Exhaust Gas Technologies. A hole was drilled and tapped allowing a compression fitting to be threaded into the exhaust manifold. The thermocouple was then inserted pre-turbocharger of a John Deere 6420 (Appendix E.1) agricultural tractor as illustrated by the red arrow in Figure 3.2.

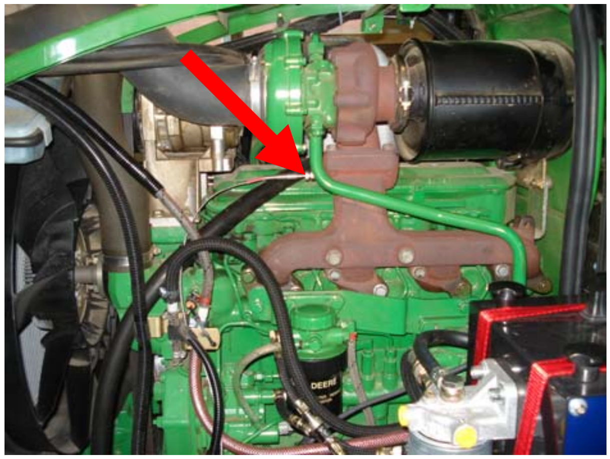


Figure 3.2. Illustration of the exhaust gas temperature thermocouple installed in the manifold of a John Deere 6420.

Wheel speed was attained in two different ways during this project. A John Deere 8300 (Appendix E.2) agricultural tractor was used for three experiments of this research. The wheel speed signal for this application was received from an existing sensor located on the top of the transmission housing. This sensor produced a pulse proportional to the speed of the transmission and was calibrated according to the speed of the wheel. Other testing was performed using a John Deere 6420. The wheel speed for this tractor was measured with a DICKEY-john® rotary encoder. The encoder was driven by a sprocket that was mounted to the rear axle of the tractor. Ground speed was measured using a DICKEY-john® ground speed radar for both tractors. The rotary encoder and the ground speed radar output a TTL level pulse signal in which pulses were counted over a time period and then converted into a ground speed. Existing Hall Effect sensors on the tractors' engines provided the pulse signal used for engine speed in both applications.

Draft measurement was performed using a three-point-hitch dynamometer that measure forces in 3-dimensions. This system was fabricated and provided by the National Soil Dynamics Laboratory in Auburn, AL. The dynamometer utilizes load cells which measure force in the direction of travel as well as side and vertical forces. The data from this transducer was collected with a SOMAT® data acquisition system (Appendix F.5) at a rate of 25Hz. An ON/OFF switch was used to initiate data collection with this system during testing. This switch was also digitally monitored with the performance monitoring system so all measurements coincided in time. When the switch was in the OFF position, a "1" was input to the text file of the performance monitoring system. During testing, the switch was turned to the ON position and a "0" was input into the text file of the performance monitoring system. In order to merge data between the performance monitoring system and the draft system, draft data was averaged on a 1-Hz basis and then merged with the performance data after field collection.

Signal Processing

A KEE Technologies ZNYX X15 computer module (Appendix F.4) was used as the mobile computer. The X15 features 2 universal serial bus (USB) ports and 4 serial port terminals making it compatible with most GPS receivers and data acquisition systems. The X15 was designed for use in controlling variable-rate (VR) application controllers, machine guidance, and built to handle the rigors of off-highway applications. Its use in this research was to handle developed software for data acquisition and as the graphical user interface (GUI) for tractor operators.

Torque signals and the digital switch used for the draft system were processed using a Measurement Computing USB-1608FS (USB) analog/digital data acquisition module (Appendix F.1). This module is capable of managing up to 8 channels of 16-bit analog input along with 8 digital input/output bits and also included an event counter. Thermocouple signals were handled with a Measurement Computing USB-TC (Appendix

F.2) that is capable of measuring up to 8 temperature inputs and 8 digital input/output bits. Programs were written in Visual Basic (VB) to configure and communicate with both Measurement Computing data acquisition modules as described in the following paragraph.

The VB programs (Appendix G) were also used to collect equipment performance data and then display data to the X15 screen. The programs featured a graphical user interface (GUI) that displayed and updated all data at 1 Hz during operation (Figure 3.3). The GUI included a display of all data being collected on equipment as well as data logging options. This feature provides the ability to view instant feedback on equipment performance while in operation. Data logging options allow you to choose a directory and create a file name to store data. Data collected during field operations is written at a rate of 1 Hz to a comma delimited text file which can then be saved to the hard drive. Field information can be archived for future reference and development of field records.

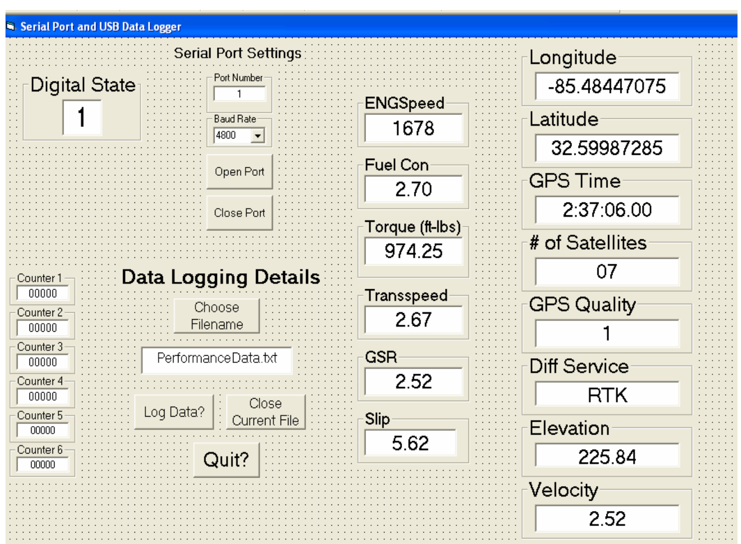


Figure 3.3. Example of the GUI during field operation as seen on the X15 screen.

The data acquisition system for the Draft dynamometer was a SOMAT® 2100 Field Computer System (FCS). This system handled signals from load cells, ground speed radar, and ultrasonic depth sensors. Data collected with this system was collected at a rate of 25 Hz and internally stored once a test was completed. The data was then wirelessly transmitted to a computer located in a van and saved as a comma delimited text file.

Depth Performance Experiment

A 0.07 hectare field located at the E.V. Smith Research and Extension Center in Shorter, AL was chosen to conduct the first field experiment. The test was conduct on March 8, 2007. The soil was Marvyn loamy sand. This experiment was performed concurrently with researchers from the USDA Agricultural Research Service (ARS) at the National Soil Dynamics Laboratory (NSDL) in Auburn, AL. The field was divided into 16 plots (Figure 3.5) with dimensions of 3.1 m by 15.2 m. This experiment had two objectives: 1.) evaluate the performance of the developed data acquisition system and 2.) collect and analyze performance data for subsoiling at two different depths.

A mechanical front wheel drive (MFWD) John Deere 8300 agricultural tractor was the test base for this experiment (Figure 3.4; Appendix E.2). A Kelley Manufacturing Company (KMC) 4-row Generation I Rip-Strip subsoiler (Appendix E.3) was used as the tillage implement.

Figure 3.4. Illustration of the John Deere 8300 and KMC subsoiler.

Two tillage depth treatments were analyzed which included a shallow depth of 22.9 cm and a deep depth of 35.6 cm. The other two treatments consisted of using or not using a prototype shank attachment which was being investigated by the USDA-ARS NDSL Conservation Tillage research group. Since this prototype attachment is under development and potentially patentable, specifics will not be discussed but referred to as “attachment” here after. The original treatment assignments were 1 for shallow with attachment, 2 for deep with attachment, 3 for shallow without attachment, and 4 for deep without attachment. All treatments were replicated 4 times. The plot layout with dimensions and treatment descriptions is presented in Figure 3.5 below:

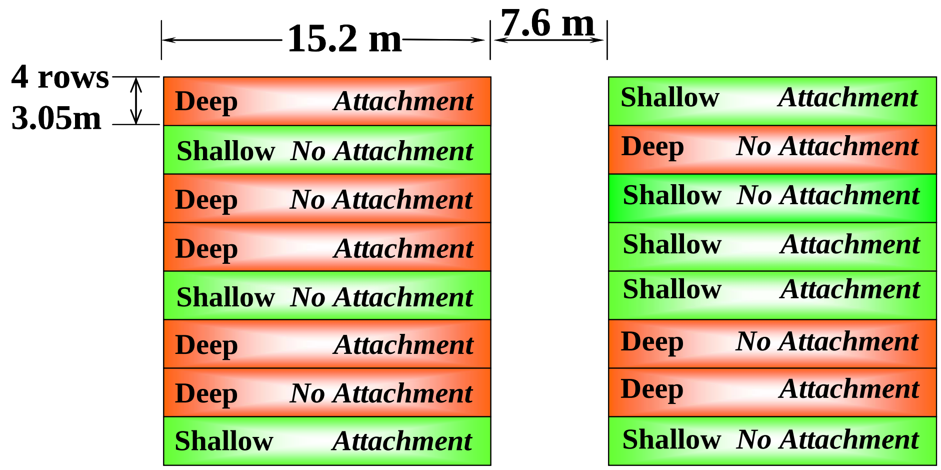


Figure 3.5. Plot layout and dimensions for the Depth Performance experiment.

The tillage depth describes the measure of distance from the shank point in the soil medium to the soil surface. The manufacturers recommended depth range for this implement was 30.5 to 40.6 cm (KMC 2007). The shallow depth chosen for this experiment was not within the manufacturer's recommendation, but the implement was still able to perform effectively at this depth. Draft force, fuel consumption, ground speed, and transmission speed were collected during the experiment. A Real-Time Kinematic (RTK) Trimble AutoPilot guidance system was used for tractor guidance during the experiment.

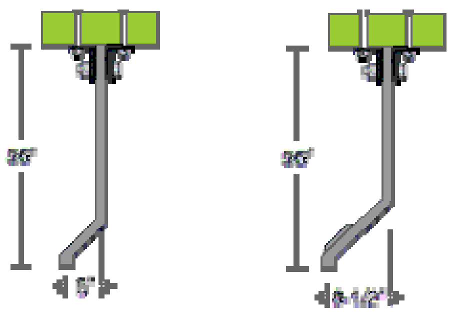
The depth for each implement was set by inserting the implement into the soil and pulling a short distance outside of the test area. The depth was measured by inserting a measurement probe into the ground and the process was repeated until the correct depth was achieved. Implement depth was set by adjusting the lift stop in the tractor cab to coincide with the desired depths. Testing was performed with the MFWD engaged. When the tractor was aligned with the plot, the implement was lowered to the desired depth. The tractor engine was set to full throttle and then tillage was initiated. Soil samples of 0 to 15.2 cm and 15.2 to 30.5 cm were collected, bagged and labeled accordingly within each plot to determine soil moisture content. Soil samples were collected in three replications per plot. Data was filtered to remove the first and last second of data collected with each plot to obtain readings for steady state operating conditions and not during subsoiler lowering and raising.

Tillage Rotation Experiment

A 0.8 hectare field at the E.V. Smith Research and Extension Center in Shorter, AL was the site of this experiment. The experiment was conducted on April 19, 2007. The soil type for this field was Marvyn loamy sand. Again, this test was also performed in conjunction with the USDA Soil Dynamics Laboratory in Auburn, AL. Tillage rotation was the focus of this experiment and was defined as the time between tillage events. Annual, biennial, and triennial tillage time rotations were analyzed for this experiment along with three different implements, for a total of 9 treatments. Annual tillage represents tillage performed every year in a plot. Biennial tillage was performed every other year with triennial tillage performed every third year.

A KMC Generation I Rip Strip in-row subsoiler, Bigham Brothers TerraTill™, and Bigham Brothers Paratill™, all 4-row configurations, were the implements used for this experiment (Appendix E). The tillage depth range was 33 to 35cm for all treatments. Each treatment was replicated 4 times for a total of 36 plots (Appendix A.1). According to the plot layout, only the plots with vertical (KMC), horizontal (Paratill™), and diagonal (TerraTill™) lines were used for this experiment. Plots dimensions were 4.05 m by 25.9 m.

The KMC implement was of a straight shank design while both Bigham Brothers implements were different bentleg design (Appendix E, Figure 3.6). The Paratill™ has a larger outward bend at 21.6 cm compared to 12.7 cm for the TerraTill™. The TerraTill™ is capable of tilling effectively at shallower depths than the Paratill™. The implements were all three point hitch or integral mounted.



TerraTill™ Paratill™

Figure 3.6. Comparison of Bigham Brother TerraTill™ and Paratill™.

The same MFWD John Deere 8300 agricultural tractor was used. Testing was performed with the MFWD disengaged. The tractor was outfitted with two data acquisition systems with one collecting draft data and the other collecting fuel consumption, axle torque, ground speed, transmission speed, and GPS positions.

Tillage Speed Experiment

A 0.5 hectare Cahaba sandy loam field located at the E.V. Smith Research and Extension Center in Shorter, AL was the site chosen for testing. This experiment was conducted on July 25, 2007. The objective of this experiment was to perform subsoiling with two different implements operated using three different transmission gears providing three speed ranges. The speed categories were slow, normal, and fast and selection will be discussed later. The two implements chosen included a 6-row KMC Generation I Rip-

Strip in-row subsoiler (Figure 3.7; Appendix E.3) and a 6-row Bigham Brothers Paratill™ (Figure 3.8; Appendix E.4)

Figure 3.7. Illustration of the Kelley Manufacturing Company (KMC) Generation I Rip-Strip.

Figure 3.8. Illustration of the Bigham Brothers Paratill™.

One of the goals of this experiment was to simulate typical equipment configurations under normal operating conditions. According to Bigham Brothers, the power rating is 22-30 kW per shank for the Paratill™ (Bigham Brothers, 2007) while the power rating for KMC Generation I Rip-Strip is 19-22 kW per shank (KMC, 2007). Testing was performed at a constant tillage depth of 30 cm which is within the manufacturer's recommendation for both implements (Appendix E). The power rating for the John Deere 8300 was approximately 149 kW so both implements are within the power range of the tractor. The depth for each implement was set by inserting the implement into the soil and pulling a short distance. The depth was then measured by inserting a measurement probe into the ground and the process was repeated until the correct depth was achieved. It was decided to perform slow speed in 2nd gear (approx. 3.0 km/h), normal in 5th gear (approx. 5.8 km/h), and fast in 8th gear (approx. 8.3 km/h); thus having 3 transmission gears between each of the speeds. These gears were chosen according to preliminary testing to determine how well the tractor responded to on-the-go gear changes, being especially cautious of engine overloading when operating at higher gears.

A total of six different treatments were performed in four replications with the site measuring 122 m by 44 m (Figure 3.9). Each plot measured 30.5 m by 5.5 m and was arranged in an 8 by 3 block configuration. The width of 5.5 m was the implement width and the length of 30.5 m was chosen to ensure that a sufficient amount of data points would be collected for each speed. The design consisted of 8 rows of 3 blocks with a 15 m transition space between blocks with each row being one implement. The treatments were assigned randomly within each block. Tillage was performed in three plot intervals with appropriate gear changes occurring on-the-go in the 15 m transition spaces. Treatments are summarized in Table 3.1.

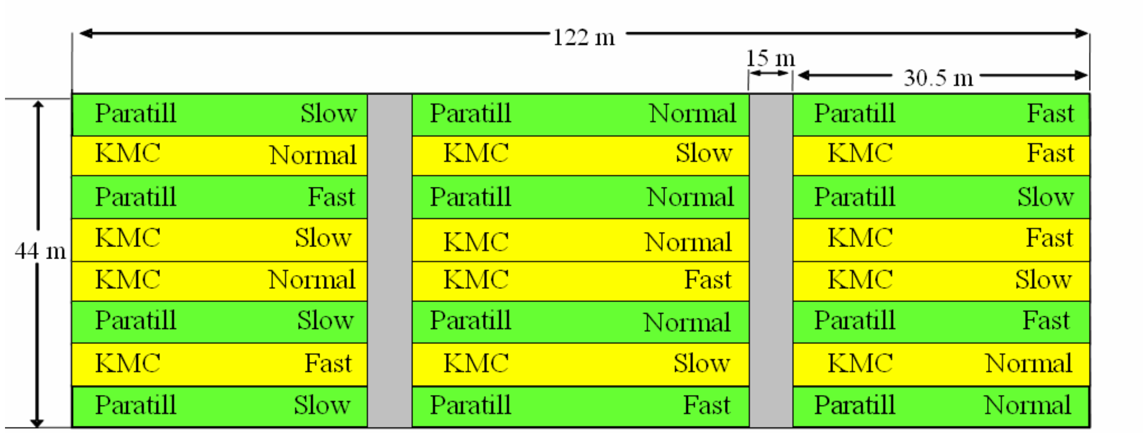


Figure 3.9. Plot layout and dimensions for the Tillage Speed experiment.

Table 3.1. Summary of treatments for the tillage speed experiment.

Treatment	Implement	Speed
1	Paratill™	Slow
2	Paratill™	Normal
3	Paratill™	Fast
4	KMC	Slow
5	KMC	Normal
6	KMC	Fast

The tractor was outfitted with two separate data acquisition systems which were described earlier in this chapter. Variables collected include draft, fuel consumption, axle torque, ground speed, transmission speed, and engine speed.

Three soil samples per plot were collected to determine soil bulk density and moisture content within each plot. A Multiple-Probe Soil Cone Penetrometer (MPSCP) fabricated by the USDA-ARS NSDL in Auburn, AL was used to obtain cone penetrometer measurements (Raper et al., 1999). A core sampling tube was attached to the MPSCP and used to exact undisturbed soil cores for soil bulk density measurement. The soil cone penetrometer and bulk density samples were collected in triplicate for each plot. The soil cores were also used to determine soil moisture content. Further explanation of this process is described in the ‘Soil Analysis’ section of this chapter.

The amount of draft and fuel consumption per unit length of shank was also calculated to compare the performance of the Paratill™ and TerraTill™ for this experiment. The length of shank was the linear distance along the center line of the shank face which contacted the soil including the point surface.

Spatial Tillage Experiment

A 1.5 hectare field at the E.V. Smith Research and Extension Center, Shorter, AL was the site for this experiment. This experiment was conducted on September 17, 2007. The goal of this test was to spatially analyze a subsoiling operation and measure the effects of three different tire pressures on the performance of the machinery. This study served two purposes: 1) show how spatial equipment performance could be used to improve equipment management for potential increased efficiency and profitability and 2) a precursor to potential use of central tire inflation (CTI) systems on off-highway vehicles to maintain optimal field performance. A KMC Generation I Rip-Strip was used in this study and operated at a constant depth of 30 to 36 cm which was within the manufactures’ recommended operating depth. The manufacturer’s power recommendations for this implement were 18.7 to 22.4 kW per shank (Appendix E.3). A John Deere 6420 agricultural tractor with an advertised 70.3 kW was utilized for testing (Appendix E.1). Preliminary testing was performed to determine the number of shanks that tractor could pull within reason. With the field conditions at that time, it was concluded that 2 shanks would provide adequate loading for this particular test. The tractor was equipped with a John Deere GreenStar RTK AutoTrac system was used for this experiment (Figure 3.10).

Figure 3.10. Illustration of the John Deere 6420 tractor equipped with a GreenStar receiver (red arrow) and KMC subsoiler used during the Tire Pressure experiment.

A data acquisition system was mounted on the tractor that monitored and collected the following variables at 1 Hz: GPS positions, fuel consumption, axle torque, engine speed, wheel speed, and ground speed. The GPS positions were obtained from the John Deere Starfire receiver via outputted National Marine Electronics Association (NMEA) sentences which were RTK corrected. Draft was not collected for this experiment. The tires on the front of the tractor were Firestone Super All Traction R-1W bias ply tires (size 13.6-24) and the recommended tire pressures ranged from 83 to 193 KPa (Petersen, 2007). The rear tires were Firestone Radial 8000 radial tires (size 18.4R34) and the manufacturer's recommended inflation pressure range was from 41 to 159 KPa (Petersen, 2007). Staying within the limit of the manufacturer's recommendations, the pressures used are summarized in Table 3.2.

Table 3.2. Summary of treatments for the tire pressure experiment.

Category	Pressure Front KPa	Pressure Rear KPa
Low	83	41
Normal	138	100
High	193	159

Figure 3.11 presents an illustration of air pressure treatment assignment for each pass within the test area. The help show the randomized treatment assignment for each pass, only the south half of the test area is presented. A wet area in the field is outlined in orange.

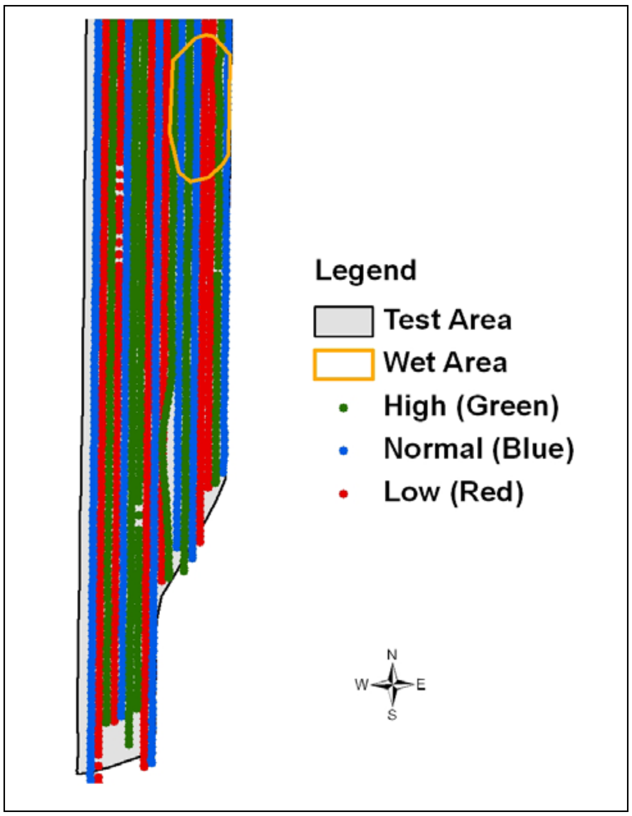


Figure 3.11. South half of Field boundary with actual study area and pressure categories.

Prior to performing tests, cone penetrometer readings and soil samples were collected randomly throughout the field. Soil samples were collected and analyzed by depth intervals of 0 to10 cm, 10 to 20 cm, and 20 to 30 cm. The six replications of each treatment were randomized by drawing numbers out of a hat that coincided with the track number of the auto-guidance system. Calibration tillage was done in the same field in order to set transmission speed and depth. The infinitely variable transmission (IVT) speed was set to a maximum of 6 km/h at full throttle. Once the tractor was aligned with the plot, the implement was lowered to the ground and data collection was initiated. Data was collected in a separate text file for each pass to keep treatments separated and minimize data loss for any system malfunction.

The field chosen for the experiment is illustrated in Figure 3.12. The field was of an irregular shape with varying terrain to access equipment performance under different field conditions. Elevation data used in the experiment was collected by a Trimble 5800 RTK survey grade GPS system and is illustrated in Figure 3.12. Equipment performance can vary according to direction of travel and elevation differences. To isolate these difference effects on equipment performance, the test area was divided into three zones for separate analysis. The three zones are outlined in Figure 3.12. Each zone contains the same number of tire pressure treatments so these effects were not considered for this analysis. A buffer of 3 m was present between zones. By examining the elevation differences, it was seen that the middle of the test area (Zone 2) had the highest elevation and was fairly level (60.1 to 61.0 m) compared to the north (Zone 1) end of the field. Zone 1 experienced a drop in elevation of about 2.5 m. Zone 3 was also relatively level.

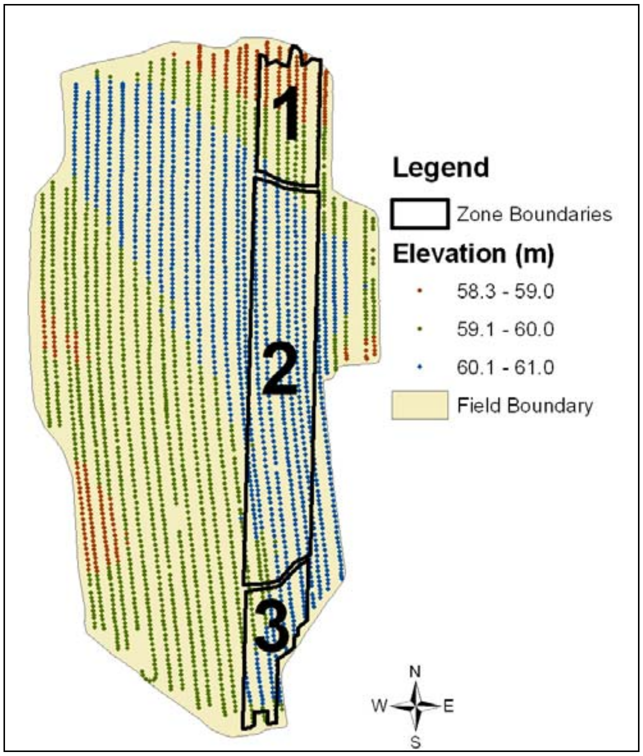


Figure 3.12. Illustration of field elevation with zones outlined.

Spatial data from this experiment was used to develop fuel consumption and fuel cost maps which can be valuable management resources. Productivity rate is a projection of how much land can be processed per hour of time and is presented as Equation 3.1. Note that this equation does not take into consideration turning and idling and assumes a constant travel speed. From productivity rate, fuel cost (Eq. 3.2) was calculated since fuel consumption was collected. Fuel cost was presented as dollars per acre by calculating the time it would take to process an acre of land.

$$PR = \left[\frac{10{,}000 \, \frac{m^2}{ha}}{(GS) * \left(1{,}000 \, \frac{m}{km}\right) * (WW)} \right] \qquad (3.1)$$

where, PR = Productivity Rate (hrs/ha)
GS = Ground Speed (km/h)
WW = Working Width (m)

$$FC = PR * FR * FP \tag{3.2}$$

where, FC = Fuel Cost ($/ha)
PR = Productivity Rate (hrs/ha)
FR = Fuel Consumption Rate (L/h)
FP = Fuel Price ($/L)

The illustration of how fuel costs vary across fields permits this variable cost to be assigned not only to a field but also at a sub-field level. Currently, most producers or managers assign costs at an enterprise level, but as equipment and farms get larger, looking at costs at the field and even at a sub-field level will be necessary to assess equipment performance and operating efficiency. This type of analysis can permit mangers to evaluate where cost savings may exist.

Soil Analysis

For the tillage rotation experiment, a multiple-probe soil cone penetrometer (MPSCP) was used to obtain cone index readings. The penetrometer attaches via a 3-point hitch and uses support links to prevent lateral and vertical movement during measurement (Raper et al., 1999). A hydraulically operated cylinder mounted between two frames performs the insertion of the cones (Raper et al., 1999). One of the frames is stationary while the other is moved down in the vertical direction during measurement. The five cones were inserted and mounted directly into five Lebow load cells (Raper et al., 1999). The load cells had about a 7 MPa capacity each. Depth is measured with a constant tension spring motor attached between frames (Raper et al., 1999). A handheld

CP40II cone penetrometer manufactured by RIMIK Electronics was used for measuring cone index for the tire pressure test.

The soil bulk density was calculated only for the implement speed test. The MPSCP frame was also capable of obtaining bulk density measurements. The soil cones were removed and replaced with one undisturbed core sampling tube. This tube contained an inner cylinder that was split into 5 cm rings. After insertion, the tube was opened and the soil was segmented into depths (Raper et al., 1999). Once the soil core was divided into 5.08 cm increments, they were placed in round tin cans and processed in a laboratory. Bulk density is described as the mass of a unit volume of dry soil (Eq. 3.3) (Brady et al., 2002).

$$B.D. = \frac{Weight\ Dry\ Soil}{Soil\ Volume} \tag{3.3}$$

where, $B.D.$ = Bulk density (g/cm^3)

Bulk Density is the weight of the oven dry soil divided by the volume of the soil. The soil samples were placed in a 105^{o}C oven for 72 hours. Moisture content was also calculated from the same samples as the bulk density. The moisture content of the soil was determined on a dry basis (db; Eq. 3.4).

$$M.C.\ db = \frac{Weight\ Water}{Weight\ Dry\ Soil} \tag{3.4}$$

where, $M.C.\ db$ = Moisture contend dry basis (dimensionless)

M.C. db is the moisture content of the dry soil and is equal to the weight of the water in the soil divided by the weight of the oven dried soil. The soil was dried at 105 ^{o} C for a period of 72 hours.

Statistical Methods

Draft data for the Depth Performance experiment was filtered to remove data at the beginning and end of tillage for each plot to only use collected data when the tractor was at operating conditions. Draft and performance data was analyzed by obtaining pooled averages for draft and fuel consumption and then compared according to depth. The tillage rotation and speed experiments were analyzed by merging the draft and performance data. Due to the difference in sampling rates of the two systems, each of the 25 readings that comprised one second of draft data were averaged and matched to the appropriate second of data collected with the performance monitoring system. The two data sets were then merged to make one data set which was then used for analysis. For the Tillage Rotation and Speed experiments, data was filtered to remove the first and last second of data to obtain data for steady operating conditions and not subsoiler lowering and raising. Data for the tire pressure experiment was filtered to remove the first 8 to10 data points to account for idle time present at the beginning for each repetition and to ensure everything was brought up to operating conditions. The data was statistically analyzed using Statistical Analysis System (SAS) statistical package. The least significant difference (LSD) test was performed using a significance level of 0.05 to test for significant differences between and within treatments.

The experiments were planned using a randomized block design in which experiment treatments are randomly assigned to blocks (Neter et al., 1974). Group comparisons were performed to test for differences between experimental treatments. The first step for statistical comparison is to formulate a null hypothesis and alternative hypothesis. The null hypothesis (H_0) for the test was that all the treatment means (μ)

were equal (Davis, 2004). The alternative hypothesis (Ha) for the test was that at least one of the means was different.

H_0: $\mu_1 = \mu_2 = \mu_3 = \ldots\ldots \mu_n$

Ha: at least one $\mu_i \neq \mu_j$

Once the hypotheses are determined, a test statistic is calculated which is defined as a statistic used to measure the acceptability of an alternative hypothesis relative to a null hypothesis. An Analysis of Variance (ANOVA) F-test was used to test the test statistic. Two models are present for this particular method which includes the full and reduced models (Ramsey et al., 1997). The full model, also called the separate means model, describes the data with separate means for each treatment. The reduced model imposes the restrictions of the null hypothesis upon the data; in this case it would assume equal means for all treatments as illustrated below (Ramsey et al., 1997).

Group:	1	2	3	4……..n	
Full model:	μ_1	μ_2	μ_3	μ_4	μ_n
Reduced model:	μ	μ	μ	μ	μ

This procedure leads us to the extra sums of squares F-test. This procedure estimates the parameters in the full and reduced models and compares the variability about the estimated means to see if they are comparable (Ramsey et al., 1997). The estimated parameter is $\overline{Y}$ and is the combined average of all observations. For the Full model, the estimated parameter is the average of all observations for each individual treatment. The Reduced model parameter assumes equal means so a grand average for all observations for all treatments is the estimated parameter (Ramsey et al., 1997).

Group:	1	2	3	4……. n	
Full model:	$\overline{Y}_1$	$\overline{Y}_2$	$\overline{Y}_3$	$\overline{Y}_4$ …...	$\overline{Y}_n$
Reduced model:	$\overline{Y}$	$\overline{Y}$	$\overline{Y}$	$\overline{Y}$	$\overline{Y}$

Residuals exist for each model and are defined as the observation value minus its estimated mean (Ramsey et al., 1997). The residual for the full model is $Yij - \overline{Y}i$, meaning the *j*th observation of the *i*th treatment subtracted by the *i*th treatment mean (Ramsey et al., 1997). The residual for the reduced model would be $Yij - \overline{Y}$, meaning the *j*th observation of the *i*th treatment subtracted by the grand average of all observation for all treatments (Ramsey et al., 1997). If the magnitudes of residuals are similar, the null hypothesis is true. When the null hypothesis is false, the magnitudes of residuals of the equal means model tend to be larger (Ramsey et al., 1997). The residual sum of squares is the sum of the squared residuals (Ramsey et al., 1997). Table 3.4 is an Analysis of Variance table for one way classifications. The extra sum of squares is the difference in the residual sums of squares between the reduced and full models (Eq. 3.5).

$$\begin{gathered}\textit{Extra sum of squares (ExtraSS)} = \\ \textit{Residual sum of squares (reduced)} - \textit{Residual sum of squares (full)}\end{gathered} \tag{3.5}$$

The extra sum of squares measures the unexplained variability in the reduced model that can be explained by the full model (Ramsey et al., 1997).

In Table 3.3 below, within groups represents the full model and Total represents the reduced model. The degrees of freedom between groups are equal to the number of groups (I) or treatments subtracted by one. The degrees of freedom for the within groups is equal to the number groups (I) subtracted from the number of individual observations (n). The degrees of freedom for the total are equal to the number of individual observations (n) minus one. The F-distribution provides a means of comparing the extra sum of squares with a known probability distribution.

Table 3.3. Analysis of variance (ANOVA) table for one-way classification.

Source	Sum of Squares	Degrees of Freedom	Mean Square	F-Statistic	p-Value
Between Groups	ExtraSS	I-1	MSB	MSB/S_p^2	
Within Groups	SSW	n-I	S_p^2		
Total	SST	n-1			

Where:

ExtraSS = SST – SSW (3.6)

$$SSW = \sum_{i=1}^{I} \sum_{j=1}^{n_i} \left(Y_{ij} - \overline{Y}_i\right)^2 \quad (3.7)$$

$$SST = \sum_{i=1}^{I} \sum_{j=1}^{n_i} \left(Y_{ij} - \overline{Y}\right)^2 \quad (3.8)$$

I = Number of groups or treatments

n = Number of individual observations

$$MSB = \frac{ExtraSS}{(I-1)} \quad (3.9)$$

$$S_p^2 = \frac{SSW}{(n-I)} \quad (3.10)$$

The p-value can be found from an F-distribution table with the degrees of freedom of the between groups and within groups. The p-value describes the probability of obtaining a value as extreme or more extreme than the one observed and the smaller the p-value is the greater the probability that the null hypothesis is true (Ramsey et al., 1997).

Fuel Consumption and Draft Estimation

Another aspect of this research was investigating methods used to estimate equipment performance. Equations have been developed to estimate certain performance variables and energy requirements for tractors and implements. These types of equations are useful to check the compatibility of tractor/implement combinations. Raper et al. (2005b) developed an equation (Eq. 3.11) to estimate a fuel rate during subsoiling for the

John Deere 8300 MFWD tractor in this research. Power-take-off data was converted to drawbar power using data available in the Nebraska Tractor Test for this tractor (Raper et al., 2005b). This equation is specific to the tractor mentioned above.

$$FR = 0.31 * DP + 9.14 \tag{3.11}$$

where, FR = fuel rate (L/h)
DP = drawbar power (kW)

Power is defined as the rate of doing work (Goering et al., 2004). Drawbar power or linear power is the product of draft and speed.

The American Society of Agricultural and Biological Engineers (ASABE) published a draft estimation equation (Eq. 3.12) in standard D497.5 (2006). This formula uses a variety of field and machine coefficients to accurately estimate draft requirements for a variety of implements. The formula for draft calculations is below.

$$D = F_i \left[A + B(S) + C(S)^2 \right] WT \tag{3.12}$$

where, D = implement draft (N)
F = dimensionless soil texture adjustment (table)
i = 1 for fine, 2 for medium, 3 for coarse textured soils
A, B, and C = machine specific coefficient (table)
S = field speed (km/h)
W = machine width, (m) or number of tools (table)
T = tillage depth (cm)

However, no machine coefficients are included in the standard to estimate draft requirements for modern tillage implements such as those of a “bentleg” design. The same coefficients were used to estimate draft for both the KMC and the Paratill™ which yielded the same results for both implements.

Equations 3.11 and 3.12 were used to estimate or calculate theoretical fuel consumption and draft from data collected during the tire pressure experiment.

Theoretical and actual values were then graphically compared to assess the accuracy of these estimation methods.

CHAPTER FOUR
RESULTS AND DISCUSSION

Introduction

The results of the four experiments conducted during this research are presented within this chapter. Equipment performance data collected during these experiments were analyzed to improve understanding of tillage operations, especially for the potential of site-specific tillage. Operational variables (tillage depth, tillage rotation, tillage speed, and tractor tire air pressure) were analyzed to evaluate their effects on tractor and tillage implement performance. Spatial maps of different tractor data were also developed to illustrate how performance data can be used to make informed management decisions and improve operational efficiency of equipment.

Depth Performance Experiment

This experiment was the first time using the developed performance monitor during field operations. Once the sensors were mounted on the equipment, the system was easily removed and installed on tractors between test days without difficult procedures or additional calibration. The switch that linked the performance monitoring system to the draft system worked well allowing data to be merged into a single file for analysis. The GUI provided an accurate display of equipment performance variables that was convenient for assessing the condition of equipment and performance system. The system proved its ability to provide accurate equipment performance data plus held up under the harsh operating environment.

Results of this experiment are presented in Table 4.1 with standard deviations (SD). The main focus of this experiment was to compare equipment performance for two tillage depths. No statistical evidence existed to conclude that the prototype attachment had an effect on the draft ($p = 0.897$) and fuel consumption ($p = 0.949$) for this experiment. Therefore, the attachment and no-attachment treatments data were pooled and analyzed according to depth only (Table 4.2).

Table 4.1. Statistical summary by treatments for the subsoiling Depth experiment.

Tillage Depth (cm)	Attachment	Draft (N)		Fuel Con (L/hr)	
		Mean*	SD	Mean*	SD
23	Yes	10,953[b]	1,922	16.5[b]	1.9
23	No	9,218[b]	1,685	16.1[b]	1.6
36	Yes	22,159[a]	2,650	19.9[a]	1.6
36	No	22,922[a]	3,061	20.3[a]	1.3

*Means with similar letters in columns are not statistically different ($\alpha = 0.05$)

Table 4.2. Summary of results for the subsoiler Depth experiment.

Tillage Depth (cm)	Draft (N)		Fuel Con (L/hr)	
	Mean*	SD	Mean*	SD
23	9,825[b]	1,904	16.3[b]	1.8
36	22,550[a]	2,893	20.1[a]	1.5

*Means with similar letters in columns are not statistically different ($\alpha = 0.05$).

Statistical differences ($p < 0.05$) existed between draft and fuel consumption for the two different depths. Mean draft increased 130% from the shallow to the deep depth while a 19% saving in fuel consumption occurred for the shallow depth over the deep depth. More variability in draft was observed at the deeper depth as seen with the higher standard deviations. As tillage depth increases, the shanks contact more area disrupting a larger soil volume causing different draft reactions in response to soil property variability. Therefore, it is expected that the standard deviation would increase with tillage depth since more volume of soil is being disrupted as depth increases which also increases the sensitivity to soil property variations.

A monetary savings of $1.59 per hectare (assuming $0.62 per liter for off-road diesel fuel) was observed for the shallow depth compared to the deeper tillage. For example, if shallow depth tillage could be performed over 500 hectares, $795.00 in fuel savings would be experienced compared to deep depth tillage.

Figure 4.1 illustrates implement draft versus fuel consumption for the two different depths of this experiment. Since only two tillage depths were used, a complete linear regression analysis was not possible. However, it is surmised that the addition of more data between 23 cm and 36 cm would generate a linear relationship between fuel consumption and draft. If the depth of compacted layers throughout a field can be measured, an economic analysis could be performed using this relationship to determine if site-specific or uniform depth tillage should be implemented. In general, this experiment proved that tillage at shallower depths can save a considerable amount of fuel and energy compared to uniform deep depth tillage. Reduced draft loads and fuel savings mean less input costs and extended equipment life.

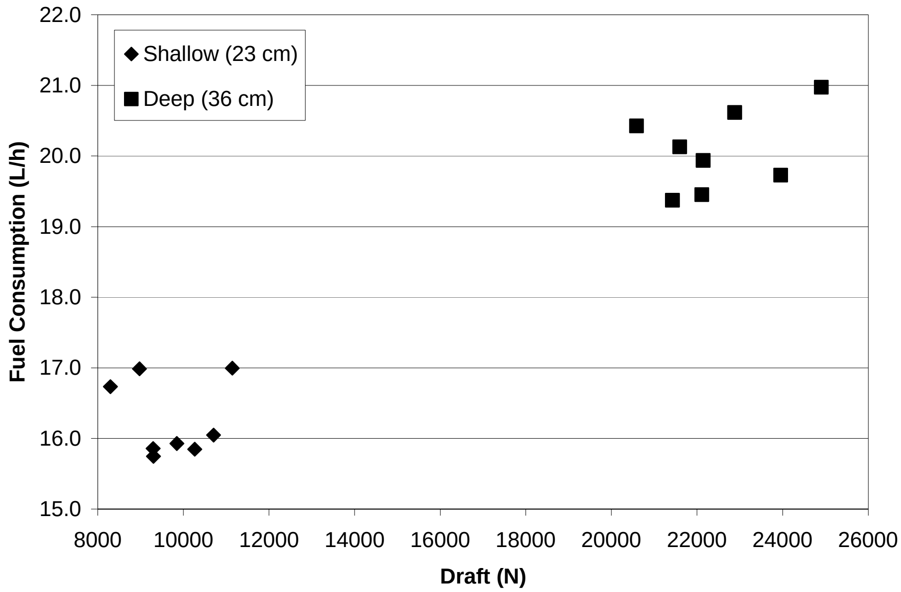


Figure 4.1. Fuel consumption vs. draft for the Depth Performance experiment.

Tillage Rotation Experiment

This test evaluated the effects of annual, biennial, and triennial tillage time rotations on equipment performance and energy requirements of three different implements. The summary of results for fuel consumption, draft, and axle torque for the three implements are provided in Table 4.3.

Table 4.3. Summary of results for the Tillage Rotation experiment.

Implement	Rotation (yrs.)	Fuel Con (L/h) Mean*	Fuel Con (L/h) SD	Draft (N) Mean*	Draft (N) SD	Torque (N-m) Mean*	Torque (N-m) SD
KMC	1	16.8[c]	0.8	12,825[d]	1,179	8,191[d]	1,970
	2	17.1[c]	0.6	13,683[cd]	845	8,711[cd]	733
	3	17.7[bc]	0.6	16,400[c]	1,443	9,963[bc]	791
Paratill™	1	18.6[b]	0.9	21,599[b]	2,360	10,372[bc]	2,140
	2	18.5[b]	0.8	20,717[b]	2,363	11,073[b]	1,359
	3	20.2[a]	1.2	26,492[a]	3,529	12,941[a]	844
TerraTill™	1	20.5[a]	0.2	25,289[a]	659	13,210[a]	689
	2	20.6[a]	0.5	25,030[a]	520	13,158[a]	812
	3	20.9[a]	0.5	26,587[a]	1,800	13,690[a]	311

*Means with similar letters in columns are not statistically different ($\alpha = 0.05$).

The results of the Least Significant Difference (LSD) test revealed that there was no statistical evidence to accept the null hypothesis that the means are equal ($p < 0.001$) for fuel consumption (Fuel Con), implement draft, and axle torque. No statistical differences existed between the annual and biennial tillage time rotations for all three variables of each implement ($p < 0.05$).

For the KMC, the data suggested that less fuel, draft, and axle torque was required compared to the Paratill™ and Terratill™. Statistical differences did exist between the annual and triennial tillage rotations in draft and torque for the KMC. The KMC biennial rotation was statistically similar to the annual and triennial rotations for all variables. A 5% increase in fuel consumption, a 28% increase in draft, and a 22% increase in axle torque occurred for the KMC when comparing the annual to the triennial rotation. There were no statistical differences between the KMC triennial rotations compared to the Paratill™ annual tillage rotation for fuel consumption and axle torque.

The Paratill™ exhibited similar trends as the KMC with no statistical differences found between the annual and biennial tillage rotations for all three variables. However, statistical differences did exist for the triennial rotation compared to the annual and biennial tillage rotations for the Paratill™. A 9% increase in fuel consumption, a 23% increase in draft, and a 25% increase in axle torque existed with the Paratill™ between the annual and triennial tillage rotations. The Paratill™ triennial results were significantly similar to all three TerraTill™ tillage rotations for all variables. Although no statistical differences were noticed between the TerraTill™ tillage rotations, there was a slight increase with each variable in the triennial rotation compared to the annual and biennial data. An increase of 2% for fuel consumption, 5% for draft, and 4% for axle torque existed for the TerraTill™ from the annual to the triennial rotation. Plots of draft vs. time for the triennial year rotation for each implement are presented in Appendix B.

Differences for all implements between the annual and biennial rotations were less than differences seen between annual and triennial rotations, and in some cases showed decreases in data from the annual to biennial years. The KMC data indicated a 2% increase in fuel consumption, a 7% increase in draft, and a 6% increase in axle torque from the annual to biennial tillage rotation. The transition between the annual and biennial rotation for the Paratill™ yielded a 0.5% decrease in fuel consumption, a 4% decrease in draft, and a 7% increase in axle torque. The TerraTill™ experienced a 0.5% increase in fuel consumption, a 1% decrease in draft, and a 0.4% decrease in axle torque between the annual and biennial year rotations. These results indicated that biennial tillage had minimal performance differences. Having the option to till every other year would save 50% on fuel costs needed to perform tillage operations compared to annual tillage. For examples, biennial tillage performed with this John Deere 8300 and TerraTill™ would save $4.89 per hectare compared to annual tillage (assuming $0.62/L for diesel fuel).

The Paratill™ exhibited higher draft and data variability for all treatments compared to the KMC and TerraTill™, particularly evident for triennial tillage. The data suggests that the Paratill™ behaves differently than the other implements. This could possibly be explained in the shape of shank which has a larger outward bend than the TerraTill™ thus, moves a larger volume of soil. In contrast, the TerraTill™ experienced the lowest variation between rotations compared to the other implements. The affects of tillage could have effected soil reconsolidation which could explain these results. However, further explanations of these affects were beyond the scope of the data.

Figure 4.2 illustrates the relationship between implement fuel consumption and draft for the tillage rotation experiment. Statistical evidence concluded that a strong linear relationship existed between fuel consumption and draft ($r^2 = 0.91$; RMSE = 0.50 L/h; $p < 0.05$). According figure 4.2, the fuel consumption at tractor under no-load and at full-throttle would be approximately 12.9 L/h based on the y-intercept of the linear fit. The Nebraska Tractor Test Data for a John Deere 8300 diesel tractor (Leviticus et al., 1995) reported 10.4 L/h fuel consumption at full throttle under no load. When comparing these numbers (12.9 vs. 10.4 L/h), they were considered close supporting the validity of this equation to predict fuel consumption based on draft. Possible differences between the Nebraska Tractor Test fuel consumption value and the value from this data could be attributed to additional loads put on the engine which included air conditioning and miscellaneous electrical equipment. Different environmental operating conditions could also impact tractor performance. The tractor used for this research also had several hundred hours of use possibly causing slight difference due to engine wear. Overall, this shows the ability of this data to be used to estimate fuel consumption if draft load is known.

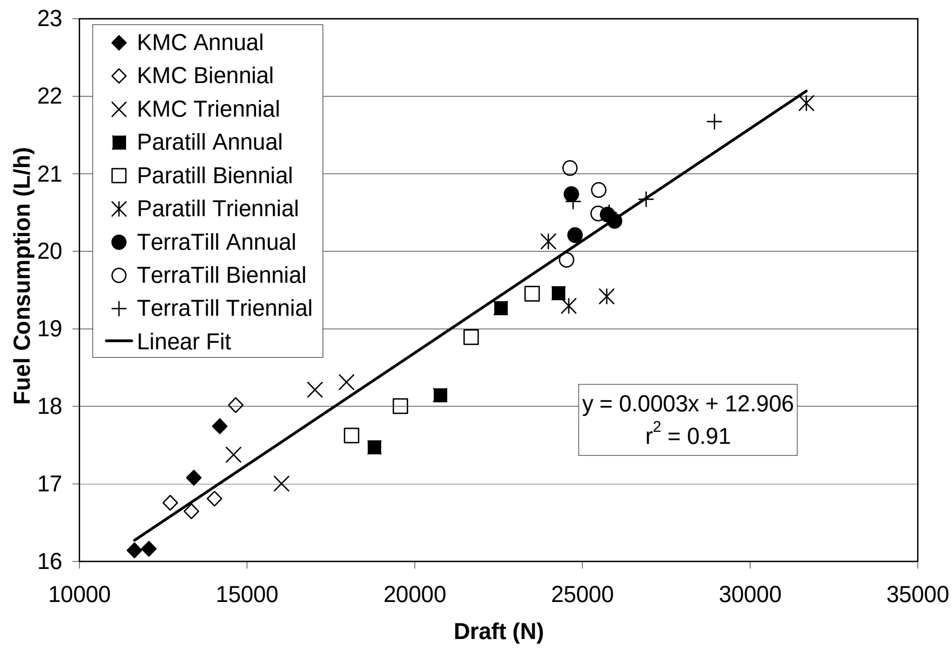


Figure 4.2. Fuel consumption vs. implement draft for the Tillage Rotation experiment.

The same data in Figure 4.2 was converted to fuel cost per hour (off-road diesel fuel price of $0.62/L) and presented in Figure 4.3. The data showed the TerraTill™ cost $2.13 more per hour to operate than the KMC and $0.96 more per hour to operate than the Paratill™.

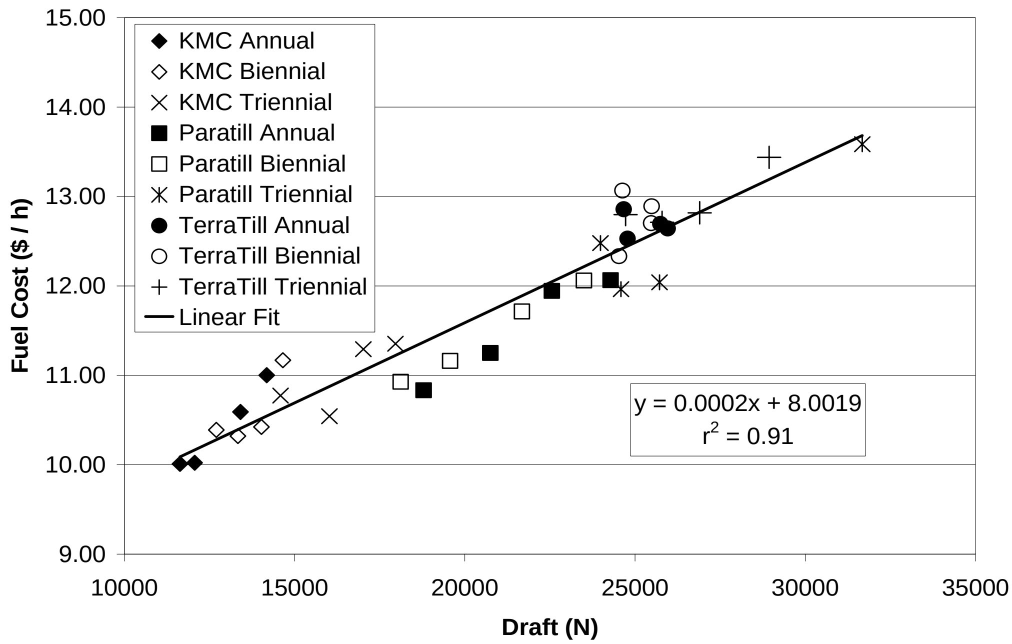


Figure 4.3. Fuel cost per hour vs. implement draft for the Tillage Rotation experiment.

Figure 4.4 shows the relationship between axle torque and fuel consumption for the tillage rotation experiment. A strong linear relationship existed between axle torque and fuel consumption (r^2=0.90; RMSE= 0.54 L/h; $p<0.05$). Axle torque reflected the amount of power input to the tractive device. As power requirements increased, fuel consumption increased.

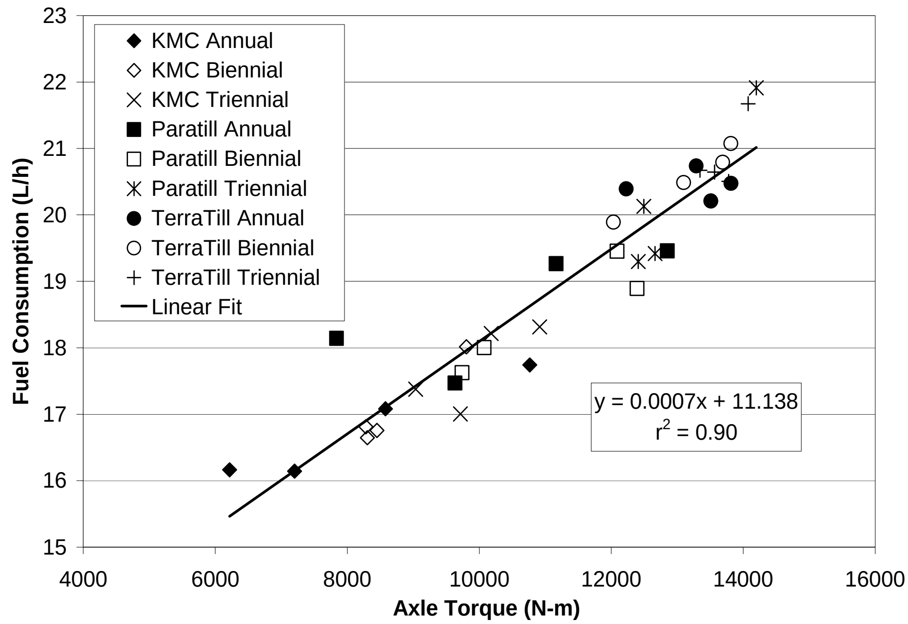


Figure 4.4. Fuel consumption vs. axle torque for the Tillage Rotation experiment.

Figures C.1, C.2, and C.3 in Appendix C present the relationship between draft and axle torque for the KMC, Paratill™ and Terratill™, respectively for the tillage rotation experiment. Moderate linear relationships were found for the KMC and Paratill™ ($p<0.05$) with r^2 values equal to 0.69 and 0.67, respectively. No linear trend existed for the TerraTill™ ($p = 0.3017$) with an $r^2 = 0.11$ indicating that the tillage rotation treatments had less of an effect on its performance. The TerraTill™ showed the least variation out of all the implements with no statistical differences found between the treatments. The KMC and TerraTill™ had lower root mean square errors (RMSE) at 1117 N and 1247 N respectively, compared to the Partill™. An RMSE of 2204 N was computed for the Paratill™'s linear fit.

Figures 4.5, 4.6, and 4.7 present draft vs. axle torque for the annual, biennial, and triennial tillage rotations for each implement. A Linear relationship seemed to exist for the annual rotations with an r^2 value of 0.73 (RMSE = 3098 N). The biennial and triennial rotations look to have increased linearity compared to the annual rotations with r^2 values equal to 0.92 (RMSE = 1580N) and 0.93 (RMSE = 1482 N), respectively. The graphs illustrate that the KMC had the lowest draft and axle torque compared to the other implement for all rotations. Draft and axle torque values for the Paratill™ tended to be in the middle of the data. The TerraTill™ had the highest draft and axle torque for all implement and rotations. Overall, the data illustrates the difference between implement behaviors which could be attributed to different implement weights and shank designs which would have effects on both draft and axle torque. The distance between the locations of the shanks relative to the center of the rear axle also has an effect on draft and axle torque.

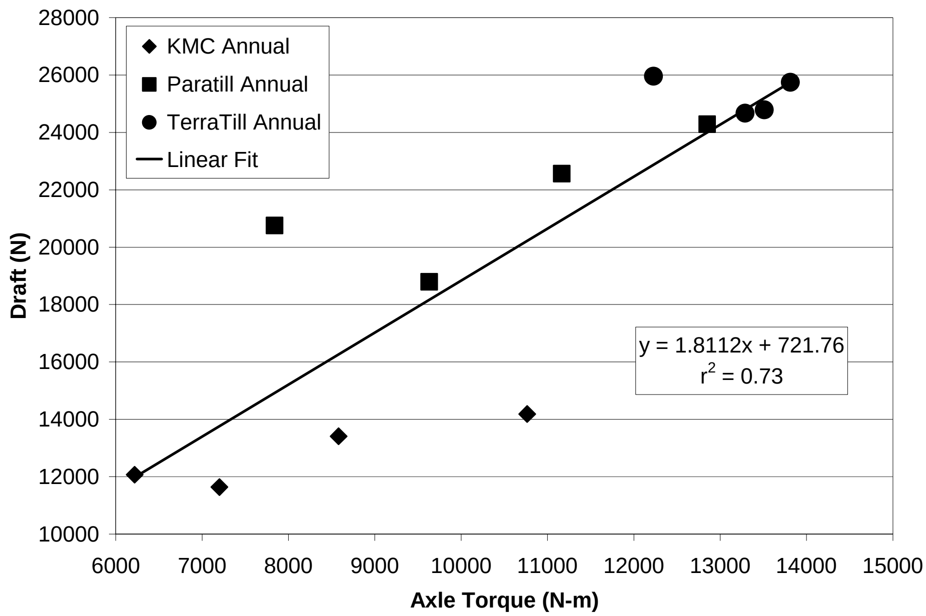


Figure 4.5. Draft vs. axle torque for the annual tillage rotation for all implements.

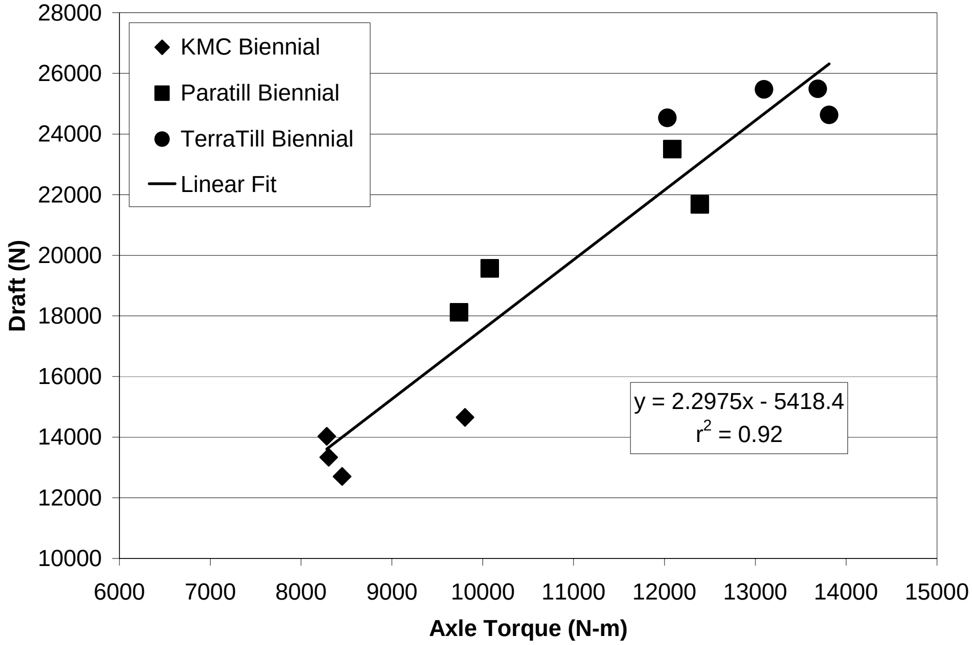


Figure 4.6. Draft vs. axle torque for the biennial tillage rotation for all implements.

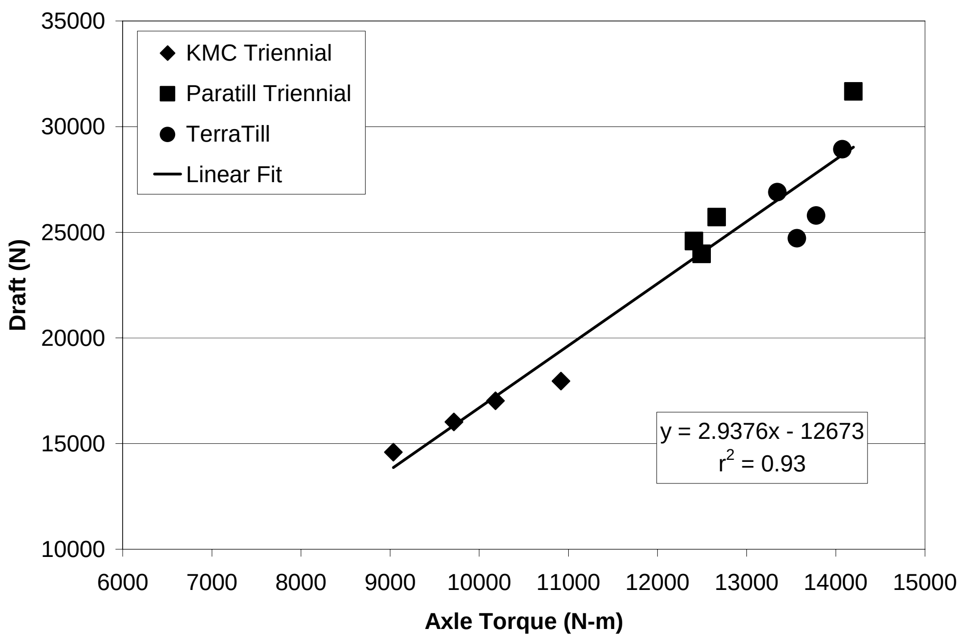


Figure 4.7. Draft vs. axle torque for the triennial tillage rotation for all implements.

In summary, a trend existed suggesting an increase in energy requirements for the triennial year tillage rotations for all implements. The KMC required the least amount of energy out of all the implements. The TerraTill™ had the highest variable values out of all implements. Reasons for this might be in the shank design having different effects on soil properties such as bulk density or cone index. The shape of the shank may disrupt soil in a way which causes it to consolidate faster and would explain why no differences in variables were experienced between tillage rotations. Therefore, future research is needed to evaluate this as a possible explanation.

Fuel consumption and draft data was also analyzed per unit length of shank for the Paratill™ and TerraTill™ and are presented in Table 4.4. The lengths of shank in contact with the soil were 56.5 cm and 54.6 cm for the Paratill™ and TerraTill™, respectively. The TerraTill™ generated larger values for both fuel consumption and draft per unit shank length even though its shank length was shorter compared to the Paratill™. Increased values for the TerraTill™ indicated this implement is not as efficient during tillage than the Paratill™ or more simply, it require more energy under the same operating conditions. No statistical differences between fuel consumption and draft per unit of shank length existed between the annual and biennial rotations for both the Paratill™ and TerraTill™. The triennial rotation showed increased values for both fuel consumption and draft per shank length for both implements which supports the results in Table 4.3. The TerraTill™ is commonly known to have less effective soil disruption along with increased horsepower per unit draft requirements compared to the Paratill™. Standardized data as such can be used to better understand implement efficiency in terms of energy requirements and effect on fuel consumption.

Table 4.4. Results for fuel consumption and draft per unit shank length for the Paratill™ and TerraTill™ implements.

Implement	Rotation (yrs.)	Fuel Con/shank length (L/h·cm)*	Draft/shank length (N/cm)*
Paratill™	1	0.328[c]	382[b]
	2	0.327[c]	367[b]
	3	0.357[b]	469[a]
TerraTill™	1	0.374[ab]	463[a]
	2	0.376[ab]	458[a]
	3	0.382[a]	487[a]

*Means with similar letters in columns are not statistically different ($\alpha = 0.05$).

Tillage Speed Experiment

The measured soil moisture content ranged from 12% to15% dry basis for the study site. Table 4.5 presents a summary of results for the implement speed experiment. The ground speed (GS) difference between the slow and normal speeds was about 2.8 km/h while the difference between the normal to fast speeds was approximately 2.5 km/h for both implements. These speed differences indicated that the speed transitions were similar between treatments. The fuel consumption (Fuel) for both implements showed a positive increase when moving from the slow to fast speeds. The fuel consumption for the Paratill™ was statistically similar to that of the KMC for each of the equivalent speeds ($p<0.05$). For the Paratill™, a 104% (slow vs. fast) and a 40% (slow vs. normal) increase in fuel consumption occurred. A slightly higher 47% increase in fuel consumption was noticed from the normal to fast speed for the Paratill™. The KMC experienced larger changes in fuel consumption yielding a 66% increase from the slow to normal speeds and a 115% increase from the slow to fast speeds.

Table 4.5. Summary of results for the Paratill™ (treatments 1, 2, and 3) and KMC (treatments 4, 5, and 6) implements over the 3 different test speeds.

Implement	GS* (km/h)	Slip* (%)	Engine* (RPM)	Fuel* (L/h)	Torque* (N·m)	Power* (kW)	Draft* (N)	Vert* (N)
Paratill™	3.0[a]	0[c]	2,275[ab]	18.9[c]	13,631[ab]	28[b]	34,130[b]	4,414[b]
Paratill™	5.8[b]	0[c]	2,264[bc]	26.4[b]	13,489[bc]	53[c]	32,719[b]	4,112[b]
Paratill™	8.3[c]	1[bc]	2,239[d]	38.8[a]	13,938[a]	101[a]	43,633[a]	7,654[a]
KMC	2.9[a]	1[b]	2,275[a]	17.7[c]	13,119[c]	27[b]	32,450[b]	-3,087[c]
KMC	5.6[d]	3[a]	2,260[c]	29.3[b]	13,920[a]	66[d]	40,581[a]	-1,654[c]
KMC	8.0[e]	4[a]	2,246[d]	38.1[a]	14,050[a]	103[a]	44,559[a]	-885[c]

*Means with similar letters in columns show no statistical differences (α = 0.05).

The Paratill™ showed no statistical difference in draft between the slow and normal speed however, a slight decrease in draft was observed. A statistical difference yielding a 31% increase in draft existed between the fast speed compared to the average of the slow and normal speeds. Draft steadily increased for the KMC as speed increased. The KMC experienced a statistical increase of 25% in draft between the slow to normal speeds. While not significant, a 10% increase in draft occurred between the normal and fast speeds. A significant increase in draft of 37% existed between slow and normal speeds.

Trends showed that as speed increased, power required to pull the implements also increased. There was no statistical difference in power at the slow and fast speeds between the implements. There was an 89% increase in Paratill™ power requirement between the slow and normal speeds with a 261% increase from the slow to fast speed. The KMC noticed a 144% increase in power requirements from the slow to normal speed with a 281% increase in power from the slow to fast speed. Axle torque data for the Paratill™ actually showed a decrease of 4% from the slow to normal speed that could possibly be explained from inherent soil moisture and terrain variability at the study site.

No statistical differences in axle torque existed between the slow and fast speeds as well as the slow and normal speeds for the Paratill™. Results for the Paratill™ showed decreases in draft and axle torque between the slow and normal speeds indicating that the implement was able to move through the soil at less effort for the normal speed compared to the slow speed. For the KMC, no statistical differences in axle torque were found for the normal and fast speed. A slightly increasing trend in axle torque was noticed as speed increased for the KMC.

As for slip, some problems were encountered with the data acquisition system which resulted in low and negative slip values. The slip data in Table 4.5 has been averaged with the negative values replaced with zeros. However, the slip was low (< 5%) during this experiment for all treatments.

Soil properties can sometimes explain equipment performance differences throughout a field. Cone index (CI) readings were measured in 5.08cm increments and are presented as an average of all readings down to the maximum depth of tillage, 35.6 cm. No statistical differences existed between CI averages between the treatments. However, treatment 1 had the lowest CI value (2.46 MPa) while 4 and 6 were the highest. After tillage, the actual depth of tillage (tillage depth in Table 4.6) was measured by excavating all disrupted soil throughout the destruction zone. Treatment 6 had the highest draft load of all the implements as well as the lowest moisture content (MC) and a high CI. This indicated that soil properties did have an effect on this treatment. Soil properties for the other treatments were considered similar. However, the soil properties in this case do not fully explain the performance results reported in Table 4.5. It is speculated that the effect of speed treatments overrode the effects of the soil properties on equipment performance. Overall, the soil properties were consistent between plots with some variability in bulk density (BD) and depth of tillage.

Table 4.6. Summary of measured soil data for the Implement Speed test.

Trt	Implement	Tillage Depth (cm)	MC db (%)	BD (g/cm^3)	CI (MPa)
1	Paratill™	29.8[ab]	15.5[a]	1.41[b]	2.46[a]
2	Paratill™	28.4[b]	15.7[a]	1.47[ab]	3.07[a]
3	Paratill™	31.3[a]	14.2[a]	1.50[a]	3.16[a]
4	KMC	26.5[c]	15.6[a]	1.40[b]	3.47[a]
5	KMC	26.2[c]	15.6[a]	1.46[ab]	2.87[a]
6	KMC	26.5[c]	12.6[a]	1.46[ab]	3.44[a]

*Means with similar letters in columns show no statistical differences ($\alpha = 0.05$).

The three point hitch dynamometer utilized during this experiment also measured vertical forces (Vert in table 4.5). The orientation of the load cell yielded negative forces as lifting the implement out of the ground and positive forces pulling the implement into the ground. The KMC and Paratill™ behaved differently (Figure 4.8). The results show differences between the Paratill™ and KMC in vertical forces and tillage depths. Tillage depths were 2 to 5 cm different between the implements. The KMC generated a negative vertical draft which caused the implement to rise up during tillage and decreased the nominal depth of tillage. The bentleg design of the Paratill™ behaved exactly opposite by pulling the implement into the ground thus yielding slightly deeper tillage depths compared to the KMC. The tillage depths were similar for the KMC as were the vertical forces which indicated the speed treatments had no effect on these variables. The Paratill™ had a large amount of variability compared to the KMC possibly due to the shape of the shank. The shape could create a different response to soil physical property variations thereby, causing forces to vary more when pulled through the soil profile. The observed differences in vertical forces between implements but also with each implement does indicate a possibly of dynamic ballasting and/or an automated central tire inflation (CTI) to maintain optimal equipment performance.

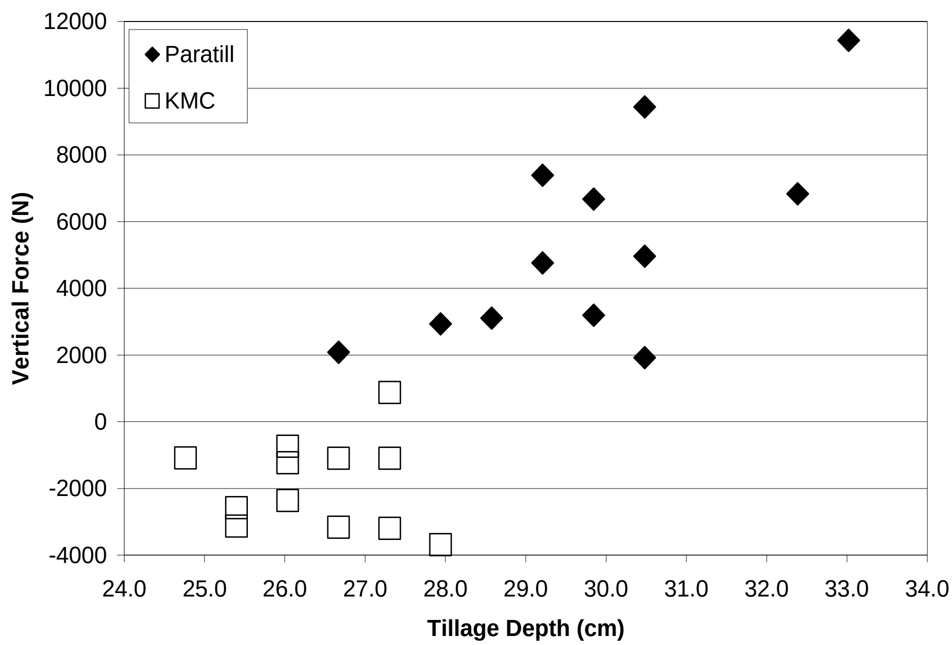


Figure 4.8. Vertical implement draft force vs. actual tillage depth.

Figure 4.9 illustrates the relationship between implement draft and fuel consumption for the Paratill™ and KMC implements. A strong linear relationship (r^2 = 0.85; RMSE = 3.98 L/h; $p < 0.001$) existed for the KMC while only a moderate one existed for the Paratill™ (r^2 = 0.59; RMSE = 6.11 L/h; $p = 0.0036$). Reasons for the moderate linear relationship for the Paratill™ could be explained by the fact that the biennial rotation for the Paratill™ did experience a decrease in draft but an increase in fuel consumption compared to treatment 1. As presented in Table 4.6, treatment 2 had the shallowest actual tillage depth and the highest moisture content for all three Paratill™ treatments. Statistical comparisons indicated that the slope for the KMC did not statistically differ for the slope of the Paratill™ ($p = 0.8522$). Similarly, no significant differences existed between the y-intercepts between the LS linear fits for each implements (p=0.1468). Since no statistical differences existed between the implements, the fuel consumption and draft for both implements were plotted together to determine and the overall relationship (Figure 4.10). A good linear relationship existed ($r^2 = 0.69$; RMSE = 5.15 L/h).

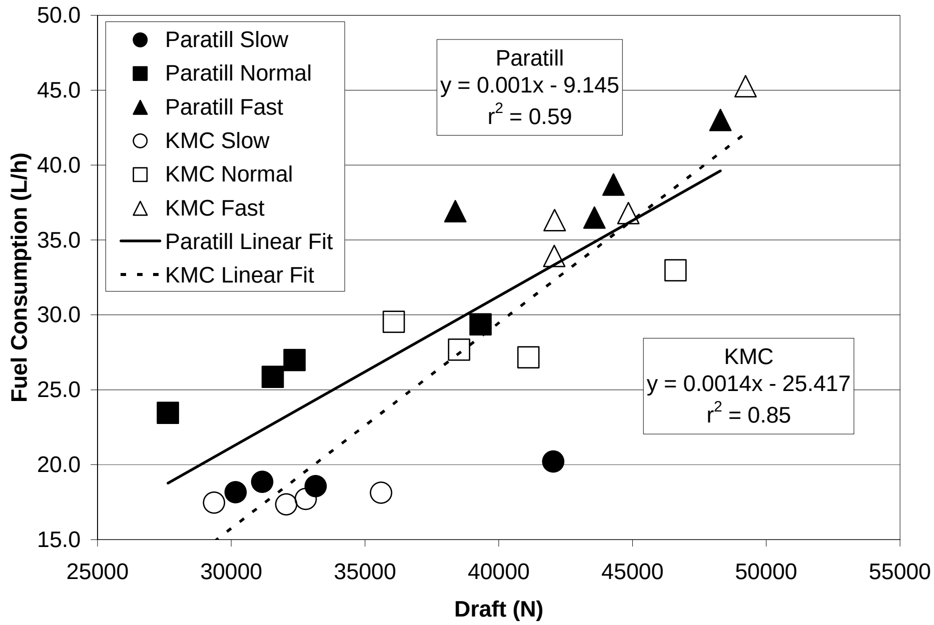


Figure 4.9. Draft vs. fuel consumption for the Implement Speed test.

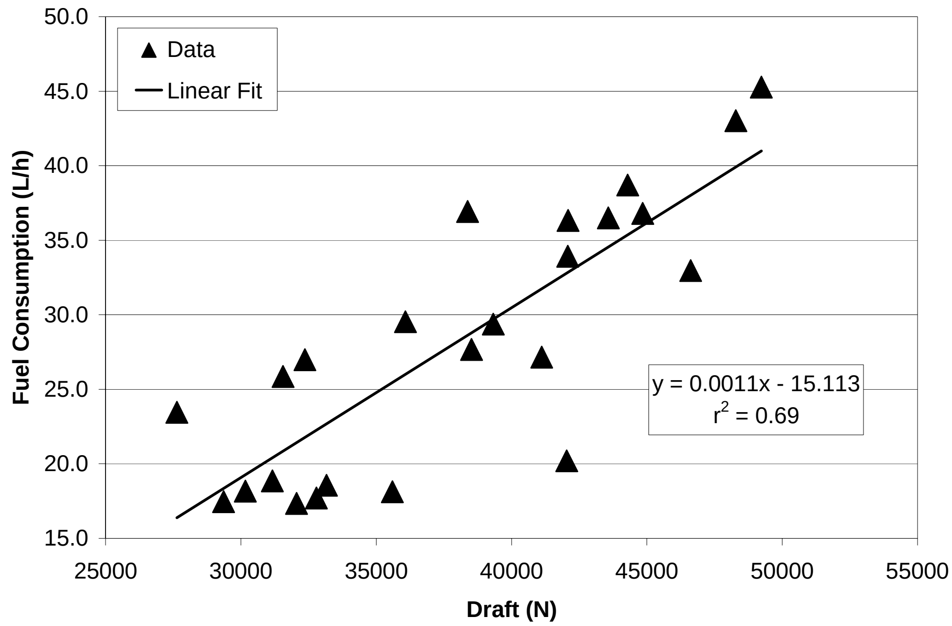


Figure 4.10. KMC/Paratill™ merged fuel consumption vs. draft data for the Implement Speed test.

Figure 4.11 presents tillage draft compared to axle torque with relationships. Moderate linear relationships were exhibited by the KMC (r^2 = 0.64; RMSE = 344.5 N-m) and the Paratill^{TM} (r^2 = 0.68; RMSE = 188.6 N-m). Statistical evidence showed that the slopes of the regression lines are the same (p = 0.1125) along with the y-intercepts (p = 0.0867). As expected, axle torque increased with draft. The overall relationship between axle torque and draft with LS linear fit is presented in Figure 4.12 (r^2 = 0.58; RMSE = 279 N-m).

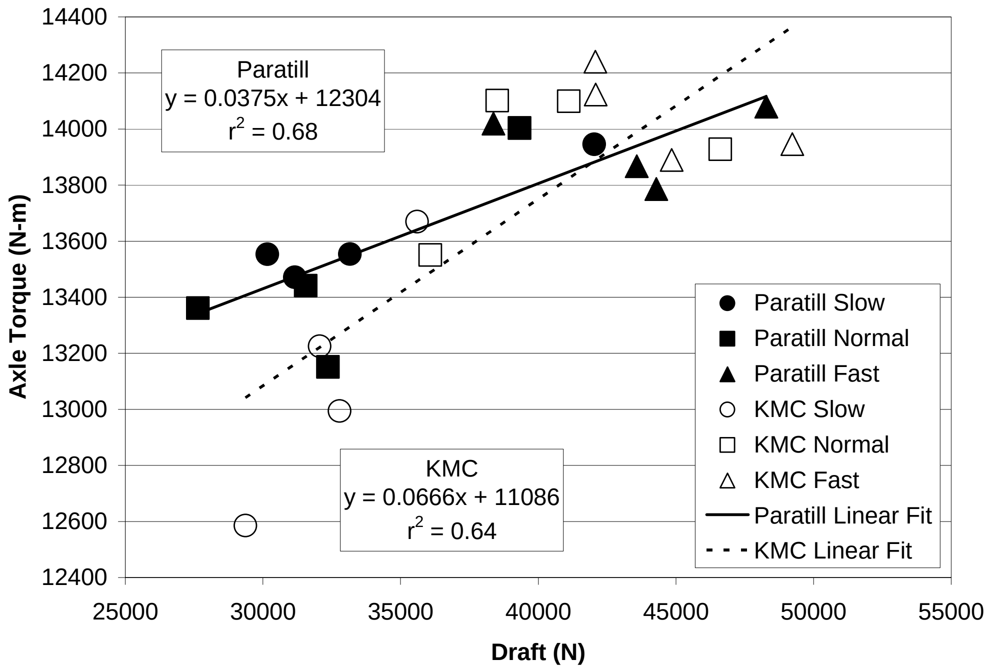


Figure 4.11. Axle torque vs. draft for the Implement Speed test.

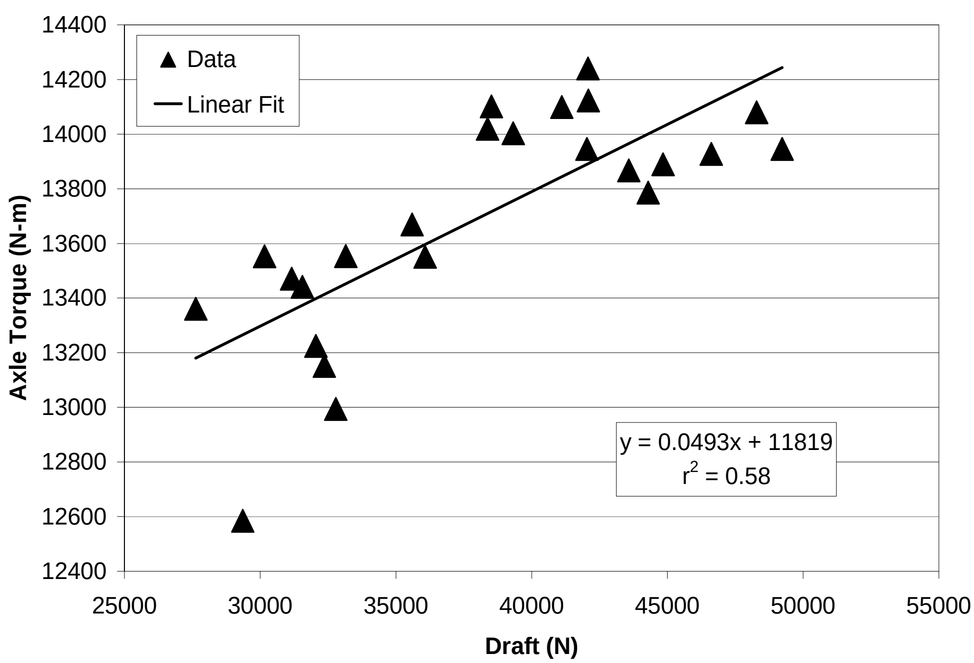


Figure 4.12. KMC/Paratill™ merged axle torque vs. draft data for the Implement Speed test.

A strong linear relationship existed between power and consumption for the Paratill™ (Figure 4.13; r^2 =0.98; RMSE = 4.28 kW) and the KMC (r^2 = 0.95; RMSE =

7.99 kW). No significant differences existed between the slopes (p = 0.6357) and y-intercepts (p = 0.3936) for these LS linear fits. The overall relationship for power and fuel consumption is presented in Figure 4.14 with the LS linear fit results. A good linear relationship (r^2 = 0.96; RMSE = 6.19 kW) existed between Power and Fuel Consumption for this particular JD 8300 tractor (Figure 4.14) regardless of speed and implement.

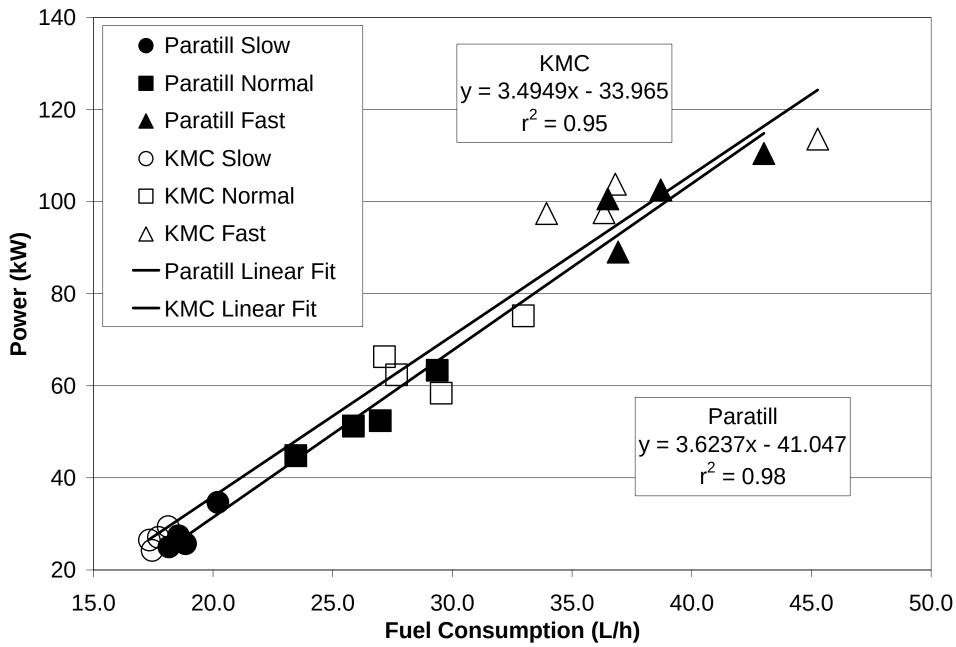


Figure 4.13. Power vs. fuel consumption for the Implement Speed test.

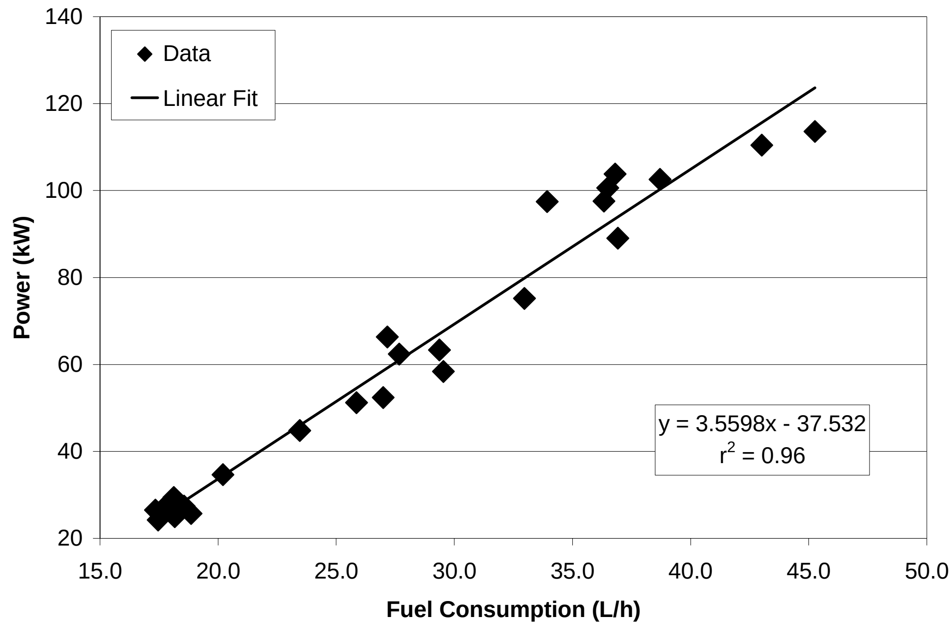


Figure 4.14. KMC/Paratill™ merged data for power vs. fuel consumption data for Implement Speed test.

In order to validate available methods used to estimate data such as draft and fuel consumption, a comparison was performed between estimated and actual fuel consumption and draft loads for the John Deere 8300 tractor used in this experiment. The estimated fuel consumption was computed using equation 3.11 (Raper et al., 2005b). Table 4.7 shows the comparison with percentage differences compared to actual fuel consumption measurements. The percentage differences were lower for the normal speed (5.6 to 5.8 km/h) compared to the slow and fast speeds for both implements which indicated that the equation might have been developed under normal operating conditions. At low speeds the equation under-estimated fuel consumption as indicated by a negative difference. The fast speed data showed that the equation over-estimated fuel consumption. The total average absolute percentage difference between actual and estimated fuel consumption was 4.8%. The results indicated a good relationship (r^2 =

0.96; RMSE=1.92 L/h) between the estimated and actual fuel consumption data (Figure 4.15). The slope (1.10) was close to 1.0 validating the accuracy of equation 3.11 to compute the fuel consumption for this John Deere 8300 tractor.

Table 4.7. Comparison of estimated and actual fuel consumption for the Tillage Speed experiment.

Implement	Speed (km/h)	Actual Fuel Con (L/hr)	Estimated Fuel Con (L/hr)*	Difference (%)
Paratill™	3.0	18.9	17.9	-5.3
Paratill™	5.8	26.4	25.6	-3.0
Paratill™	8.3	38.8	40.2	+3.6
KMC	2.9	17.7	17.3	-2.3
KMC	5.6	29.3	28.9	-1.4
KMC	8.0	38.1	40.0	+4.9

*Values calculated from Raper et al., 2005b.

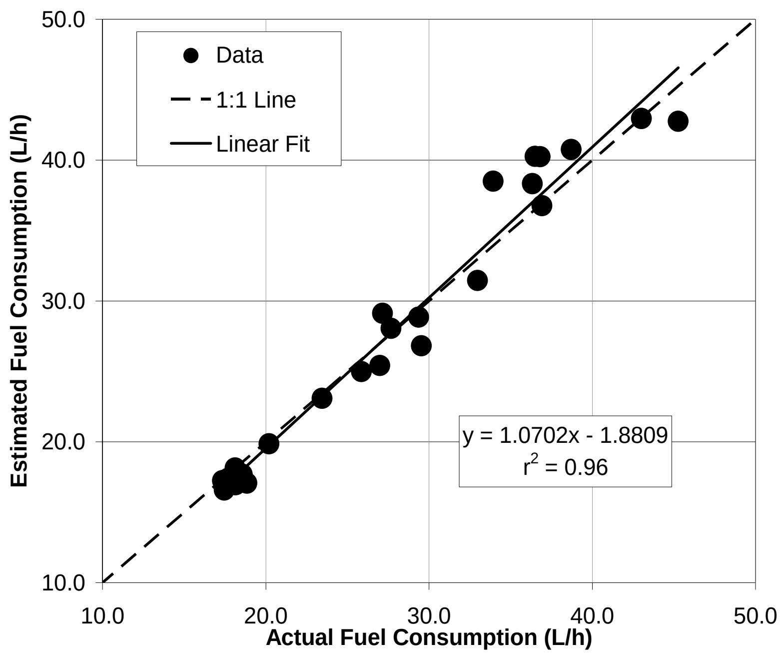


Figure 4.15. Estimated vs. actual fuel consumption for the Implement Speed experiment.

Table 4.8 presents a comparison of the estimated versus actual draft values for the implement speed test. According to the results, the difference between the actual and estimated draft for the Paratill™ were larger than the differences for the KMC. No machine coefficients were proved for the Paratill™ so the same coefficients were used to estimate draft for both the KMC and the Paratill™ which yielded the same results for both implements. The total average absolute percentage difference between actual and estimated draft was 8.2%. Due to the rising popularity of non-traditional tillage implements, these results suggest the need for an updated standard to reflect the data collected and differences that may exist in current tillage equipment compared to older equipment.

Table 4.8. Results of estimated vs. actual draft requirements.

Implement	Speed (km/h)	Actual Draft (N)	Estimated Draft (N)	Difference (%)
Paratill™	3.0	34,130	33,589	-1.6
Paratill™	5.8	32,719	40,329	+23.3
Paratill™	8.3	43,633	48,540	+11.3
KMC	3.0	32,450	33,589	+3.5
KMC	5.8	40,581	40,329	-0.6
KMC	8.3	44,559	48,540	+8.9

Figure 4.16 shows the relationship of estimated vs. actual draft for the implement speed experiment. The KMC data indicated a strong linear relationship (r^2=0.94) between estimated and actual draft values illustrating the accuracy of the draft estimation equation provided by the ASAE standard D497.4 (2003). However, a lower linear relationship (r^2= 0.69: RMSE = 3596 N) suggested that a coefficient is needed to better estimate draft for new tillage implements.

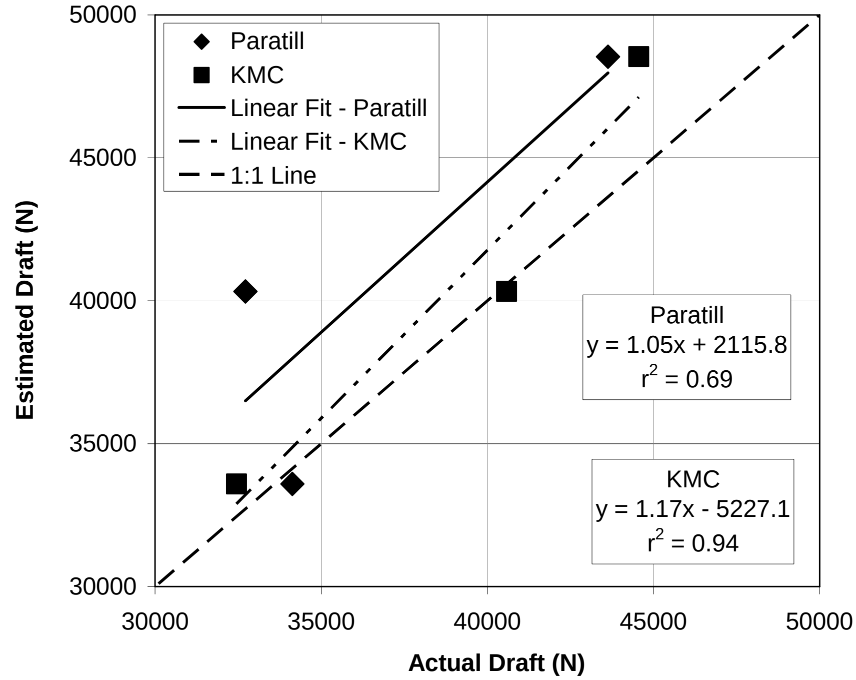


Figure 4.16. Estimated vs. actual draft for the Paratill™ and KMC implements.

Figure 4.17 presents the comparison of estimated and actual draft values for the implement speed experiment without separating out implement data. A good linear relationship existed ($r^2 = 0.77$; RMSE = 3576 N). However, draft tended to be overestimated.

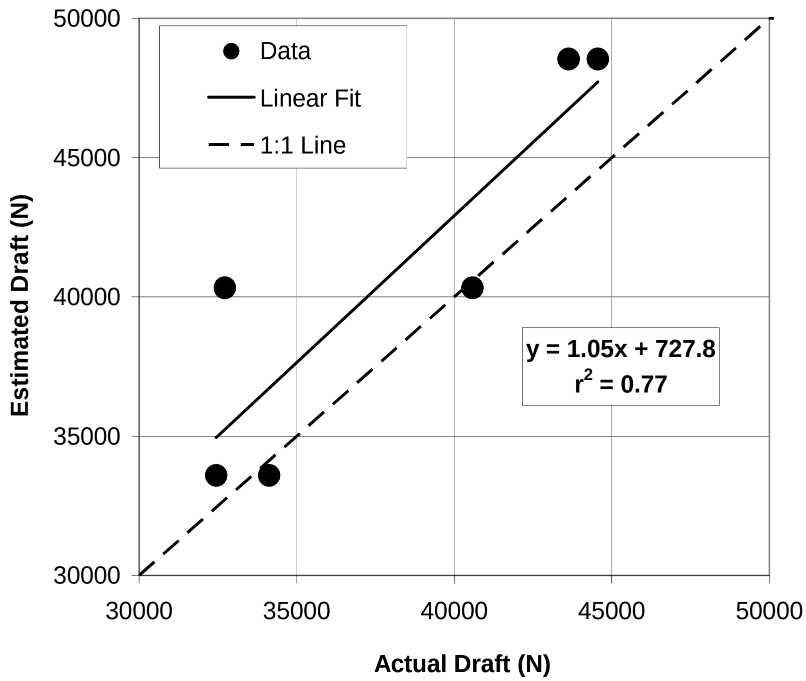


Figure 4.17. Estimated vs. actual draft for the Implement Speed experiment.

Spatial Tillage Experiment

A summary of the tire pressure treatment results for the spatial tillage experiment is presented in Table 4.9. The average moisture content dry basis for the test area was 13.5%. Statistical differences existed between tire pressure treatments for all variables.

Table 4.9. Summary of results for the Spatial Tillage experiment.

Pressure	Fuel* (L/hr)	Wheel* (km/h)	GS* (km/h)	Slip* (%)	Eng Speed* (rpm)	EGT* (ºC)	Torque* (N-m)
High	13.7[c]	6.0[a]	5.5[a]	7.2[c]	2239[a]	393[c]	3771[c]
Normal	14.0[b]	5.9[b]	5.4[b]	8.8[b]	2216[b]	403[b]	4053[b]
Low	14.3[a]	5.8[c]	5.1[c]	12.2[a]	2189[c]	412[a]	4417[a]

*Means with similar letters in columns are not statistically different ($\alpha = 0.05$).

The high pressure treatment experienced the lowest fuel consumption at 13.7 L/h which was 2.2% lower than the normal pressure treatment (14.0 L/h) and 4.4% less than the low pressure treatment (14.3 L/h). Figure 4.18 present maps of fuel consumption for each tire pressure. Fuel consumption varied across the site for each treatment. The low tire pressure showed increased fuel consumption compared to the other pressures as illustrated with red and dark green colored areas in the map. The high pressure showed the least amount of fuel consumption throughout the test site as noticed with light green and orange colors. Higher levels of fuel were consumed near the ends the test area for each tire pressure treatments. The field was later divided into 3 zones to closer investigate theses area, the results of which are presented later in this section.

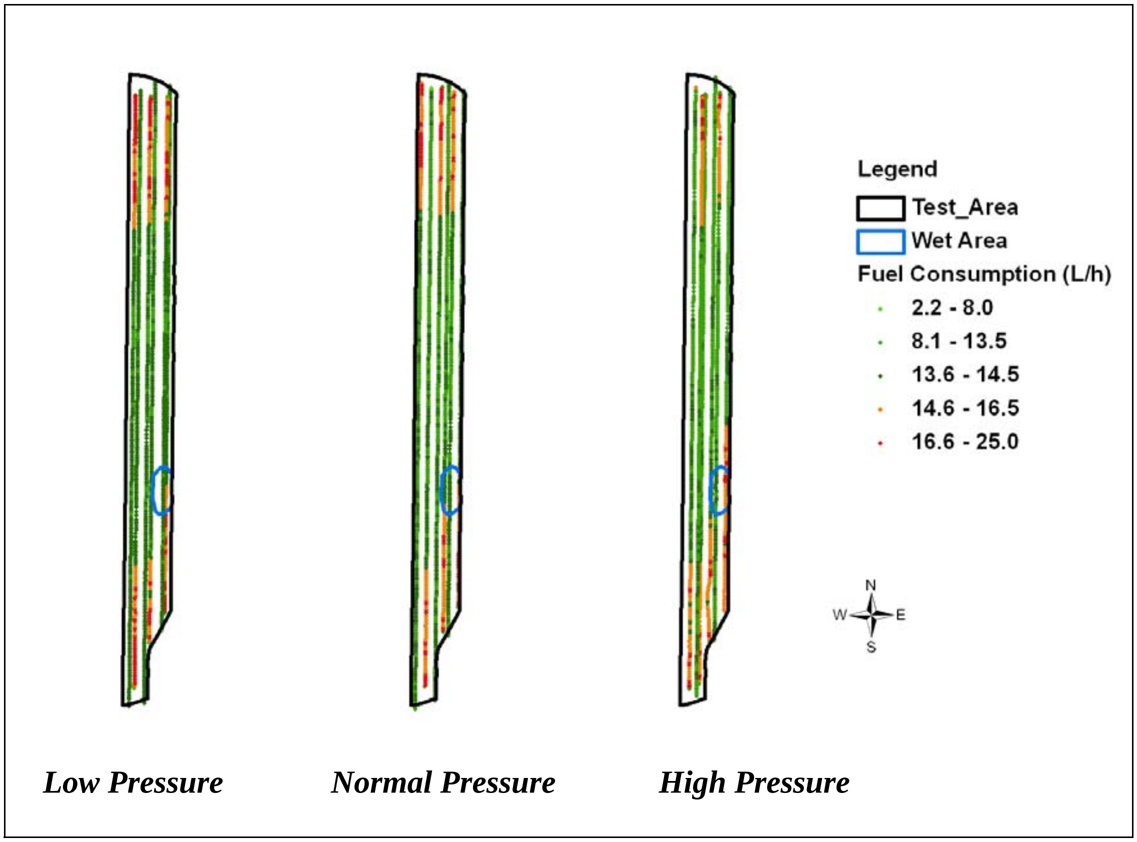


Figure 4.18. Illustrations of fuel consumption for each tire pressure treatment.

The results in Table 4.9 show that slip for the low pressure treatment was the highest of all treatments at 12.2%. The high pressure had the lowest slip at 7.2%. A 22% increase in slip was noticed from the high (7.2%) to normal tire air pressure (8.8%) and a surprising 69% increase in slip occurred from the high (7.2%) to low tire air pressure (12.2%). The optimum slip values for firm soil are 8% to10% (ASABE standard EP496.3, 2006). The field conditions at the time were immediately after a corn harvest which was considered firm soil. The normal pressure (8.8%) was within the recommended slip range and the high pressure (7.2%) and low pressure (12.2%) were not. The high pressure average slip values were slightly lower than recommended while the low pressure treatment was about 2% higher than what is recommended for firm soil.

Figure 4.19 presents maps that illustrate slip throughout the field for each of the tire pressure treatments. The low tire pressure showed increased slip values indicated by the orange color prominent in the map. Lower slip values were noticed with the normal tire pressure illustrated by less orange and increased green color throughout the test area compared to the low air pressure. The high tire pressure showed the lowest slip values indicated by the light green color present throughout the test area. An area of high moisture was also present in the field caused increased slip values for all tire pressures. These results suggested that a threshold tire air pressure might exist where optimum performance could be achieved, but after this point is exceeded, performance rapidly decreases. These types of maps are useful in quickly indicating areas of low performance. Field efficiency could be quantified in order to make management decisions on whether remediation should be performed to improve efficiency and performance.

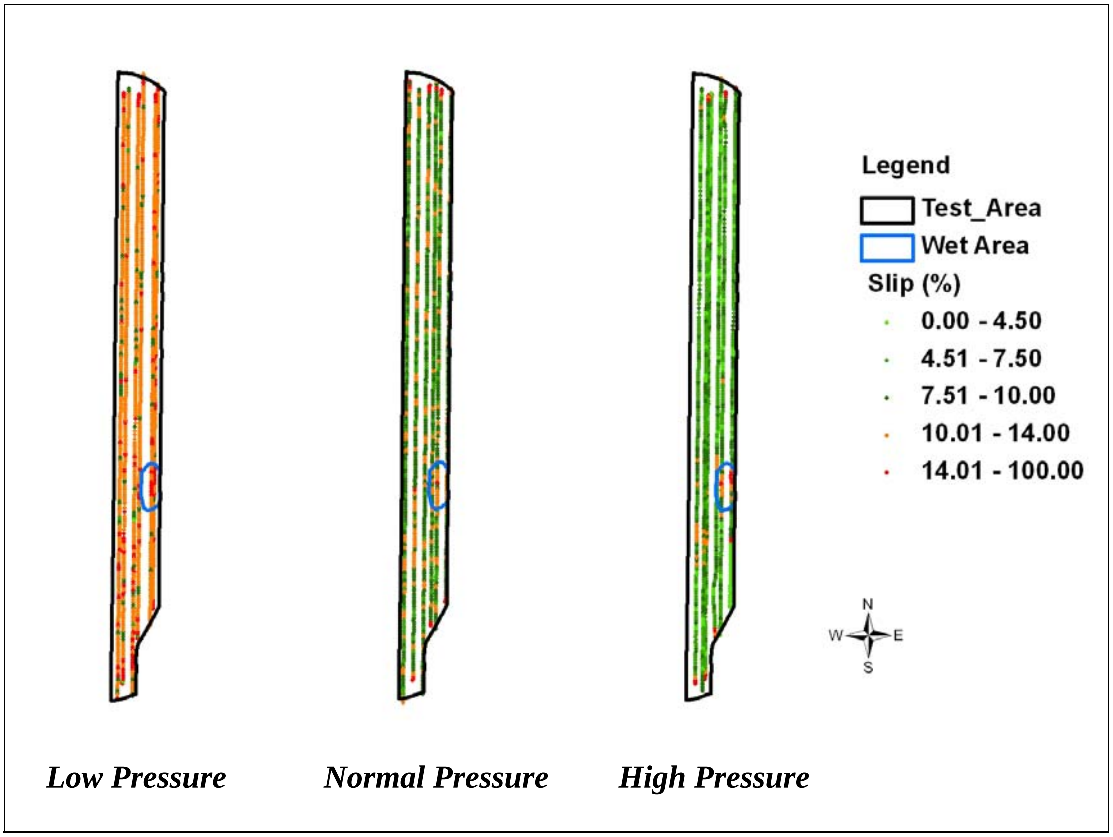


Figure 4.19. Maps of slip for each tire pressure for the Spatial Tillage experiment.

Exhaust Gas Temperature (EGT), torque, and engine speed are often used to indicate the degree of engine load. The results in Table 4.9 showed that the low tire pressure had the highest EGT and axle torque out of all treatments. Figure 4.20 presents maps of EGT during the duration of the tire pressure experiment. The low tire pressure experienced increased EGTs compared to the normal and high pressures, indicated by the dark orange color prominent in this zone. The replications for the high pressure seemed to have lower exhaust gas temperatures compared to the other treatments. The maps highlighted that EGT did vary across the site for all tire pressures. This result suggested that the engine was experiencing increased loads during the low pressure treatments compared to the other treatments. Explanations for this could be that at low tire pressure, the rear tires experienced severe side wall deflection. Air pressure low enough to cause tire deformation could possibly have a negative effect on equipment performance as seen with the results of this experiment.

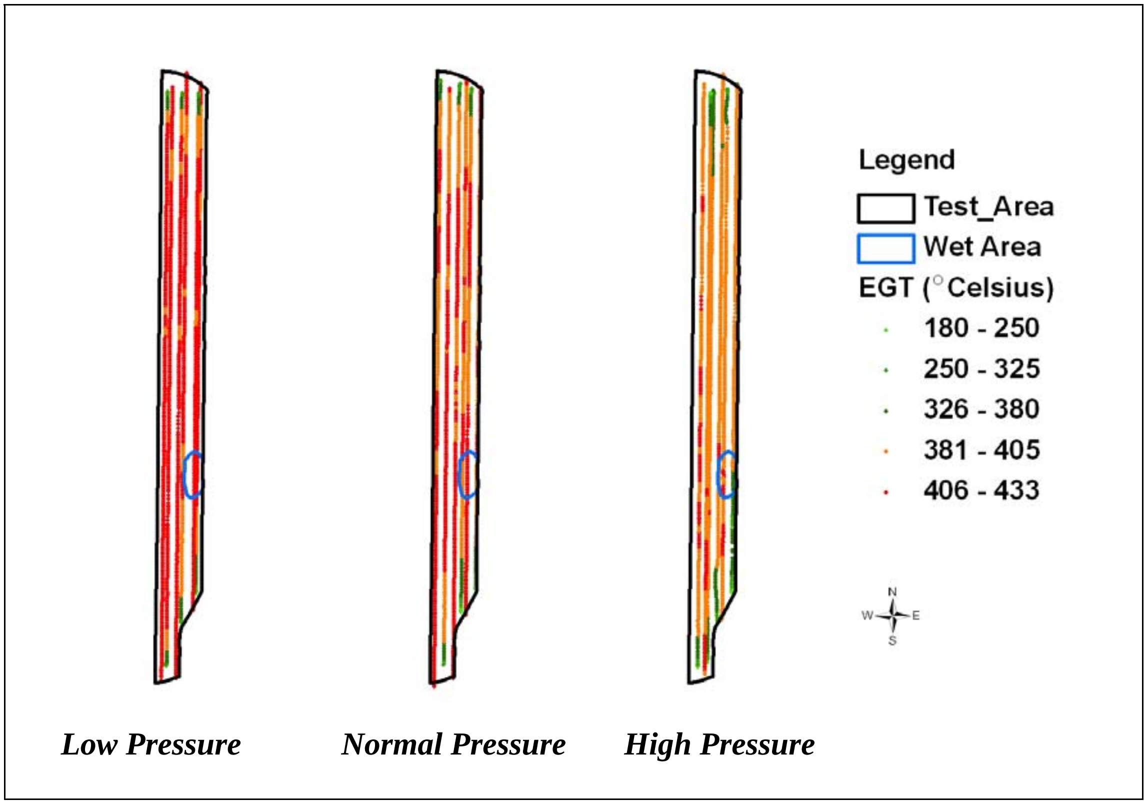


Figure 4.20. Illustrations of EGT for each tire pressure treatment.

Figure 4.21 presents maps of axle torque throughout the test area for each pressure of the tire pressure experiment. A wide range of variability can be seen in the map. The low pressure treatment seemed to experience increase axle torque throughout the field indicated by more orange and red colors compared to the normal and high pressure treatments. The high pressure treatment showed the lowest axle torque throughout the field illustrated by increased green color compared to the low and normal pressures. Areas of low performance can be pointed out according to increased axle torque values noticed in the high moisture area, outlined in blue.

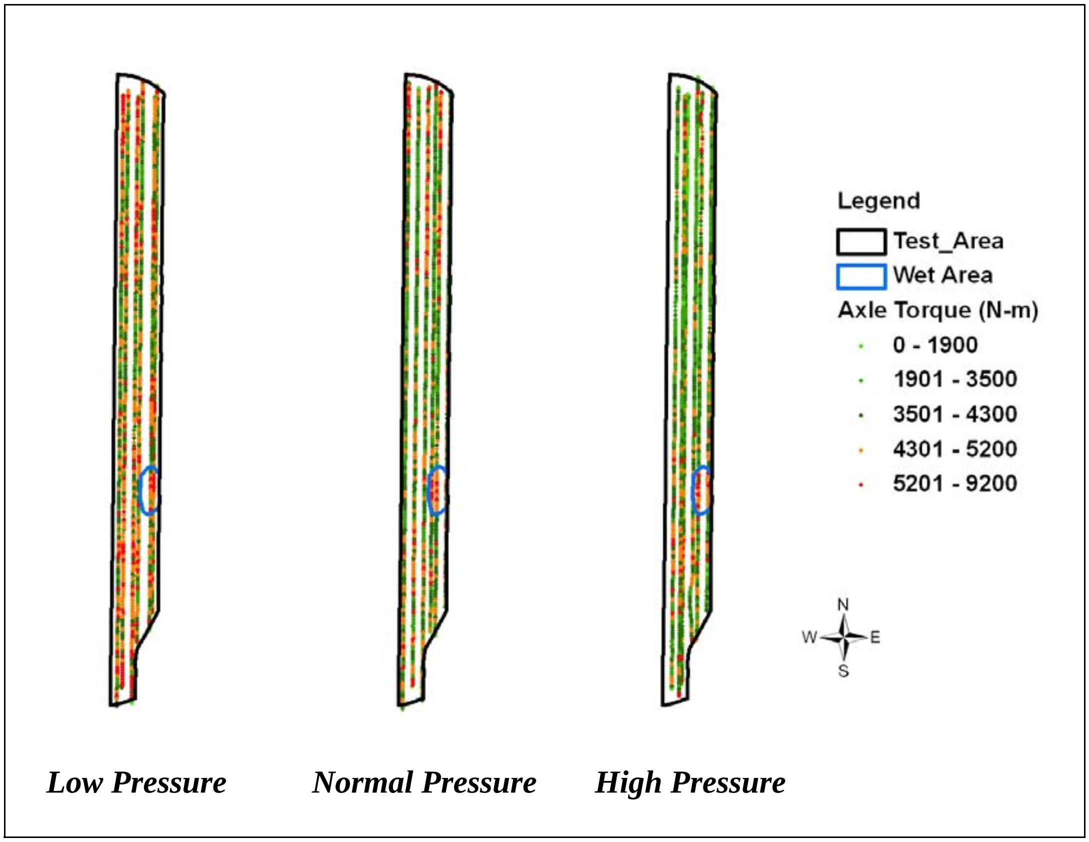


Figure 4.21. Map of axle torque for the Spatial Tillage experiment.

A fuel cost analysis was performed to demonstrate the capabilities of precision technologies for use in the agricultural industry. Productivity for the tire pressure experiment was measured in hours per hectare and cost analysis was calculated as United States (U.S.) dollars per hectare (Table 4.10). There were no statistical differences found between any of the tire pressures for productivity ($p = 0.3204$). There were statistical differences between the low pressure compared to the other treatments for fuel cost ($p<0.05$). The low tire pressure (1.06 h/ha) seemed to have slightly lower productivity than the high (1.01 h/ha) and normal (1.01 h/ha) tire pressures by about 5% even though not statistically different. The results indicate a savings of 8.7% in fuel cost per hectare between for the high tire pressure compared to the low tire pressure. A fuel savings 3.3% per hectare was also indicated with the high pressure compared to the normal pressure.

Table 4.10. Summary of fuel cost analysis for the Tire Pressure Experiment.

Pressure	Productivity (h/ha)*	Fuel Cost (US $/ha)*
High	1.01[a]	8.53[b]
Normal	1.01[a]	8.82[b]
Low	1.06[a]	9.34[a]

*Means is similar letters in columns are not statistically different ($\alpha = 0.05$).

Figure 4.21 presents a spatial representation of fuel cost throughout the testing area for each tire pressure. The maps underscore the differences in fuel cost between the treatments. The low pressure indicated increased fuel cost compared to the normal and high tire pressure as highlighted with more dark orange color throughout the site. The normal pressure showed decreased fuel cost throughout the field as compared to the low pressure treatment. The high pressure treatments showed the lowest fuel costs throughout the field indicated with more green color. For managers, these types of maps can provide quick feedback on not only fuel costs but also other variable costs associated with equipment.

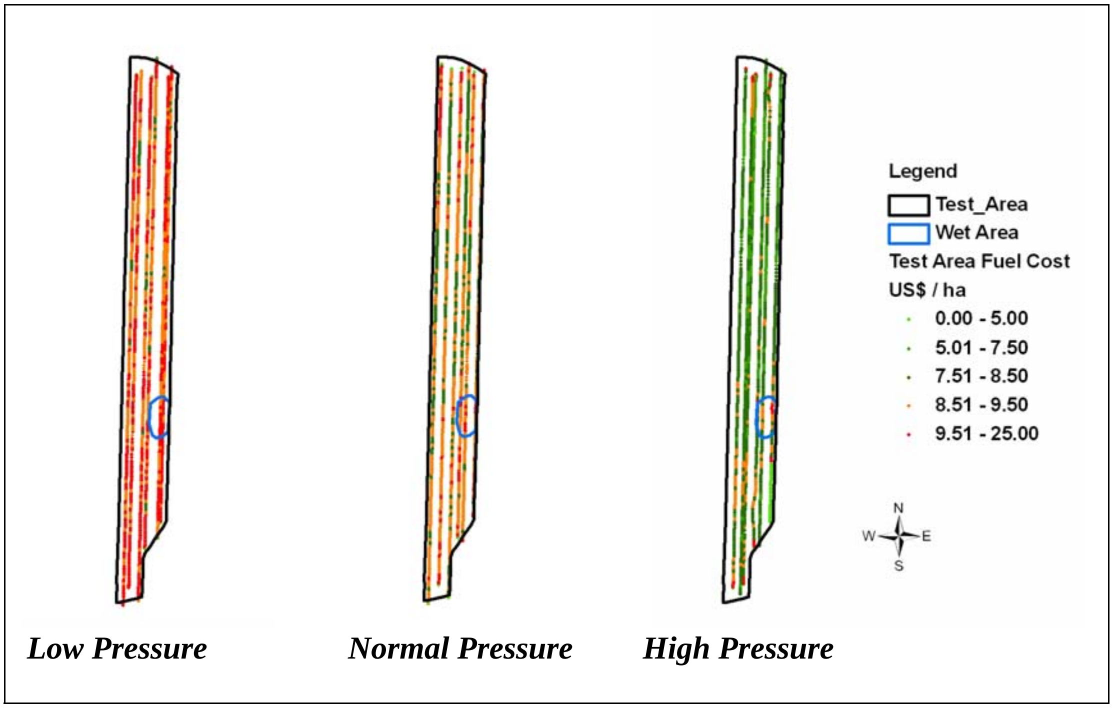


Figure 4.21. Illustrations of fuel cost for each tire pressure treatment.

The data contradicts the hypothesis of an overall increase in tractor performance with decreased tire pressure. Traditional theory leads to believe that as tire pressure is decreased, the contact area between the traction device and the soil increases, thus increasing traction and performance. The results showed the higher air pressures performed better than the lower air pressure. Explanations for this could have been due to errors in the experimental methods for this project. It was speculated that lower tire pressures caused a decrease in the rolling radius of the rear tires which affected the depth of the rigidly mounted implement. At lower tire pressures, the implement tilled at deeper depths compared to higher air pressures thus impacting the results of the experiment. Nevertheless, the tire pressure treatments did have an influence on the performance of the equipment and the information from this experiment provided a basis for future experiments with closer attention on tire pressure effects on tillage depth. The effects of tire pressure on tillage depth were overlooked in this experiment and should indefinitely be accounted for in related research.

Travel Direction Analysis

The tire pressure experiment test area was divided into 3 zones for analysis according to differences in elevation (Figure 4.22). Zone 1 was experienced a relatively large elevation change compared to the other zones. Zone 2 was the central section of the test area and showed small elevation changes. Zone 3 did not experience large elevation differences.

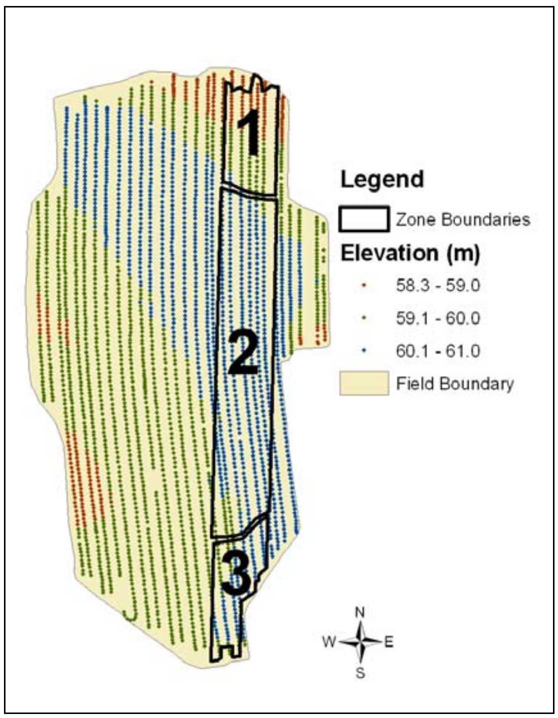


Figure 4.22. Illustration of field elevation with different zones outlined based on existing slope variations within the study site.

An elevation profile for the test area with zones outlined is presented in Figure 4.23 that shows how the elevation changed throughout the field. Zone 1 experienced the greatest change in elevation consisting of about a 2.5 m vertical rise over about 70m linear distance from the north to south direction. A slight elevation increase was noticed at the north end of zone 2 of less than 1 meter, however the remainder of the zone was relatively level. Zone 3 noticed a very small increase in elevation from the north to south direction of this zone.

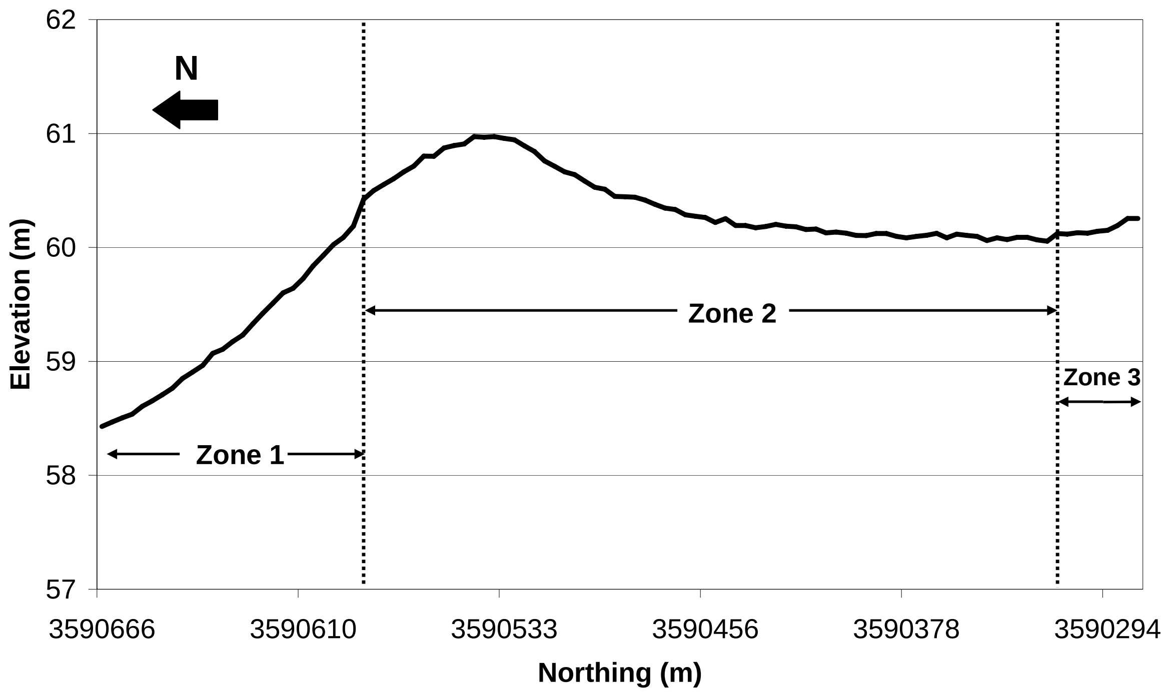


Figure 4.23. Illustration of elevation vs. northing for the test area of the Spatial Tillage experiment. This plot only shows a single cross section of the plot area and did vary for each pass.

Table 4.11 presents the results for the zone comparisons for the spatial tillage experiment. No statistical differences were noticed between zone 1 and 3. However, zone 3 did have the highest average fuel consumption out of all zones. Even though zone 1 experienced larger elevation differences, it had lower fuel consumption compared to zone 3. This could possibly be explained with the direction of travel performance comparisons which are presented in Table 4.12.

Table 4.11. Summary of results for field attribute effects on equipment performance.

Zone	Fuel* (L/h)	Wheel* (km/h)	GSR* (km/h)	Engine* (RPM)	Slip* (%)	EGT* (ºC)	Torque* (N-m)
1	14.7[a]	6.1[a]	5.5[a]	2297[a]	9.4[a]	395[ab]	4009[a]
2	13.7[b]	5.8[b]	5.3[b]	2180[b]	9.5[a]	405[a]	4533[a]
3	15.0[a]	6.1[a]	5.5[a]	2283[a]	9.7[a]	389[b]	4218[a]

*Means with similar letters in columns are not statistically different ($\alpha = 0.05$).

The results for the comparisons of travel directions for zone are presented in Table 4.12. Statistical differences were noticed for fuel consumption (Fuel), engine speed (Engine), EGT, axle torque (Torque), wheel speed (Wheel), and ground speed (GS) ($p < 0.001$). No statistical differences were evident for slip with $p = 0.7625$. For zone 1, when tilling southbound the tractor had to tow uphill and northbound it was traveling downhill. According to the results (Table 4.12), zone 1 experienced a 23% increase in fuel consumption for the south direction compared to the north direction. A 17.3% increase in fuel consumption existed for the north direction of zone 3. No statistical differences were noticed between the north and south travel directions for zone 2. Zones 1 and 3 were located toward the ends of the test area meaning tillage would have initialized in the south direction of zone 1 and in the north direction of zone 3. Once the tractor begins tillage, it requires some time to get up to its natural operational state. During this time, the engine might notice increased loadings for a short period which would cause increased performance values for these directions. These effects could have had an influence on the results of this analysis.

Table 4.12. Results for travel direction effects on the different tractor variables.

Zone	Direction**	Fuel* (L/h)	Engine* (RPM)	EGT* (°C)	Torque* (N-m)	Wheel* (km/h)	GS* (km/h)	Slip* (%)
1	N	13.3[c]	2215[b]	399[bc]	3499[c]	5.9[e]	5.4[b]	8.7[a]
	S	16.4[a]	2399[a]	389[c]	4646[b]	6.4[ab]	5.7[a]	10.4[a]
2	N	13.8[b]	2190[bc]	403[b]	4896[a]	5.8[ce]	5.3[bc]	9.5[a]
	S	13.6[bc]	2167[cd]	408[ab]	4080[a]	5.8[cd]	5.2[bc]	9.6[a]
3	N	16.1[a]	2396[a]	368[d]	4177[a]	6.4[a]	5.8[a]	9.8[a]
	S	13.7[b]	2142[d]	415[a]	4269[a]	5.7[d]	5.2[c]	9.5[a]

*Means with similar letters in columns are not statistically different ($\alpha = 0.05$).
** N and S represent North and South travel directions respectively.

Figures 4.24, 4.25, and 4.26 illustrate the relationship between ground speed and slip for zones 1, 2, and 3, respectively. North and south travel directions were analyzed separately for zones 1 and 3. Zone 2 showed no statistical differences between directions so the data was not separated for Figure 4.25. The data from zone 1 showed slightly higher ground speeds for the south direction compared to the north direction. This difference could be explained by traveling uphill causing higher engine load thereby increasing engine speed due to the engine governor for this zone which would result in higher ground speeds compared to traveling downhill. Zone 3 showed slightly higher ground speed for the north travel direction. In zone 2, some points of increased ground speed are noticed which occurred at the transition area between zones 1 and 3. Overall as slip increased, the ground speed decreased thereby increasing time in the field. More time in the field equates to lower levels of productivity and increased expenses.

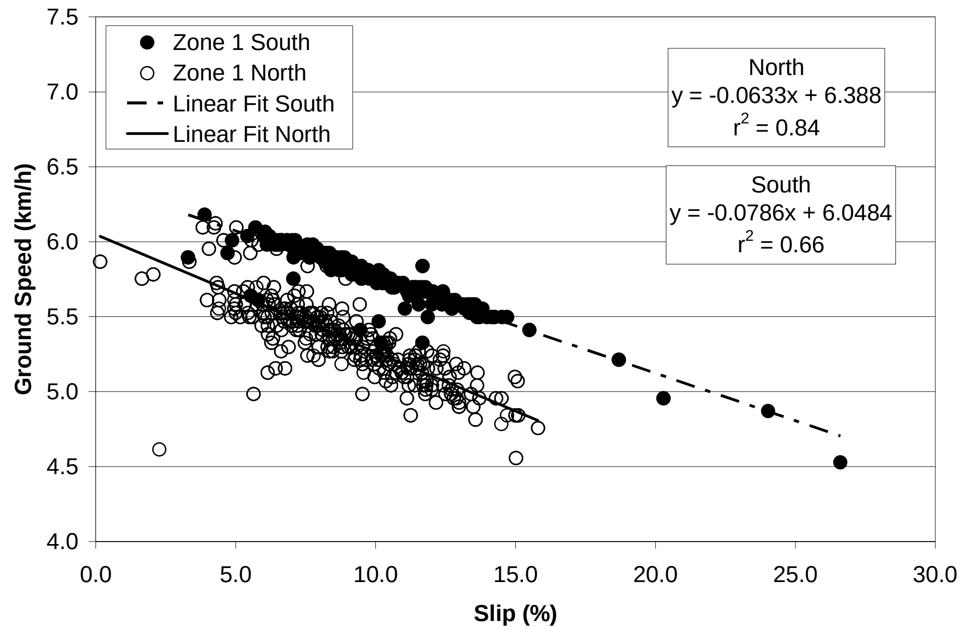


Figure 4.24. Zone 1 ground speed vs. slip for the Spatial Tillage experiment.

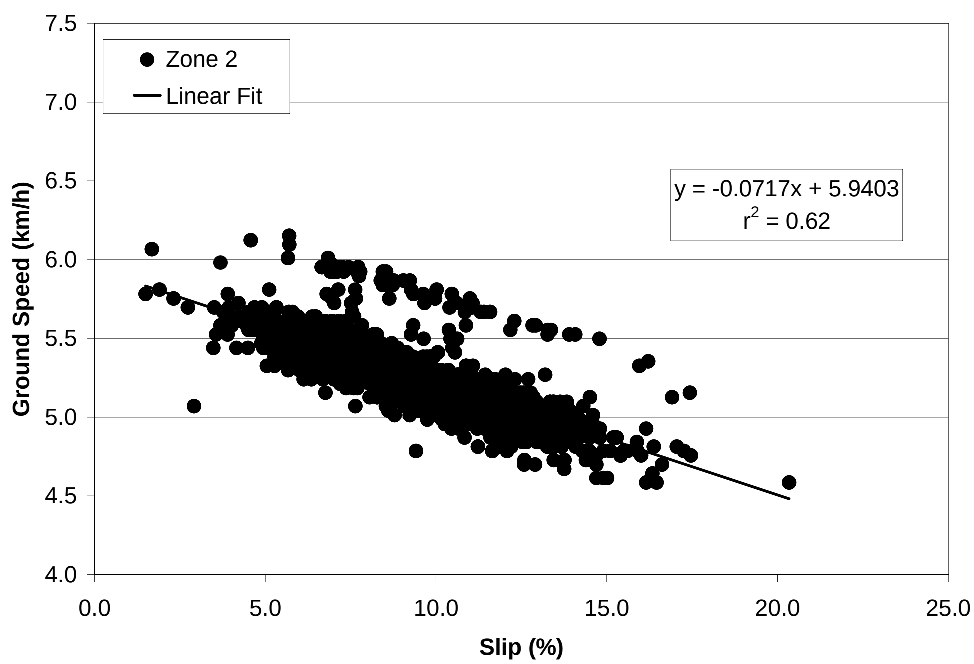


Figure 4.25. Zone 2 ground speed vs. slip for the Spatial Tillage experiment.

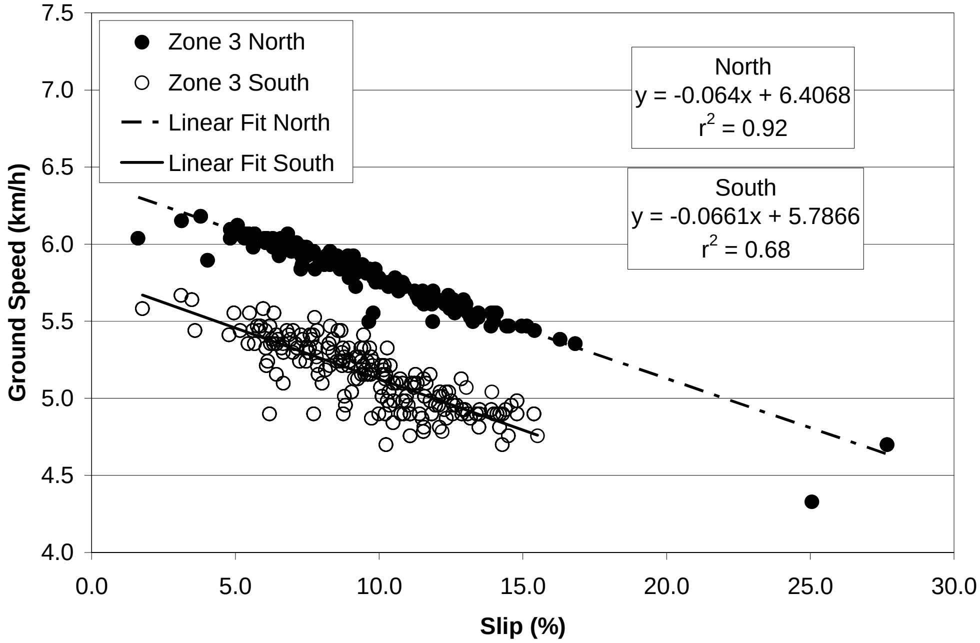


Figure 4.26. Zone 3 ground speed vs. slip for the Spatial Tillage experiment.

Figures D.13, D.14, and D.15 in Appendix D illustrate the relationships between fuel consumption and slip for zones 1, 2, and 3, respectively. The data illustrated that traveling upslope increased fuel consumption for zones 1 and 3. However, weak relationships existed for all zone and travel direction.

Figure 4.27 illustrates the relationship between fuel consumption and EGT for the north and south direction of zones 1 and 3 as well as data from zone 2. Weak linearity was present for the south and north directions of travel with r^2 values equal to 0.35 and 0.25, respectively. Zone 2 illustrated very weak linearity ($r^2 = 0.01$). The results showed that EGT was not an accurate indicator of fuel consumption. However, zone 2 showed slightly lower fuel consumption compared to the north and south direction for zones 1 and 3. Monitoring EGT could be a valuable tool in estimating the degree of engine load.

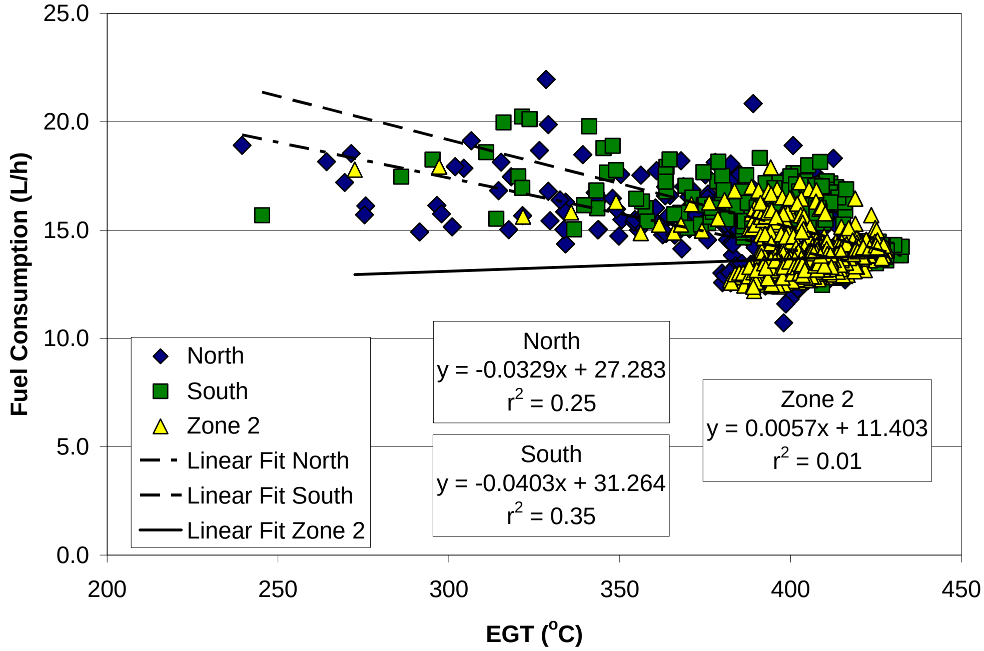


Figure 4.27. Fuel consumption vs. exhaust gas temperature for the Tire Pressure experiment.

Additional data was collected for the rest of field to get a better perspective on performance variability across the field with focus on fuel consumption (Figure 4.28). According to the map, higher fuel costs are more concentrated towards the field ends, which are indicated by a darker shade of orange in the map. A map of this nature can be useful in analyzing operator tendencies and in developing ways to improve efficiency by altering operator habits. A field performance database could also be useful in making field specific management decisions by knowing exactly were money is being spent. Further, fuel cost maps for all equipment which operate in a field can be used in economic analyses which consider both variable and fixed costs to develop accurate cost and profit maps. These maps can quickly pinpoint areas where profits are occurring and what might be the largest cost contributing to loss.

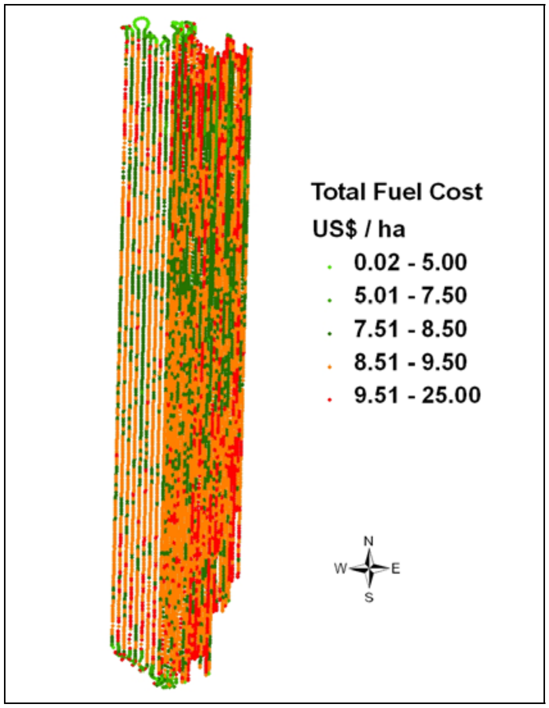


Figure 4.28. Total fuel cost for Spatial Tillage experiment field data.

In summary, spatial performance data has the potential to effectively manage equipment in a more site-specific basis. The data can be used to also conduct on-farm research to evaluate equipment setup and combinations which improve management and ultimately saves input costs. This type of data could also be used for site-specific economic analysis and potential real-time equipment adjustments to maintain optimal performance.

SUMMARY AND CONCLUSIONS

Summary

The goal of this research was to develop a data acquisition system so that equipment performance data could be monitored, collected, and analyzed for deep tillage processes while varying operational variables. The data acquisition system's ability to provide data reliably and accurately was tested and proven during the first experiment.

Energy intensive tillage processes were investigated to develop methods for improving efficiency and optimizing performance to save operational costs for producers. Results from the first experiment using a KMC Generation I Rip-Strip in-row subsoiler at two different depths indicated that a 130% increase in draft and a 23% increase in fuel consumption occurred from the shallow to the deep tillage depth. Therefore, tillage at shallower depths reduces draft loads on equipment and thus reduces fuel consumption. Site-specific tillage methods have potential to save in operational costs if compaction layers are located in shallower depths, as illustrated with the results for this experiment.

An experiment was performed to investigate three different tillage (annual, biennial, and triennial) rotations and their effects on three different implements. No statistical differences existed between annual and biennial year rotations for all variables and implements. According to the results, performing triennial tillage requires more energy and increases fuel consumption. If soil compaction is managed properly by controlled traffic and other methods, biennial tillage could save 50% in operational costs.

In terms of implements, the KMC required the least amount of draft, fuel consumption, and axle torque out of all the implements. The Paratill™ had higher energy requirements and fuel consumption than the KMC. The TerraTill™ experienced the largest fuel consumption, draft, and axle torque of all the implements. The TerraTill™ had the least amount of differences between tillage rotation treatments possibly due to its design creating different soil disruption characteristics causing alternative soil consolidation over time. In summary, choosing an implement that can perform effectively while saving in energy requirements can save money and decrease equipment wear, as illustrated with the results of this experiment.

The speed experiment results showed that as the speed of tillage increased fuel consumption increased. The Paratill™ experienced a 4% decrease in draft and a 40% increase in fuel consumption from the slow to normal speed. Even though draft and axle torque decreased between this transition, engine data indicated increased load with lower RPMs and increased fuel consumption. A significantly larger difference was experienced from the slow to the fast speed with a 29% increase in draft and a 105% increase in fuel consumption. The KMC results indicated 66% and 25% increase in fuel consumption and draft respectively from the slow to normal speed. The transition between the slow and normal speed for the KMC resulted in a 37% increase in draft and more than double the fuel consumption with a 115% increase. Increases in fuel consumption suggest that the slow speed of approximately 3 km/h could save in operational costs with a sacrifice of lower productivity rates. Soil cone index, moisture content, and bulk density were also measured for this test. In some cases, soil properties have an effect on implement draft and other performance variables. The fast speed for the KMC had the highest draft load out of all treatments along with the lowest moisture content and a high cone index. However, soil properties between the other treatments showed little variation. It was speculated that the experimental speed treatments tended to override the effects of the soil properties on performance results. The results suggest that an optimum speed exists where productivity does not suffer and performance is optimum.

The equation developed by Raper et al. (2005b) proved to be fairly accurate compared to the original results of the implement speed test. The total average absolute percentage difference between actual and estimate fuel consumption was 4.8%. Estimates for normal speed fuel consumption had the lowest differences compared to the slow and fast speeds. However, the slow speed estimates were underestimated and the fast speed estimates tended to be overestimated. These trends indicated the equation was most likely developed according to normal operating conditions and tends to deviate when moving from this operating condition. Accurate fuel consumption estimation can be used in sizing tractors to implements when a draft load is available.

A draft estimation equation was presented in ASABE standard D497.5 (2006). The formula utilized predetermined coefficients to estimate implement draft under different soil conditions for a variety of implements. The total average absolute percentage difference between actual and estimated draft was 8.2%. The estimated draft results were compared with actual data from the implement speed experiment. The formula was accurate in estimating draft load for the KMC straight shank subsoiler but was less successful in estimating draft for a bentleg subsoiler. However, no estimation values were available for calculating draft for the Bigham Brothers Paratill™ or any other bentleg design implements. With the growing popularity of bentleg implements, further research might lead into updating the available estimation coefficients to include modern implement designs.

A tire pressure test was performed to quantify the effects of three different tire pressures on tractor performance. The highest tire pressure showed improved performance compared to the low air pressure. According to the data, the lowest air pressure showed a 5% increase in fuel consumption, a 69% increase in slip, and a 17% increase in axle torque compared to the high tire air pressure. Maps presented in this research showed the decreased performance of the low pressure treatments which were illustrated with high slip, increased EGT, and increased fuel consumption. However, decreased performance seen with the lower tire pressure could have been caused by deeper tillage depths as a result of decreased rolling radius of the tire at the lower pressures. Sub-field spatial analysis was also performed comparing elevation and direction of travel with tractor performance. Results show that traveling downhill reduced fuel consumption compared to traveling upgrade. Differences in performance were also noticed between north and south travel directions which could possibly be improved with different tractor speed/gear configurations to optimize performance. The capability to collect and analyze spatial performance data enables managers to spatially plan tillage routes and perform field remediation in problem areas to improve efficiency in order to save on crop input costs incurred by tillage operations techniques.

We learned that equipment performance changed in response to adjustments in operational variables. However, the results indicated that changes in one variable can significantly impact other variables as seen in the results of the tire pressure experiment. Implement selection, terrain, and tillage frequency all impact draft and fuel consumption.

The use fuel consumption sensors on tractors and other machinery provides valuable feedback to assess energy use and more accurate information on fuel use costs for different operations. When this sensor is coupled with GPS positions, on-farm research and spatial profit maps can be developed to refine equipment management, site-specifically, and define impacts on profit margins and crop production. In conclusion, combinations of operational variables, and not just one, need to be considered to truly optimize performance.

General Conclusions

The conclusions of this research are as follows:

1) The performance monitor was easily removed and transferred between tractors; however some time was required to install transducers on each vehicle. Once the transducers were installed, the performance monitor was quickly operable. The system was able to properly operate under the harsh operating environments. The ability of the system to achieve sampling rates above 1 Hz would have been useful in some situations, but was restricted due to program complexity and limited processing power of the X15 computer console. The GUI proved useful in providing real-time viewing of performance variables and indicating problems with the data acquisition system. Overall, the developed performance monitor performed well during in-field operations and provided quality data to assess tractor and implement performance during tillage operations.

2) Tractor and implement performance data results indicated that tillage at the shallow depth of 22.9 cm reduced draft by 54% and fuel consumption by 17% compared

to tillage at 35.6 cm. With site-specific tillage in mind, the results proved that tillage at depths shallower than uniform deep tillage can save in energy and costs. The tillage rotation experiment showed that the KMC had the lowest energy requirements while TerraTill™ produced the largest. No differences in performance variables between annual and biennial tillage for all implements were found. However, results did show increases of 6% to 25% in draft leading way to 2% to 9% increases in fuel consumption for the triennial rotation for the three implements. This experiment illustrated that management decisions like implement selection and tillage time rotation can save time, energy, and expense if managed properly. Speed effects resulted in 104% and 115% increases (slow to fast) in fuel consumption for the Paratill™ and KMC, respectively. The tire pressure experiment resulted in 41% and 4.2% decreases in slip and fuel consumption, respectively, from the low tire air pressure to the high tire air pressure. In conclusion, the presented results quantified the effects of varying equipment operational variables on equipment during tillage operations.

3) The depth performance experiment data showed saving of $1.59 per hectare in fuel cost for the shallow depth compared to the deeper depth thus, identifying the savings potential for site-specific tillage. The results for the tillage rotation experiment indicated a savings of $2.13 per hour in fuel when operating the KMC instead of the TerraTill™. A savings of $4.89 per hectare in fuel costs are also possible with the implementation of biennial over annual tillage. The proper implement selection and tillage rotation combined with site-specific tillage methods can lead to cost savings. The spatial tillage experiment showed how performance variables changed in response to direction of travel and elevation changes. The fuel cost maps provided a different perspective for analysis

with the ability to visualize costs and saving potential through site-specific analysis with the use of spatial tractor and equipment performance data. In conclusion, on-the-go adjustments of operational variables (including tillage depth, travel speed, and tire pressure) to compensate for changes in terrain can optimize performance and reduce input costs during tillage.

Future Research

Soil type and soil properties can have a significant influence on performance behavior, especially during tillage operations. Future research should include repeating some of the tests presented in this research under different soil types and conditions. Eventually, the future direction of this research will be towards thorough studies on energy and performance monitoring of site-specific tillage methods. With fuel prices continually increasing, producers will be looking for ways to cut costs to preserve profit margins which includes reducing fuel usage and conserving energy during tillage operations. Site-specific tillage will give the farmer an opportunity to save time and money with minimal effects on crop yield. Similarly, automated site-specific tillage equipment is needed to fully take advantage of this management philosophy plus equipment that has the ability to measure the depth of compaction layer on-the-go needs to be developed.

Equipment adjustments such as tire inflation pressure are also areas of interest for future research. The tire pressure test was a prelude to future research which could entail investigating the use of central tire inflation systems (CTIS) to adjust tire air pressure during field operations to maintain efficient use of equipment. An improved understanding of this variable may lead to advanced development of central tire inflation (CTI) systems for agricultural tractors. The ability to adjust tire pressure on-the-go, either manually or automatically through the uses of in-cab controls, may lead to improved performance but most importantly reduced energy requirement and ultimately money savings for farmers.

Performance data was spatially mapped in one test of this research. Future research should include spatially monitoring performance data under larger acreage. This spatial data could be an advantageous management tool that could be used to quantify and analyze equipment performance on a sub-field basis instead of an entire field basis. Similar to yield monitoring technology today, equipment performance can be mapped and analyzed within the field to pinpoint areas of low efficiency. Remediation could take place in these problem areas to increase performance and save energy and money. From an environmental standpoint, reducing fuel consumption and energy requirements decreases the amount of emissions released into the atmosphere. In years to come, every effort will be taken to achieve environmental friendly farming.

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APPENDIX A

Tillage Rotation Experimental Layout

A.1 Plot layout of tillage rotation experiment

N →

4 rows (plot width 4.05m); plot length 25.9m; alley 7.6m

101 6 T32	102 1 NT	103 8 S21	104 10 S31	105 12 P11	106 9 S22	107 11 S32	108 14 P22	201 5 T31	202 11 S32	203 12 P11	204 3 T21	205 2 T11	206 7 S11	207 9 S22	208 8 S21	301 3 T21
109 15 P31	110 2 T11	111 16 P32	112 13 P21	113 7 S11	114 5 T31	115 3 T21	116 4 T22	209 14 P22	210 4 T22	211 6 T32	212 10 S31	213 15 P31	214 1 NT	215 16 P32	216 13 P21	309 8 S21

301 3 T21	302 2 T11	303 1 NT	304 12 P11	305 15 P31	306 11 S32	307 7 S11	308 6 T32	401 11 S32	402 5 T31	403 15 P31	404 7 S11	405 13 P21	406 16 P32	407 10 S31	408 9 S22
309 8 S21	310 5 T31	311 10 S31	312 13 P21	313 14 P22	314 16 P32	315 4 T22	316 9 S22	409 4 T22	410 12 P11	411 14 P22	412 3 T21	413 1 NT	414 2 T11	415 8 S21	416 6 T32

A.2 Table of treatment descriptions for tillage rotation experiment.

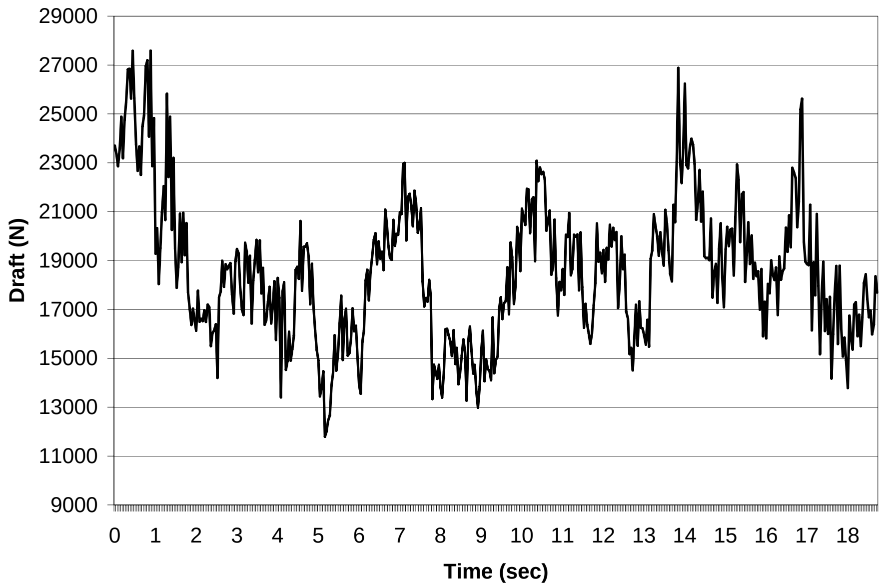
Trt #	Implement	Trt	Trt Code	Starting Year
1		No-tillage	NT	
2	TerraTill™	Annual	T11	2001
3	TerraTill™	Biennial	T21	2001
4	TerraTill™	Biennial	T22	2002
5	TerraTill™	Triennial	T31	2001
6	TerraTill™	Triennial	T32	2002
7	KMC	Annual	S11	2001
8	KMC	Biennial	S21	2001
9	KMC	Biennial	S22	2002
10	KMC	Triennial	S31	2001
11	KMC	Triennial	S32	2002
12	Paratill™	Annual	P11	2001
13	Paratill™	Biennial	P21	2001
14	Paratill™	Biennial	P22	2002
15	Paratill™	Triennial	P31	2001
16	Paratill™	Triennial	P32	2002

APPENDIX B

Tillage Rotation Experiment Draft vs. Time Graphs

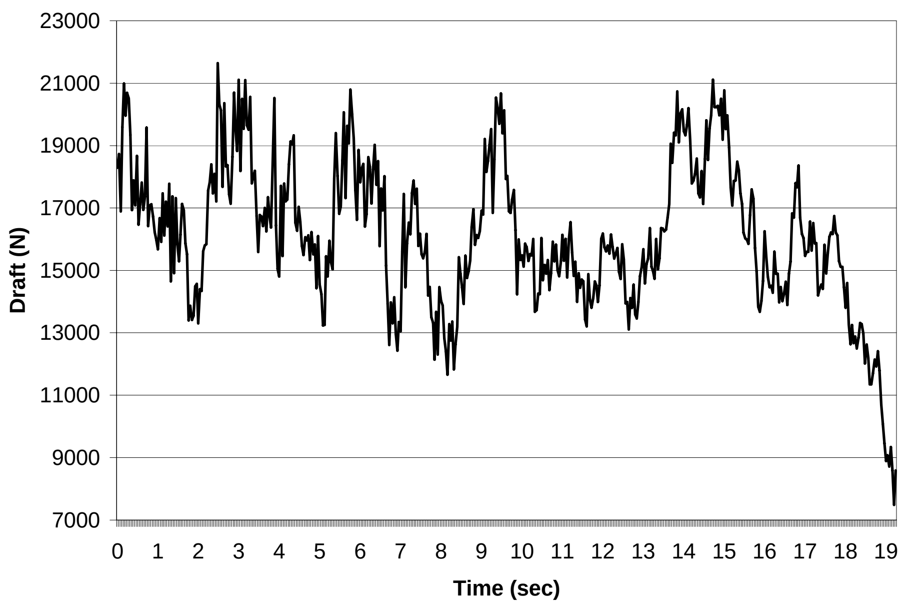
B.1 KMC Plot 104 Triennial Rotation Draft vs. Time.

M.C.$_{db}$ = 10.8%



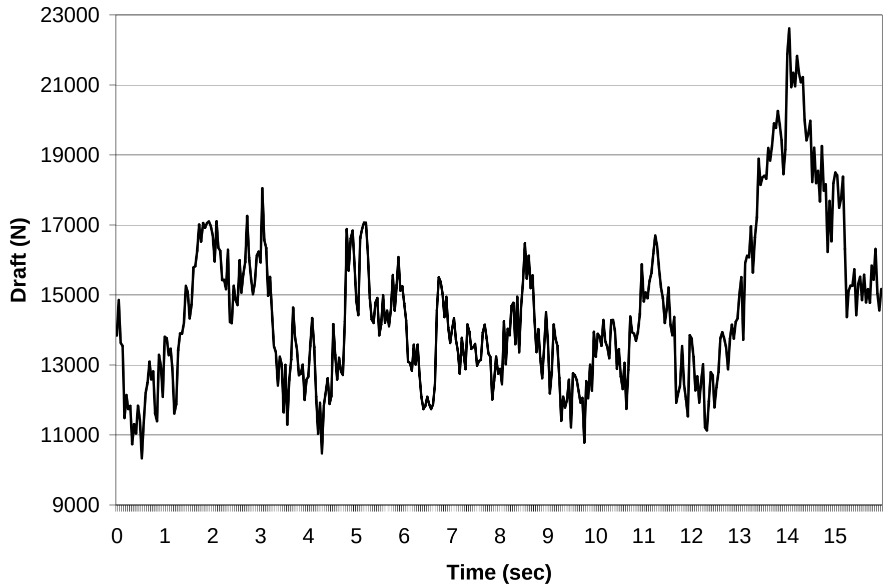
B.2 KMC Plot 212 Triennial Rotation Draft vs. Time.

M.C.$_{db}$ = 9.5%



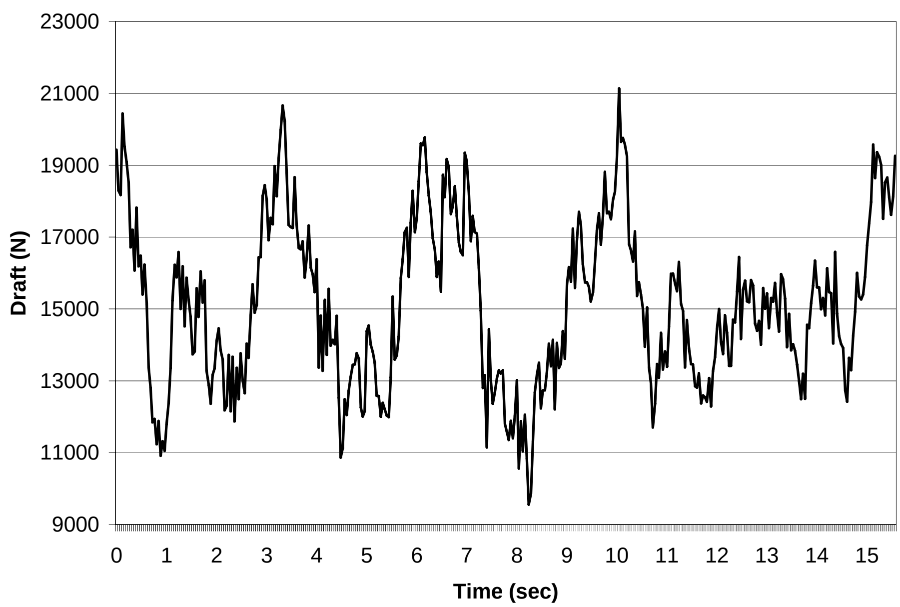
B.3 KMC Plot 311 Triennial Rotation Draft vs. Time.

M.C.$_{db}$ = 9.2%



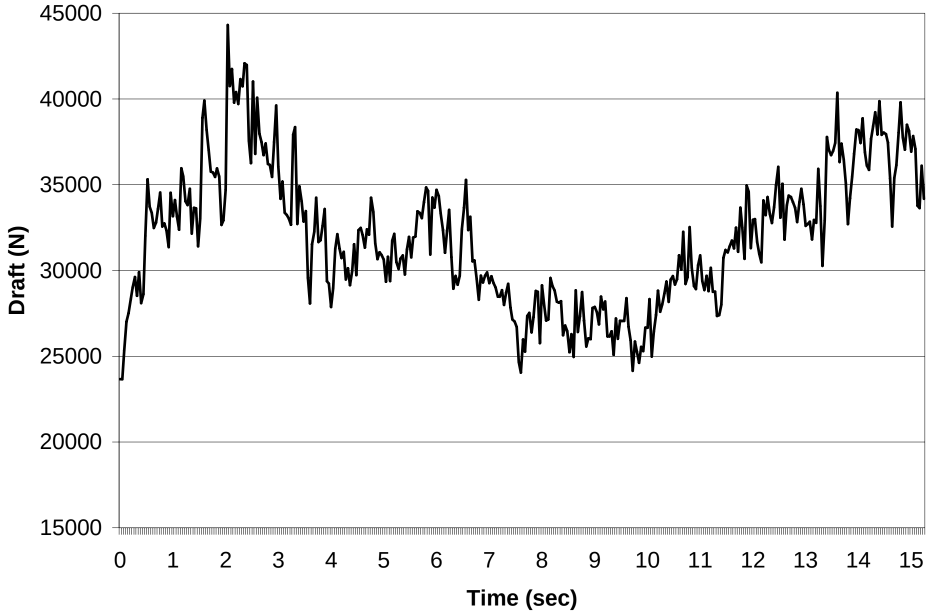
B.4 KMC Plot 407 Triennial Rotation Draft vs. Time.

M.C.$_{db}$ = 9.0%



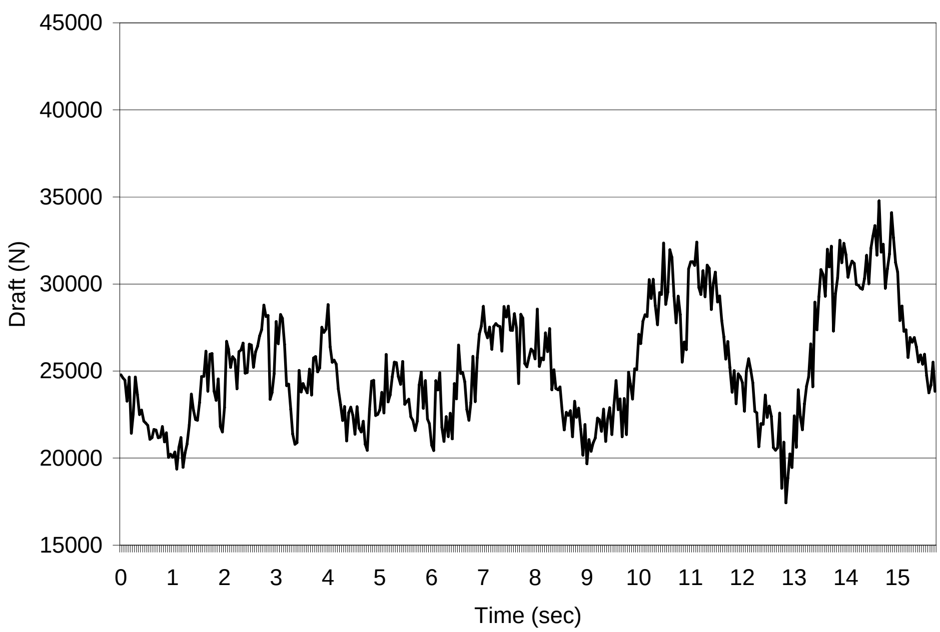
B.5 Paratill™ Plot 109 Triennial Rotation Draft vs. Time.

M.C.$_{db}$ = 10.1%



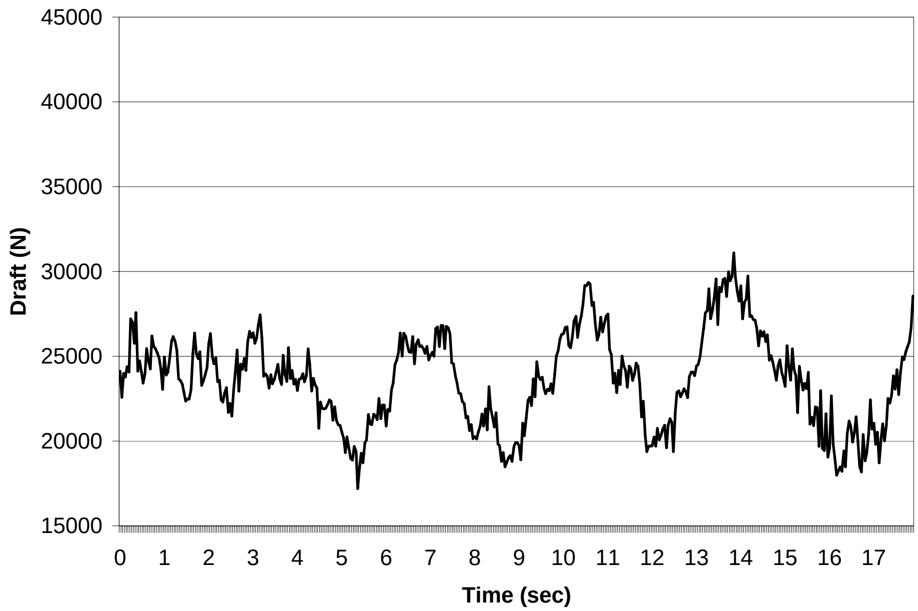
B.6 Paratill™ Plot 213 Triennial Rotation Draft vs. Time.

M.C.$_{db}$ = 10.3%



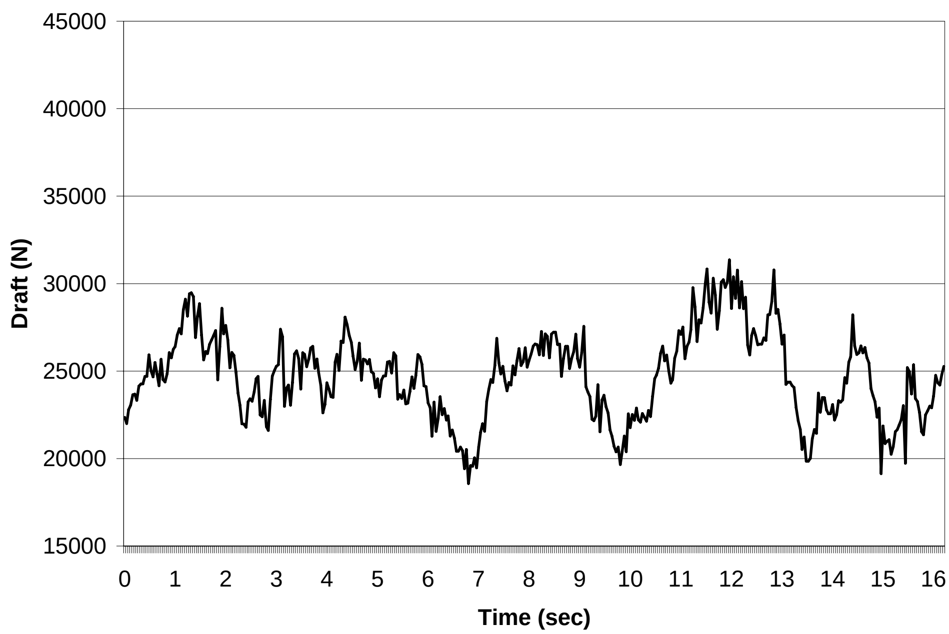
B.7 Paratill™ Plot 305 Triennial Rotation Draft vs. Time.

M.C.$_{db}$ = 9.1%



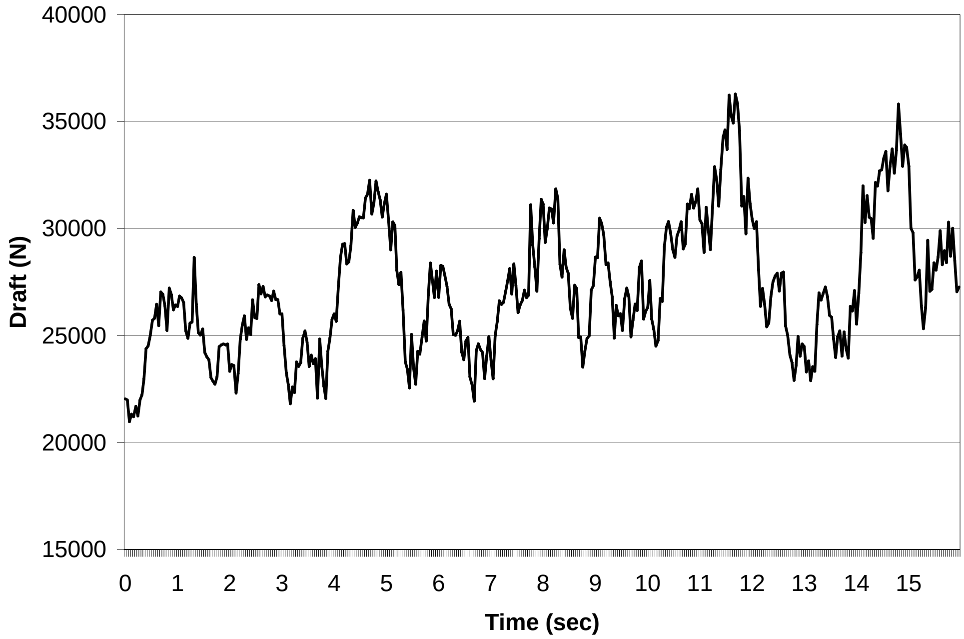
B.8 Paratill™ Plot 403 Triennial Rotation Draft vs. Time.

M.C.$_{db}$ = 8.8%



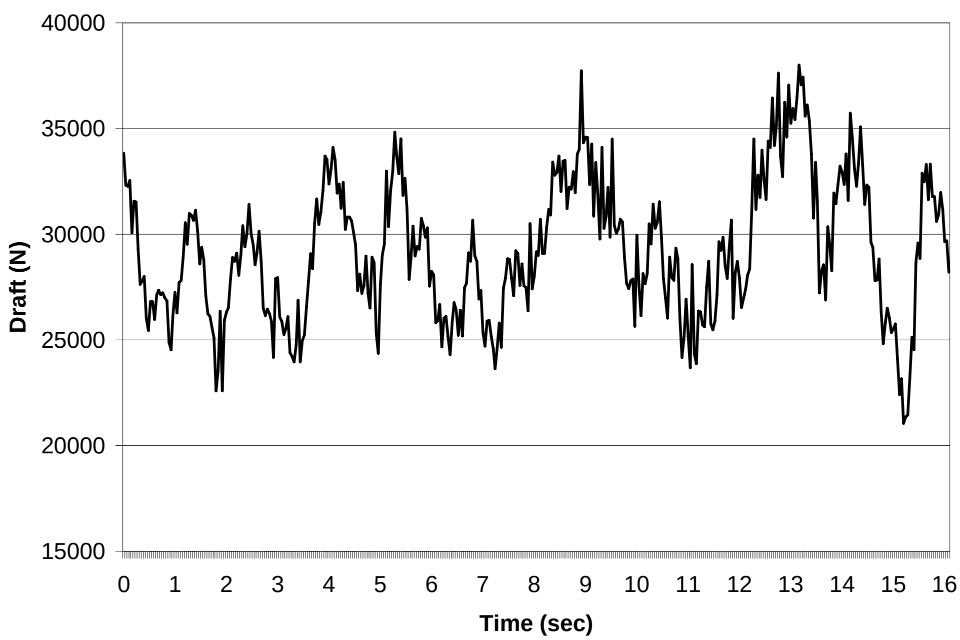
B.9 TerraTill™ Plot 114 Triennial Rotation Draft vs. Time.

M.C.$_{db}$ = 10.4%



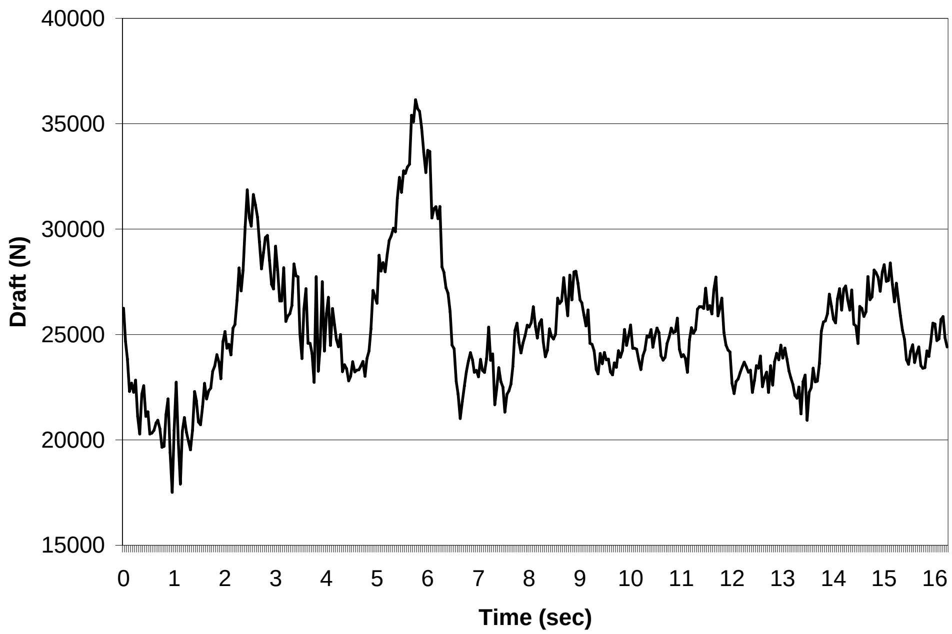
B.10 TerraTill™ Plot 201 Triennial Rotation Draft vs. Time.

M.C.$_{db}$ = 9.4%



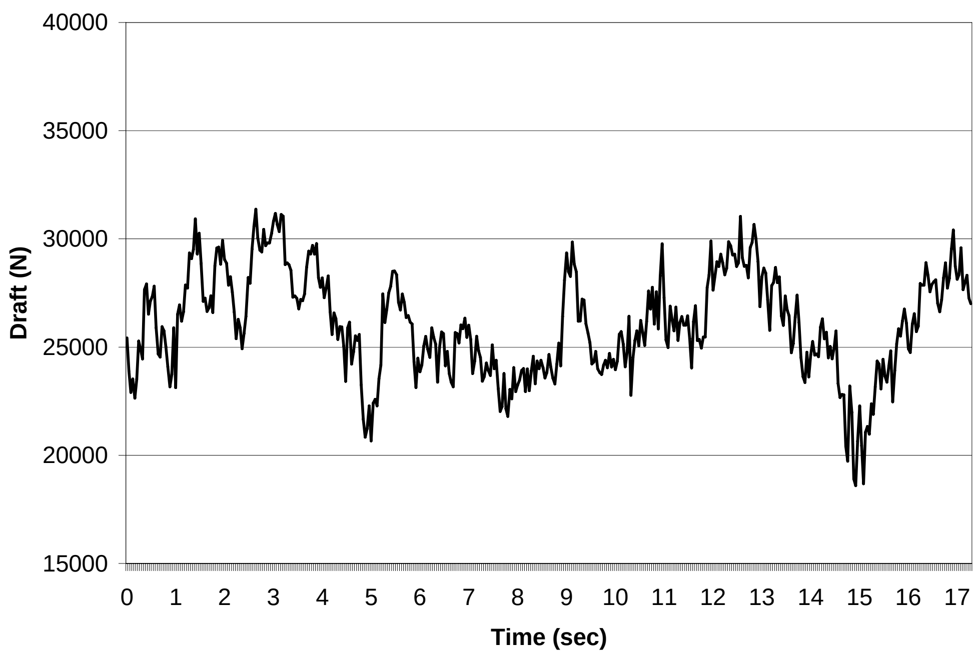
B.11 TerraTill™ Plot 310 Triennial Rotation Draft vs. Time.

M.C.$_{db}$ = 8.8%



B.12 TerraTill™ Plot 402 Triennial Rotation Draft vs. Time.

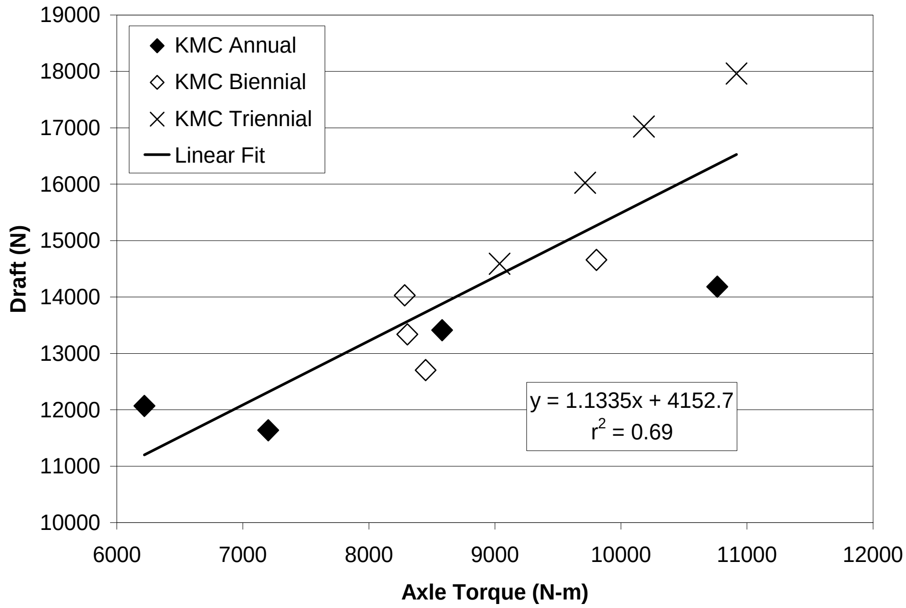
M.C.$_{db}$ = 8.7%



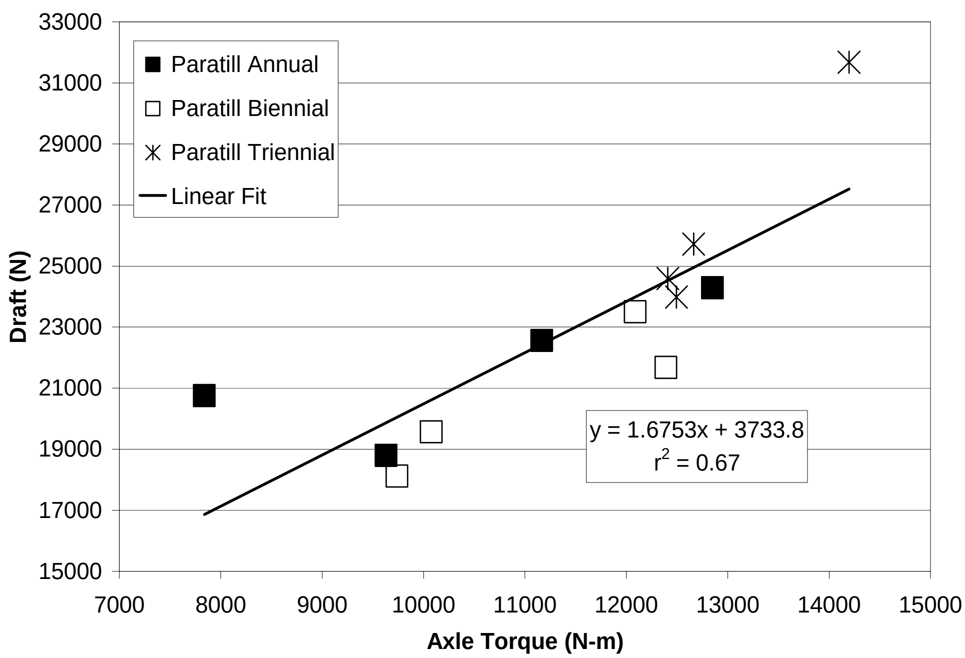
APPENDIX C

Tillage Rotation Experiment Draft vs. Axle Torque Graphs

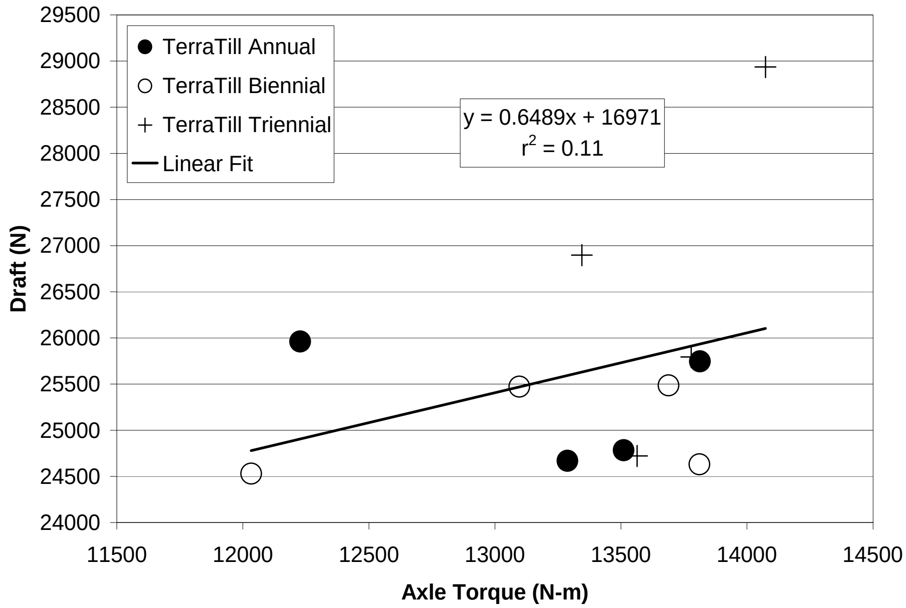
C.1 KMC draft vs. axle torque for the Tillage Rotation experiment.



C.2 Paratill™ draft vs. axle torque for the Tillage Rotation experiment.



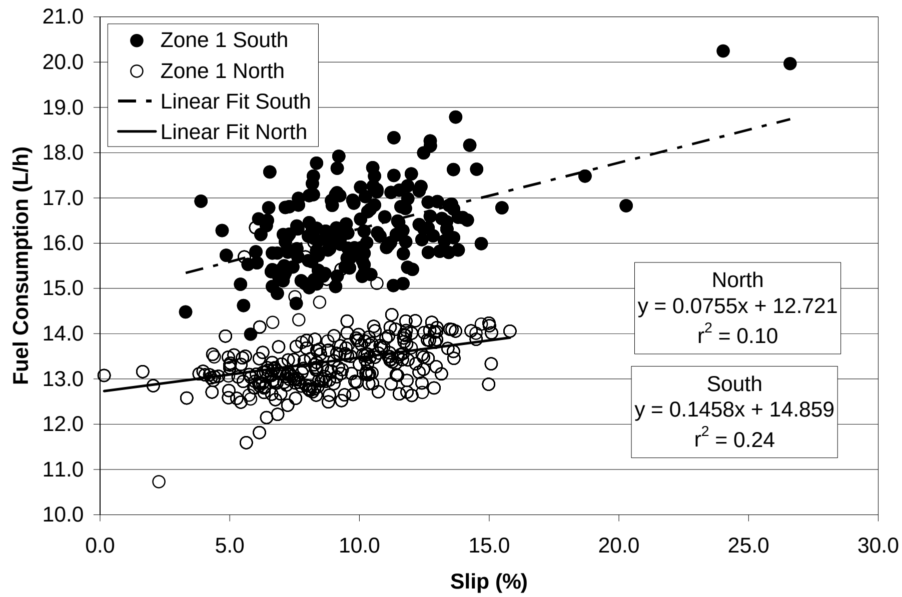
C.3 TerraTill™ draft vs. axle torque for the Tillage Rotation experiment.



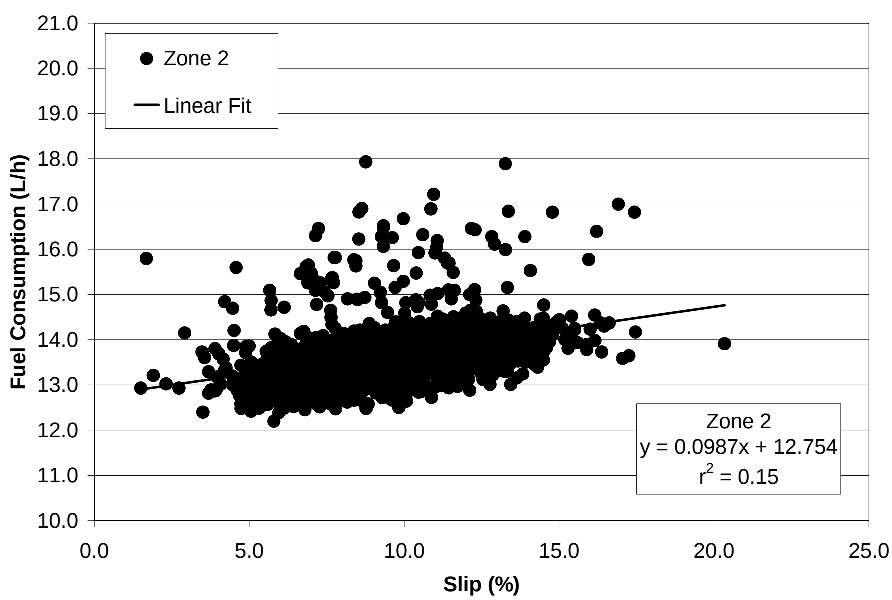
APPENDIX D

Graphs for Spatial Tillage Experiment

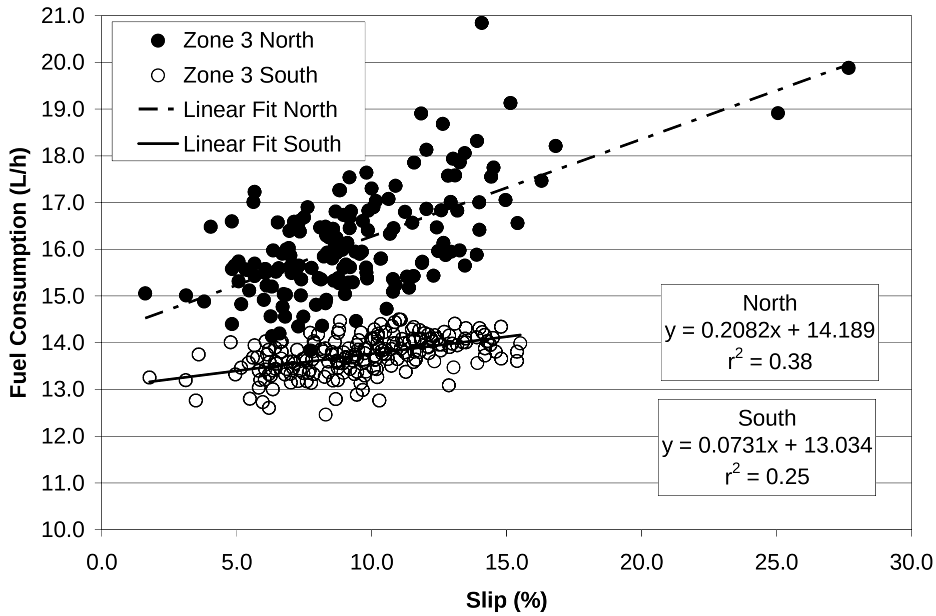
D.1 Spatial Tillage Experiment Zone 1 Fuel Consumption vs. Slip.



D.2 Spatial Tillage Experiment Zone 2 Fuel Consumption vs. Slip.



D.3 Spatial Tillage Experiment Zone 3 Fuel Consumption vs. Slip.



APPENDIX E

Tractor and Implement Specifications

E.1 John Deere Model 6420 Tractor

Tractor Power:

PTO rated, kW:	70.3

Engine:

Manufacturer:	John Deere
Fuel:	Diesel
Aspiration:	Turbocharger with intercooler
Cylinders:	4
Displacement, L:	4.5
Rated engine speed, RPM:	2300
Cooling:	liquid
Oil Capacity, L: 15.9	

Transmission:

Type:	Infinitely Variable Transmission

Mechanical:

MFWD:	Yes

Dimensions:

Weight with ballast, kg:	5715
Front, kg:	2490
Rear, kg:	3234
Wheelbase, mm:	2400

Other:

Equipped with a John Deere GreenStar AutoTrac system with the capabilities of using SF1, SF2, or RTK correction services. The system has an Integrated Terrain Compensation Module (ITCM). RTK level correction was used during this research.

E.2 John Deere Model 8300 Tractor

Tractor Power:	
PTO rated, kW:	149
Engine:	
Manufacturer:	John Deere
Fuel:	Diesel
Aspiration:	Turbocharger with intercooler
Cylinders:	6
Displacement, L:	7.6
Rated engine speed, RPM:	2200
Cooling:	liquid
Oil Capacity, L:	21.5
Transmission:	
Type:	Powershift
Mechanical:	
MFWD:	Yes
Dimensions:	
Weight, kg:	8673
Wheelbase, mm:	2950

Other:
Equipped with a Trimble Real-Time Kinematic (RTK) AutoPilot guidance system.

E.3 Kelley Manufacturing Company (KMC) Generation I Rip-Strip

(a) Side view of KMC shank (b) Front view of KMC shank
Shank images courtesy of Raper et al, 2005c.

Manufacturer:	Kelley Manufacturing Company, Tifton, GA
Implement:	Generation I Rip-Strip
Attachments:	Rubber tire press wheels
Shank type:	Straight
Shank thickness, mm:	2.5
Operational speed range, km/h:	6.4 to 8.8
Optimum depth range, cm:	30.5 to 40.6
Minimum depth range:	N/A

E.4 Bigham Brothers Paratill™

(a) Side view of Paratill™ shank (b) Front view of Paratill™ shank

Shank images courtesy of Raper et al., 2005c.

Manufacturer:	Bigham Brothers, Lubbock, TX
Implement:	Paratill™
Attachments:	Smooth pipe roller
Shank type:	Bentleg
Shank thickness, mm:	2.5
Operational speed range, km/h:	6.4 to 8
Optimum depth range, cm:	35.6 to 43.2
Minimum depth, cm:	30.5

E.5 Bigham Brother TerraTill™

(a) Side view of TerraTill™ (b) Front view of TerraTill™ shank

Shank images courtesy of Raper et al., 2005c

Manufacturer:	Bigham Brothers, Lubbock, TX
Implement:	Terratill™
Attachments:	Smooth pipe roller
Shank Type:	Bentleg
Shank Thickness, mm:	2.5
Operational speed range, km/h:	6.4 to 8
Depth range, cm:	35.6 to 43.2
Minimum depth range:	N/A

APPENDIX F

Electronic Specifications

F.1 Measurement Computing USB-1608FS

Analog Input:

A/D converter type:	16-bit successive approximate type
Number of channels:	8 single ended
Resolution:	16-bit
Input ranges:	±10V, ±5V, ±2V, ±1V
Sampling rate:	0.6 S/s to 50 kS/s software programmable

Digital Input/Output:

Digital type:	CMOS
Number of channels:	8
Input high voltage:	2.0V min, 5.5V absolute max

External Trigger:

Trigger mode:	Edge sensitive: user configurable for CMOS compatible rising and falling edge.
Trigger latency:	10µs max
Trigger pulse width:	1µs min
Input high voltage:	4.0V min, 5.5V absolute max
Input low voltage:	1.0V max, -0.5V absolute min
Input leakage current:	±1.0 µA

External Clock Input/Output:

Type:	Bidirectional
Direction:	input/output, software selectable
Input clock rate:	50kHz max
Clock pulse width:	Input: 1µs max Output: 5µs max

Counter Section:

Type:	Event counter
Resolution:	32 bits
Max input frequency:	1MHz

Microcontroller:

Type:	High performance 8-bit RISC
Program memory:	16384 words
Data memory:	2048 bytes

Power:

Supply current:	<100mA, USB enumeration
USB power:	4.5V min, 5.25 V max
Output current:	350 mA max

F.2 Measurement Computing USB-TC

Analog Input:

A/D converter type:	4 duel 24-bit, Sigma-Delta type
Number of channels:	8 differential
Channel configuration:	Thermocouple sensor type
Differential input range:	Thermocouple, ± 0.080V
Resolution:	24-bit
Thermocouple compatible:	J, K, S, R, B, E, T, or N

Digital Input/Output:

Digital type:	CMOS
Number of I/O:	8
Configuration:	Independently configured for input/output
Pull-up/pull-down config:	All pins pulled up to +5V via 47K resistors. Pull down to ground also available.
Digital I/O transfer rate:	Digital input – 50 port reads or single bit reads per second typ. Digital output – 100 port writes or single bit writes per second typ.
Input high voltage:	2.0 V min, 5.5 V absolute max.
Input low voltage:	0.8 V max, -0.5 V absolute min.
Output low voltage	0.7 V max
Output high voltage	3.8 V min

Memory:

EEPROM:	1024 bytes isolated micro reserved for sensor configuration 256 bytes USB micro for external application use

Microcontroller:

Type:	Two high performance 8-bit RISC microcontrollers

Power:

USB +5V voltage range:	4.75 V min. to 5.25 V max.

F.3 Corrsys Datron DFL3 Fuel Consumption Monitor

Measuring range:	1 to 150 l/h
Resolution (internal):	0.333 cm^3 / flank pulse
Digital output:	500 pulses / cm^3, TTL-signal
Measuring accuracy:	$\pm$0.5%
Reproducibility:	$\pm$0.2%
Media:	Diesel fuel
Operating pressure:	5 bar max
Pressure drop:	0 bar (internal pump compensation)
Max. permitted fuel temp:	170 C
Vibration damping:	$\approx$ 2%
Shock resistance:	10g
Operating voltage:	12V DC
Power input:	Fuel pump 12 V, 2.4 A
	Electronics 12V, 0.8 A
Dimensions:	320 x 300 x 290 mm
Weight:	13.2 kg

F.4 KEE Technologies ZYNX X15 Console

Console:

Processor:	300 MHz
Memory:	256 MB
Operating system:	Windows 98
Display size:	162 mm (6.4 in.)
Solid state drive:	1 GB
Audio:	Mono
External line:	Output only
Mounting bracket:	RAM mount
USB ports:	2 x USB 1.0
Serial RS232 ports:	4
PS2 ports:	1
VGA ports:	1
ISO 11783 Canbus ports:	1

F.5 SOMAT 2100 Field Computer System

*Mechanical***:**

Operating range:	20 – 70C
Case material:	Aluminum alloy
Protection:	Short circuit protection
Power:	CMOS components
Max power consumption:	5 watts
Sampling rate:	5000 Hz/channel
Memory:	32KB
Processor module weight:	0.6 lbs
Data transfer rate:	115.2 Kbau

Power Communications Module:

Dimensions:	3 x 4.25 x 0.41 in
Weight:	0.3 lbs
Current draw:	2.0 mA

Analog Transducer Module:

Input voltage ranges:	+0.1V, +1.0V, +10V
Configuration:	Software programmable
Dimensions:	3 x 4.25 x .41 in
Weight:	0.3 lbs

Digital Input/Output Module:

Channels:	6 bidirectional I/O lines
Connection:	30 pin bus connector
Dimensions:	3 x 4.25 x .58 in
Weight:	0.4 lbs
Current draw:	7mA
Output current:	10mA per output line

MUX Interface Module:

Converter:	12 bit A/D converter
Number of outputs:	4
Connection:	30 pin bus connector
Supported sensors:	Thermocouple temperature measurement
Dimensions:	3 x 4.25 x .58 in
Weight:	0.4 lbs
Current draw:	40 mA

Programmable Filter Module:

Purpose:	Low-pass filters for strain gauge and analog transducer modules

Connection:	30-pin bus connector
Dimensions:	3 x 4.25 x .41 in
Weight:	0.3 lbs
Current draw:	6.3 mA
Noise floor:	-80 dB

Pulse Counter Module:

Connection:	30-pin bus connector
Dimensions:	3 x 4.25 x .41 in
Weight:	0.3 lbs
Current draw:	10 mA
Pulse width:	0.1 ms – 1 second
Input voltage range:	2V to 150V (peak to peak)
Frequency:	1 to 32,000 Hz

Strain Gauge Signal Condition Module:

Dimensions:	3 x 4.25 x .41 in
Weight:	0.3 lbs
Effective conversion time:	270 µs pulsed, 2 µs continuous strain measurement range (single gauge)
Minimum strain:	$\pm$900 µstrain or $\pm$2.1 mV
Maximum strain:	$\pm$5270 µstrain or $\pm$12.5 mV

F.6 Binsfeld Engineering TorqueTrak 9000®

F.6.1 BT9000 Transmitter

Sensor Input:	Full (four-arm) Wheatstone Bridge strain gage (350 standard)
Bridge Input:	5.0 VDC, Regulated
Sensor & Power Connection:	Screw terminal block
Transmitter Power Input:	7.5 to 12VDC, 60mA max with 350 bridge (9V battery typical)
Transmission Frequency:	903-922 MHz
Transmitter Battery Life:	12 hours (9V lithium, 350 bridge, 25°C)
Transmit Distance:	20 feet or more
G-force Rating:	3000 g's (steady state) (e.g. 6500 rpm on a 5 inch diameter shaft)
Operating Temperature:	0 – 70°C (32 – 158°F)
Size and Weight:	1.05" x 1.95" x 0.70" 2 oz

F.6.2 RD9000 Receiver

Receiver Output Signal:	±10 VDC, field adjustable down to ±5 VDC
Receiver Output Connection:	5-way binding posts (banana jacks)
Receiver Power Input:	12VDC nominal (10 - 18VDC acceptable), 250mA max (110VAC or 220VAC adapter provided)
Operating Temperature:	0 – 70°C (32 – 158°F)
Size and Weight:	5.5" x 7.5" x 1.5" 3 lbs

F.6.3 TT9000 System

Resolution:	14 bits (±full scale = 16,384 points)
Gain Error:	±0.1% (±0.5% before scale calibration)
Gain Drift:	±0.02%FS/°C over operating temperature range
Zero Error:	±0.1%FS (±1% typical before activating AutoZero)
Zero Drift:	±0.02%FS/°C over operating temperature range
Frequency Response:	0 - 250 Hz (-3dB max @ 250Hz)
Delay:	5.4 msec, typical
Slew Rate:	6V/msec, typical
Sample Rate:	1276 samples/sec

APPENDIX G

Visual Basic programming code for research experiments

G.1 Depth Performance and Tillage Rotation Experiments Code

The following code was written for Visual Basic and was used for the depth performance experiment and the tillage rotation experiments. Variables that were collected included GPS coordinates, GPS quality, # satellites, GPS velocity, GPS time, fuel consumption, wheel speed, ground speed, slip, torque (tillage rotation only), and digital switch position.

```
'DATA TYPE OF VARIABLES ARE DEFINED

Public OPENFILE As Boolean
Dim BoardName As String
Dim BoardNum As Integer
Dim Ulstat As Long
Dim TempBoard As String
Dim TempNum As Integer
Dim filelocation As String
```

```
'CONTROLS THE PROCESS OF CHOOSING A FILENAME AND LOCATION TO LOG DATA

Private Sub ChooseFilename_Click()
    On Error Resume Next

    CommonDialog1.DialogTitle = "CHOOSE DATA FILENAME"
    'TITLES THE CHOOSE FILENAME DIALOG BOX
    CommonDialog1.ShowOpen
    'OPENS THE CHOOSE FILENAME DIALOG BOX IN ANOTHER WINDOW
    FilenameDisplay.Text = CommonDialog1.FileName
    'DISPLAY THE CHOSEN FILE TO THE GRAPHICAL USER
    INTERFACE

    Open CommonDialog1.FileName For Append As #1
    'ASSIGNS THE CHOSEN FILE TO BE WRITTEN

    Print #1, "COUNTER1, COUNTER2, COUNTER3, FUEL, GSR,
    TRANS, ENGINESPE, SLIP, TORQUE"
    'PRINTS COLUMN LABELS AT THE TOP OF SELECTED FILE ABOVE

    OPENFILE = True
    LogData.Enabled = True
    'ENABLE THE LOGDATA BUTTON ON GUI

End Sub
```

```
'CLOSES THE GPS SERIAL PORT
Private Sub ClosePort_Click()
MSComm1.PortOpen = False
End Sub
```

```
'THIS CONTROLS THE CLOSE CURRENT FILE BOTTON ON THE FORM

Private Sub cmdCloseFile_Click()

    Close #1    'CLOSES THE FILE BEING LOGGED TO
    OPENFILE = False    'CLOSES FILE
    LogData.Value = 0   'TURNS THE LOGDATA OFF
    LogData.Enabled = False 'ENABLES THE LOGDATA BUTTON

End Sub
```

```
'THIS CLOSES THE PROGRAM
Private Sub cmdCloseProgram_Click()
End
End Sub
```

```
'THIS IS THE PROCEDUCED EXECUTE ON PROGRAM STARTUP
Private Sub Form_Load()

'BEFORE OPENING COMM2, CHECK PORT NUMBER
MSComm2.PortOpen = True 'OPENS THE EXTERNAL COUNTER ON PORT 2

'FILLS THE BAUD RATE LIST
Baud.Clear
Baud.AddItem "2400"
Baud.AddItem "4800"
Baud.AddItem "9600"
Baud.AddItem "19200"
Baud.AddItem "38400"
Baud.AddItem "56000"
Baud.Text = "4800"

CommonDialog1.InitDir = "C:\"
'DEFINES THE DIRECTORY OF THE OPENFILE DIALOG COMMAND
CommonDialog1.DefaultExt = ".txt"
'SETS UP THE DEFAULT EXTENSION AS A TEXT FILE

'CONFIGURES THE PROGRAM TO COMMUNICATE WITH USB-1608FS BOARD

    BoardNum = 0 '<==============THIS IS THE BOARD NUMBER
    THAT INSTACAL HAS ASSIGNED FOR THE 1608 BOARD

    BoardName = "                                        "
    Ulstat = cbGetBoardName(BoardNum, BoardName)
    Myboard = BoardName
    Myboard = Trim$(Myboard)
    bdlen = Len(Myboard) - 1
```

```
    Myboard = Left(Myboard, bdlen)

    'THE FOLLOWING IS AN ERROR HANDLER IF BOARDNUM DOES NOT
    MATCH IN INSTACAL
    If (Myboard <> "PMD-1608FS") And (Myboard <> "USB-
    1608FS") Then
        MyMessage = "A USB/PMD-1608FS was not assigned to
        Board " & BoardNum & " in InstaCal." & Chr$(13) _
        & "Please run InstaCal to verify the board number"
        & Chr$(13) _
        & "and/or change BoardNum = " & BoardNum & " in the
        Form_Load event" & Chr$(13) _
        & "to the correct board number.  Then re-run this
        program." 'ERROR MESSAGE IF USB-1608FS BOARD IS NOT DETECTED
   r = MsgBox(MyMessage, vbExclamation, "USB/PMD-1608FS not detected.")

      End

End If

        Ulstat = cbErrHandling(PRINTALL, DONTSTOP)
        If Ulstat <> 0 Then Stop

  'THE FOLLOWING CONFIGURES THE DIGITAL PORT ON USB-1608FS
   BOARD

      PortNum = AUXPORT   'DEFINES PORT
      Direction% = DIGITALIN  'ASSIGNS PORT DIRECTION AS INPUT
      Ulstat = cbDConfigBit(BoardNum, PortNum, 0,Direction%) 'CALLS
      FUNCTION TO CONFIGURE BOARD
      If Ulstat <> 0 Then Stop

End Sub
```

```
Private Sub OpenPort_Click()

    'SETS UP GPS COMM PORT
    MSComm1.CommPort = USDAGPSLogger.PortNum.Text
    'LOOKS AT THE PORT NUMBER CHOSEN IN THE FORM

    MSComm1.Settings = USDAGPSLogger.Baud.Text & ",n,8,1"
    'ASSIGNS THE BUAD RATE TO WHAT WAS ASSIGNED IN THE DROP BOX LOCATED
    ON THE FORM

    'THE FOLLOWING USED AS ERROR MESSAGE INDICATING THAT THE PORT IS
    ALREADY IN USE

    If MSComm1.PortOpen = True Then
        MsgBox "THE PORT IS ALREADY IN USE"
        Exit Sub
    End If

    MSComm1.PortOpen = True 'OPENS THE GPS COMM PORT FOR RECIEVING
```

```
End Sub
```

```
'THIS CONTROLS THE FUNCTIONS OF THE GPS COMM PORT
Private Sub MSComm1_OnComm()

'MSComm1 ROUTINE DEFINES OPERATIONS ON NEW SERIAL MESSAGE RECEIVE
INTERRUPT

   On Error Resume Next
    If MSComm1.CommEvent = comEvReceive Then 'CHECK FOR NEW MESSAGE
    RECEIVED
        BUFFER_LENGTH = MSComm1.InBufferCount
    Else
        BUFFER_LENGTH = 0
    End If

    While BUFFER_LENGTH > 5
        BUFFER_ARRAY = BUFFER_LEFTOVER & MSComm1.Input 'ADD NEW MESSAGE
        TO BUFFER
        BUFFER_LENGTH = Len(BUFFER_ARRAY)'OBTAINS LENGTH OF BUFFER
        ARRAY
        START_POS = InStr(BUFFER_ARRAY, "$GPGGA") 'DEFINE START OF
        MESSAGE STRING FOR GGA STRING
        START_POS1 = InStr(BUFFER_ARRAY, "$GPVTG") 'DEFINE START OF
        MESSAGE STRING FOR VTG STRING
        END_POS = START_POS + 100 'InStr(BUFFER_ARRAY, "*") ' DEFINE
        END OF MESSAGE FOR GGA STRING
        END_POS1 = START_POS1 + 100 'InStr(BUFFER_ARRAY, "*")' DEFINE
        END OF MESSAGE FOR VTG STRING

        If START_POS = 0 Then Exit Sub 'FOR GGA STRING
        If END_POS = 0 Then Exit Sub

        If START_POS1 = 0 Then Exit Sub 'FOR VTG STRING
        If END_POS1 = 0 Then Exit Sub

        'THE FOLLOWING STATEMENTS SPLITS THE GGA DATA STRING
        DATA_STRING = Mid(BUFFER_ARRAY, START_POS + 1, END_POS -
        START_POS - 1) 'SPLIT GGA DATA STRING
        DATA_ARRAY = Split(DATA_STRING, ",") 'SECTIONS THE STRING
        ACCORDING TO ","
        SA = DATA_ARRAY(0) 'DEFINES SOURCE ADDRESS OF NEW MESSAGE
        BUFFER_LEFTOVER = Mid (BUFFER_ARRAY, END_POS + 1)  'COLLECTS
        UNUSED BUFFER

        'THE FOLLOWING STATEMENTS SPLITS THE VTG DATA STRING
        DATA_STRING1 = Mid(BUFFER_ARRAY, START_POS1 + 1, END_POS1 –
        START_POS1 - 1) 'SPLIT DATA STRING
        DATA_ARRAY1 = Split(DATA_STRING1, ",")  'SECTIONS THE STRING
        ACCORDING TO ","
        SA = DATA_ARRAY1(0) 'DEFINE SOURCE ADDRESS OF NEW MESSAGE
        BUFFER_LEFTOVER1 = Mid(BUFFER_ARRAY1, END_POS1 + 1)  'COLLECT
        UNUSED BUFFER
```

```
Dim GPSTIMEVAR As String

GPSTIMEVAR = DATA_ARRAY(1)

'THE FOLLOWING FORMATS AND DISPLAYS TIME TO THE DISPLAY
GPSTime.Text = Format(Left(GPSTIMEVAR, 2) & ":" & Mid(GPSTIMEVAR, 3, 2)
      & ":" & Right(GPSTIMEVAR, 5), "######") 'SPLITS AND FORMATS GPS
      TIME ARRAY

'THE FOLLOWING FORMATS AND DISPLAYS LATITUDE TO THE DISPLAY
Lat.Text = Format(Left(DATA_ARRAY(2), 2) + (Right(DATA_ARRAY(2),
      Len(DATA_ARRAY(2)) - 2)) / 60, "##.########")'DATA_ARRAY(2) IS
      LATITUDE, BUT MUST BE CONVERTED TO DECIMAL DEGREES

'THE FOLLOWING FORMATS AND DISPLAYS LONGITUDE TO THE DISPLAY
Lon.Text = Format(Left(DATA_ARRAY(4), 3) + (Right(DATA_ARRAY(4),
      Len(DATA_ARRAY(4)) - 3)) / 60, "-##.########")'DATA_ARRAY(4) IS
      LONGITUDE, BUT MUST BE CONVERTED TO DECIMAL DEGREES

Quality.Text = DATA_ARRAY(6) 'DISPLAYS GSP QUALITY TO THE DISPLAY
Sates.Text = DATA_ARRAY(7) 'DISPLAYS # OF SATELLITES TO THE DISPLAY
Elevation.Text = DATA_ARRAY(9) 'DISPLAYS ELEVATION TO THE DISPLAY
Velocity.Text = DATA_ARRAY1(7) * 0.62137 'FROM VTG STRING
AND CONVERT TO MPH

            'THE FOLLOWING CLASSIFIES THE DIFFERENTIAL SERVICE
            If Sates.Text = 0 Then
                GPSLogger.DiffService = "NO CORRECTION"
            ElseIf Sates.Text = 1 Then
                GPSLogger.DiffService = "NON-DIFF GPS FIX"
            ElseIf Sates.Text = 2 Then
                GPSLogger.DiffService = "WAAS CORRECTION"
            End If

'CONTROLS THE LOGGING FUNCTION
If (LogData.Value = 1) And (OPENFILE = True) Then

'IF THE ABOVE IS TRUE, THE PROGRAM LOGS THE FOLLOWING
VALUES TO THE TEXT FILE
Write #1, Lon.Text, Lat.Text, Sates.Text, Quality.Text, Elevation.Text,
GPSTime.Text, Velocity.Text, Fuel.Text, TRANSspeed.Text, COUNTER(2),
GSRspeed.Text, COUNTER(3), Slip.Text, Torque.Text, ShwBitVal.Text

      End If

            Wend

End Sub
```

```
'READS ANALOG SIGNAL FOR TORQUE
Private Sub tmrConvert_Timer()

    Chan% = 0   'CHANNEL NUMBER
    Range = BIP10VOLTS  'DEFINES ANALOG RANGE
```

```
    Ulstat = cbAIn(BoardNum%, Chan%, Range, DataValue%) 'CALLS FUNCTION
    TO CONFIGURE USB-1608FS

    If Ulstat <> 0 Then Stop    'ERROR FUNCTION
    Range = BIP10VOLTS  'DEFINES RANGE FOR FUNCTION BELOW
    Ulstat = cbToEngUnits(BoardNum%, Range, DataValue%, EngUnits!)
    'CALLS FUNCTION TO CONFIGURE CHANNEL OUTPUT FORMAT

    If Ulstat <> 0 Then Stop    'ERROR FUNCTION
    Torque.Text = EngUnits * (-1474)  'MEASURED VOLTAGE MULTIPLIED BY
    CONSTANT TO OBTAIN UNITS OF FT-LBS

End Sub
```

```
'MSComm2 ROUTINE DEFINES OPERATIONS ON NEW SERIAL MESSAGE FOR COUNTER
BOARD

Private Sub MSComm2_OnComm()

    On Error Resume Next    'ERROR FUNCTION

    If MSComm2.CommEvent = comEvReceive Or (MSComm2.CommEvent =
    comEvRing) Then 'CHECK FOR NEW MESSAGE RECEIVED
        BUFFER_LENGTH = MSComm2.InBufferCount
    Else
        BUFFER_LENGTH = 0
    End If

    While BUFFER_LENGTH > 5
        BUFFER_ARRAY = BUFFER_LEFTOVER & MSComm2.Input    'ADD NEW
        MESSAGE TO BUFFER
        START_POS = InStr(BUFFER_ARRAY, "%") 'DEFINE START OF MESSAGE
        STRING AT CHANNEL 1
        END_POS = START_POS + 7 'InStr(BUFFER_ARRAY, "!")' DEFINE
        END OF MESSAGE STRING
        BUFFER_LENGTH = END_POS - START_POS 'Len(BUFFER_ARRAY)
        'BUFFERLENGTH SET EQUAL TO LENGTH OF MESSAGE

        If START_POS = 0 Then Exit Sub 'IF NO BUFFER, END SUB
        If END_POS = 0 Then Exit Sub

        DATA_STRING = Mid(BUFFER_ARRAY, START_POS + 1, END_POS –
        START_POS + 1) 'SPLITS DATA STRING
        DATA_ARRAY = Split(DATA_STRING, ",") 'SPLITS DATA STRING
        ACCORDING TO ","

        CounterID = DATA_ARRAY(0) 'ASSIGNS A NUMBER FOR EACH SECTION
        OF BUFFER ARRAY
        Frequency = DATA_ARRAY(1) 'INCREMENTS THE NUMBER
        COUNTER(CounterID).Text = Frequency 'RENAMES EACH SECTION OF
        BUFFER TO COUNTER()

        Fuel.Text = COUNTER(1) * 0.001902 'CONVERTS FREQUENCY TO
        GALLONS PER HOUR AND OUTPUTS TO DISPLAY
```

```
        TRANSspeed.Text = COUNTER(2) * 0.035 'CONVERTS FREQUENCY TO
        TRANS SPEED AND OUTPUTS TO DISPLAY
        GSRspeed.Text = COUNTER(3) * 0.0303 'CONVERTS FREQUENCY TO
        GROUND SPEED AND OUTPUTS TO DISPLAY
        Slip.Text = (1 - (GSRspeed.Text / TRANSspeed.Text)) * 100
        'CALCULATES SLIP AND OUTPUTS TO DISPLAY

        BUFFER_LEFTOVER = Right(BUFFER_ARRAY, END_POS + 1) 'COLLECTS
        UNUSED BUFFER
      Wend

End Sub
```

```
'THE FOLLOWING READ THE STATE OF THE DIGITAL SWITCH SO THAT DRAFT DATA
CAN BE COMBINED WITH THIS DATA
Private Sub tmrReadInputs_Timer()
    ' read the bits of AUXPORT digital input and display
    '  Parameters:
    '       BoardNum     :the number used by CB.CFG to describe this
                          board
    '       PortTupe%    :the type of port
    '       BitNum%      :the number of the4 bit to read from the port
    '       BitValue%    :the value read from the port

'THIS SUB IS SWITCH FROM '1' TO '0' WHEN DRAFT DATA IS BEING TAKEN

    PortType% = AUXPORT
    BitNum% = 0 'DEFINES WHICH DIGITAL PORT

      Ulstat = cbDBitIn(BoardNum, PortType%, BitNum%, BitValue%)
      'CONFIGURES DIGITAL PORT
      If Ulstat <> 0 Then Stop 'ERROR FUNCTION
      ShwBitVal.Text = Format$(BitValue%, "0")'DISPLAY BIT VALUE ON
      FORM

End Sub
```

G.2 Tillage Speed Experiment Code

This code was used for the implement speed experiment. GPS information was not collected for this experiment. The following was displayed and collected for this experiment: fuel consumption, wheel speed, GSR, axle torque, and implement draft.

```
'DATA TYPE OF VARIABLES ARE DEFINED

Public OPENFILE As Boolean
Dim BoardName As String
Dim BoardNum As Integer
Dim Ulstat As Long
Dim filelocation As String
```

```
'CONTROLS THE PROCESS OF CHOOSING A FILENAME AND LOCATION TO LOG DATA

Private Sub ChooseFilename_Click()
    On Error Resume Next

    CommonDialog1.DialogTitle = "CHOOSE DATA FILENAME"
    'TITLES THE CHOOSE FILENAME DIALOG BOX
    CommonDialog1.ShowOpen
    'OPENS THE CHOOSE FILENAME DIALOG BOX IN ANOTHER WINDOW
    FilenameDisplay.Text = CommonDialog1.FileName
    'DISPLAY THE CHOSEN FILE TO THE GRAPHICAL USER
    INTERFACE

    Open CommonDialog1.FileName For Append As #1
    'ASSIGNS THE CHOSEN FILE TO BE WRITTEN

    Print #1, "COUNTER1, COUNTER2, COUNTER3, COUNTER4, FUEL, GSR,
    TRANS, ENGINESPE, SLIP, TORQUE, DIGSTATE"
    'PRINTS COLUMN LABELS AT THE TOP OF SELECTED FILE ABOVE

    OPENFILE = True
    LogData.Enabled = True  'ENABLE THE LOGDATA BUTTON ON GUI

End Sub
```

```
'THIS CONTROLS THE CLOSE CURRENT FILE BOTTON ON THE FORM

Private Sub cmdCloseFile_Click()

    Close #1    'CLOSES THE FILE BEING LOGGED TO
    OPENFILE = False    'CLOSES FILE
    LogData.Value = 0   'TURNS THE LOGDATA OFF
    LogData.Enabled = False 'ENABLES THE LOGDATA BUTTON
```

```
End Sub
```

```
'THIS CLOSES THE PROGRAM
Private Sub cmdCloseProgram_Click()
End
End Sub
```

```
Private Sub Form_Load()

'THESE ARE THE PROCEDURES EXECUTED ON PROGRAM STARTUP

'BEFORE OPENING COMM2, CHECK PORT NUMBER
MSComm2.PortOpen = True 'OPENS THE EXTERNAL COUNTER ON PORT 2

'DEFINES THE DIRECTORY OF THE OPENFILE DIALOG COMMAND
CommonDialog1.InitDir = "C:\"
'SETS UP THE DEFAULT EXTENSION AS A TEXT FILE
CommonDialog1.DefaultExt = ".txt"

'CONFIGURES THE PROGRAM TO COMMUNICATE WITH USB-1608FS BOARD

    BoardNum = 0 '<==============THIS IS THE BOARD NUMBER
    THAT INSTACAL HAS ASSIGNED FOR THE 1608 BOARD

    BoardName = "                                        "
    Ulstat = cbGetBoardName(BoardNum, BoardName)
    Myboard = BoardName
    Myboard = Trim$(Myboard)
    bdlen = Len(Myboard) - 1
    Myboard = Left(Myboard, bdlen)

    'THE FOLLOWING IS AN ERROR HANDLER IF BOARDNUM DOES NOT
    MATCH IN INSTACAL
    If (Myboard <> "PMD-1608FS") And (Myboard <> "USB-
    1608FS") Then
        MyMessage = "A USB/PMD-1608FS was not assigned to
        Board " & BoardNum & " in InstaCal." & Chr$(13) _
        & "Please run InstaCal to verify the board number"
        & Chr$(13) _
        & "and/or change BoardNum = " & BoardNum & " in the
        Form_Load event" & Chr$(13) _
        & "to the correct board number.  Then re-run this
        program."
   r = MsgBox(MyMessage, vbExclamation, "USB/PMD-1608FS not detected.")

      End

End If

        Ulstat = cbErrHandling(PRINTALL, DONTSTOP) 'UNIVERSAL LIBRARY
        FUNCTION FOR ERROR HANDLING
        If Ulstat <> 0 Then Stop
```

```
  'THE FOLLOWING CONFIGURES THE DIGITAL PORT ON USB-1608FS
   BOARD
      PortNum = AUXPORT   'DEFINES PORT
      Direction% = DIGITALIN  'ASSIGNS PORT DIRECTION AS INPUT
      Ulstat = cbDConfigBit(BoardNum, PortNum, 0,Direction%) 'CALLS
      UNIVERSAL LIBRARY FUNCTION TO CONFIGURE BOARD
      If Ulstat <> 0 Then Stop

End Sub
```

```
'READS ANALOG SIGNAL FOR TORQUE
Private Sub tmrConvert_Timer()

    Chan% = 0   'CHANNEL NUMBER
    Range = BIP10VOLTS  'DEFINES ANALOG RANGE
    Ulstat = cbAIn(BoardNum%, Chan%, Range, DataValue%) 'CALLS FUNCTION
    TO CONFIGURE USB-1608FS

    If Ulstat <> 0 Then Stop    'ERROR FUNCTION
    Range = BIP10VOLTS  'DEFINES RANGE FOR FUNCTION BELOW
    Ulstat = cbToEngUnits(BoardNum%, Range, DataValue%, EngUnits!)
    'CALLS FUNCTION TO CONFIGURE CHANNEL OUTPUT FORMAT

    If Ulstat <> 0 Then Stop    'ERROR FUNCTION
    Torque.Text = EngUnits * (1474)  'MEASURED VOLTAGE MULTIPLIED BY
    CONSTANT TO OBTAIN UNITS OF FT-LBS

End Sub
```

```
'MSComm2 ROUTINE DEFINES OPERATIONS ON NEW SERIAL MESSAGE FOR COUNTER
BOARD

Private Sub MSComm2_OnComm()

    On Error Resume Next    'ERROR FUNCTION

    If MSComm2.CommEvent = comEvReceive Or (MSComm2.CommEvent =
    comEvRing) Then 'CHECK FOR NEW MESSAGE RECEIVED
        BUFFER_LENGTH = MSComm2.InBufferCount
    Else
        BUFFER_LENGTH = 0
    End If

    While BUFFER_LENGTH > 5
        BUFFER_ARRAY = BUFFER_LEFTOVER & MSComm2.Input    'ADD NEW
        MESSAGE TO BUFFER
        START_POS = InStr(BUFFER_ARRAY, "%") 'DEFINE START OF MESSAGE
        STRING AT CHANNEL 1
        END_POS = START_POS + 7 'InStr(BUFFER_ARRAY, "!")' DEFINE
        END OF MESSAGE STRING
        BUFFER_LENGTH = END_POS - START_POS 'Len(BUFFER_ARRAY)
        'BUFFERLENGTH SET EQUAL TO LENGTH OF MESSAGE
```

```
        If START_POS = 0 Then Exit Sub 'IF NO BUFFER, END SUB
        If END_POS = 0 Then Exit Sub

        DATA_STRING = Mid(BUFFER_ARRAY, START_POS + 1, END_POS –
        START_POS + 1) 'SPLITS DATA STRING
        DATA_ARRAY = Split(DATA_STRING, ",") 'SPLITS DATA STRING
        ACCORDING TO ","

        CounterID = DATA_ARRAY(0) 'ASSIGNS A NUMBER FOR EACH SECTION
        OF BUFFER ARRAY
        Frequency = DATA_ARRAY(1) 'INCREMENTS THE NUMBER
        COUNTER(CounterID).Text = Frequency 'RENAMES EACH SECTION OF
        BUFFER TO COUNTER()

        Fuel.Text = COUNTER(1) * 0.001902 'CONVERTS FREQUENCY TO
        GALLONS PER HOUR AND OUTPUTS TO DISPLAY
        TRANSspeed.Text = COUNTER(2) * 0.035 'CONVERTS FREQUENCY TO
        TRANS SPEED AND OUTPUTS TO DISPLAY
        GSRspeed.Text = COUNTER(3) * 0.0303 'CONVERTS FREQUENCY TO
        GROUND SPEED AND OUTPUTS TO DISPLAY
        Engspeed.Text = COUNTER(4) * 1.3 'CONVERTS FREQUENCY TO ENGINE
        SPEED AND OUTPUTS TO DISPLAY
        Slip.Text = (1 - (GSRspeed.Text / TRANSspeed.Text)) * 100
        'CALCULATES SLIP AND OUTPUTS TO DISPLAY

        BUFFER_LEFTOVER = Right(BUFFER_ARRAY, END_POS + 1) 'COLLECTS
        UNUSED BUFFER

'THIS WRITES THE DATA TO THE TEXT FILE
Write #1, COUNTER(1), COUNTER(2), COUNTER(3), COUNTER(4), Fuel.Text,
GSRspeed.Text, TRANSspeed.Text, Engspeed.Text, Slip.Text, Torque.Text,
ShwBitVal.Text

      Wend
End Sub
```

```
'THE FOLLOWING READ THE STATE OF THE DIGITAL SWITCH SO THAT DRAFT DATA
CAN BE COMBINED WITH THIS DATA
Private Sub tmrReadInputs_Timer()
    ' read the bits of AUXPORT digital input and display
    ' Parameters:
    '   BoardNum     :the number used by CB.CFG to describe this
                          board
    '   PortTupe%    :the type of port
    '   BitNum%      :the number of the4 bit to read from the port
    '   BitValue%    :the value read from the port

'THIS SUB IS SWITCH FROM '1' TO '0' WHEN DRAFT DATA IS BEING TAKEN
    PortType% = AUXPORT
    BitNum% = 0 'DEFINES WHICH DIGITAL PORT

      Ulstat = cbDBitIn(BoardNum, PortType%, BitNum%, BitValue%)
      'CONFIGURES DIGITAL PORT
      If Ulstat <> 0 Then Stop 'ERROR FUNCTION
      ShwBitVal.Text = Format$(BitValue%, "0")'DISPLAY BIT VALUE ON
```

```
        FORM
End Sub
```

G.3 Spatial Tillage Experiment Code

The following code was used for the tire pressure test. This program displayed and collected GPS information, exhaust gas temperature (EGT), axle torque, fuel consumption, wheel speed, ground speed, and engine speed.

```
'THE VARIABLE DATA TYPES ARE DEFINED
Public OPENFILE As Boolean
Dim BoardName As String
Dim BoardNum As Integer
Dim Ulstat As Long
Dim TempBoard As String
Dim TempNum As Integer
Dim filelocation As String
```

```
'THE FOLLOWING OPERATES THE CHOOSEFILENAME BUTTON ON THE FORM
Private Sub ChooseFilename_Click()

    On Error Resume Next

    CommonDialog1.DialogTitle = "CHOOSE DATA FILENAME" 'DEFINES THE
    TITLE OF THE DIALOG BOX
    CommonDialog1.ShowOpen 'CREATES ANOTHER WINDOW SO THE DIRECTORY OF
    THE INPUT FILE CAN BE DEFINED
    FilenameDisplay.Text = CommonDialog1.FileName 'DISPLAY THE CHOSEN
    FILE IN THE TEXT BOX ON THE FORM

    Open CommonDialog1.FileName For Append As #1 'OPENS THE FILE FOR
    DATA INPUT

    Print #1, "LON, LAT, SATES, QUALITY, ELEV, GPS_TIME, VELOCITY,
    FUEL_CON, FUELCNT, WHEEL, WHEELCNT, GSRSPEE, GSRCNT, ENGSPEED,
    ENGCOUNT, SLIP, EGT, TORQUE"  'PRINTS LABELS AT THE TOP OF SELECTED
    TEXT FILE

    OPENFILE = True 'ASSIGNS "TRUE" TO THE OPENFILE VARIABLE
    LogData.Enabled = True 'ENABLES THE LOGDATA BUTTON ON THE FORM

End Sub
```

```
Private Sub ClosePort_Click()
MSComm1.PortOpen = False
    'CLOSES COMM PORT 1

End Sub
```

```
Private Sub CloseProgram_Click()
```

```
End 'TERMINATES THE PROGRAM

End Sub
```

```
Private Sub Command2_Click()

    Close #1 'CLOSES THE APPEND TO TEXT FILE
    OPENFILE = False 'CLOSES TEXT FILE
    LogData.Value = 0 'DEFINES LOGDATA VALUE TO ZERO
    LogData.Enabled = False 'ENABLES THE LOGDATA BUTTON ON THE FORM

End Sub
```

```
Private Sub Form_Load()

'BEFORE OPENING COMM2,CHECK PORT NUMBER
MSComm2.PortOpen = True 'OPENS THE EXTERNAL COUNTER PORT

'FILLS THE BAUD RATE DROP DOWN LIST IN THE FORM
Baud.Clear
Baud.AddItem "2400"
Baud.AddItem "4800"
Baud.AddItem "9600"
Baud.AddItem "19200"
Baud.AddItem "38400"
Baud.AddItem "56000"
Baud.Text = "4800"

CommonDialog1.InitDir = "C:\" 'DEFINES THE DEFAULT OPENING DIRECTORY
CommonDialog1.DefaultExt = ".txt" 'DEFINES THE DEFAULT LOGGING FILE
                                   EXTENSION AS .TXT

'CONFIGURE THE PROGRAM TO COMMUNICATE WITH USB-1608FS DATA AQUISITION
BOARD
    BoardNum = 0 '<==============THIS IS THE DEFAULT BOARD NUMBER
                 'CHANGE IT TO WHAT INSTACAL HAS ASSIGNED FOR THE USB-
                  1608FS BOARD
    BoardName = "                                         "
    Ulstat = cbGetBoardName(BoardNum, BoardName)
    Myboard = BoardName
    Myboard = Trim$(Myboard)
    bdlen = Len(Myboard) - 1
    Myboard = Left(Myboard, bdlen)
      If (Myboard <> "PMD-1608FS") And (Myboard <> "USB-1608FS") Then
      MyMessage = "A USB/PMD-1608FS was not assigned to Board " &
      BoardNum & " in InstaCal." & Chr$(13) _ & "Please run InstaCal to
      verify the board number" & Chr$(13) _ & "and/or change BoardNum =
      " & BoardNum & " in the Form_Load event" & Chr$(13) _ & "to the
      correct board number.  Then re-run this program."

    r = MsgBox(MyMessage, vbExclamation, "USB/PMD-1608FS not
    detected.")
End
```

```
    End If

Ulstat = cbErrHandling(PRINTALL, DONTSTOP)
        If Ulstat <> 0 Then Stop

    'CONFIGURE THE PROGRAM TO COMMUNICATE WITH USB-TC BOARD
    TempNum = 1   '<========THIS IS THE DEFAULT BOARD NUMBER
                    'CHANGE IT TO WHAT INSTACAL HAS ASSIGNED FOR THE
                    USB-TC
    TempBoard = "                                       "
    Ulstat = cbGetBoardName(TempNum, TempBoard)
    TCboard = TempBoard
    TCboard = Trim$(TCboard)
    tclen = Len(TCboard) - 1
    TCboard = Left(TCboard, tclen)
    If (TCboard <> "USB-TC") And (TCboard <> "USB-TEMP") Then
        MyWords = "A USB-TC was not assigned to Board " & TempNum & "
        in InstaCal." & Chr$(13) _ & "Please run InstaCal to verify the
        board number" & Chr$(13) _ & "and/or change BoardNum = " &
        TempNum & " in the Form_Load event" & Chr$(13) _ & "to the
        Correct board number.  Then re-run this program."
    r = MsgBox(MyWords, vbExclamation, "USB-TC not detected.")

End

    End If

   Ulstat = cbErrHandling(PRINTALL, DONTSTOP)
   If Ulstat <> 0 Then Stop


End Sub
```

```
Private Sub OpenPort_Click()
    'SET UP COMM PORT
    MSComm1.CommPort = BioTractorLogger.PortNum.Text
    MSComm1.Settings = BioTractorLogger.Baud.Text & ",n,8,1"

    If MSComm1.PortOpen = True Then
        MsgBox "THE PORT IS ALREADY IN USE"
        Exit Sub
    End If

    MSComm1.PortOpen = True

End Sub
```

```
Private Sub MSComm1_OnComm()
'MSComm1 ROUTINE DEFINES OPERATIONS ON NEW SERIAL MESSAGE RECEIVE
INTERRUPT

    On Error Resume Next
```

```
    If MSComm1.CommEvent = comEvReceive Then 'CHECK FOR NEW MESSAGE
RECEIVED
        BUFFER_LENGTH = MSComm1.InBufferCount
    Else
        BUFFER_LENGTH = 0
    End If

    While BUFFER_LENGTH > 5
        BUFFER_ARRAY = BUFFER_LEFTOVER & MSComm1.Input 'ADD NEW MESSAGE
        TO BUFFER
        BUFFER_LENGTH = Len(BUFFER_ARRAY)
        START_POS = InStr(BUFFER_ARRAY, "$GPGGA") 'DEFINE START OF
        MESSAGE STRING FOR GGA STRING
        START_POS1 = InStr(BUFFER_ARRAY, "$GPVTG") 'DEFINE START OF
        MESSAGE STRING FOR VTG STRING
        END_POS = START_POS + 100 'InStr(BUFFER_ARRAY, "*") ' DEFINE
        END OF MESSAGE FOR GGA STRING
        END_POS1 = START_POS1 + 100 'InStr(BUFFER_ARRAY, "*") ' DEFINE
        END OF MESSAGE FOR VTG STRING

        If START_POS = 0 Then Exit Sub 'FOR GGA STRING
        If END_POS = 0 Then Exit Sub

        If START_POS1 = 0 Then Exit Sub 'FOR VTG STRING
        If END_POS1 = 0 Then Exit Sub

        'THE FOLLOWING STATEMENTS SPLIT THE GGA DATA STRING
        DATA_STRING = Mid(BUFFER_ARRAY, START_POS + 1, END_POS –
        START_POS - 1) 'SPLIT GGA DATA STRING
        DATA_ARRAY = Split(DATA_STRING, ",")
        SA = DATA_ARRAY(0) 'DEFINE SOURCE ADDRESS OF NEW MESSAGE
        BUFFER_LEFTOVER = Mid(BUFFER_ARRAY, END_POS + 1) 'COLLECT
        UNUSED BUFFER

        'THE FOLLOWING STATEMENTS SPLIT THE VTG DATA STRING
        DATA_STRING1 = Mid(BUFFER_ARRAY, START_POS1 + 1, END_POS1 –
        START_POS1 - 1) 'SPLIT DATA STRING
        DATA_ARRAY1 = Split(DATA_STRING1, ",")
        SA = DATA_ARRAY1(0)      'DEFINE SOURCE ADDRESS OF NEW MESSAGE
        BUFFER_LEFTOVER1 = Mid(BUFFER_ARRAY1, END_POS1 + 1)  'COLLECT
        UNUSED BUFFER

            Dim GPSTIMEVAR As String
            GPSTIMEVAR = DATA_ARRAY(1)
            GPSTime.Text = Format(Left(GPSTIMEVAR, 2) & ":" &
            Mid(GPSTIMEVAR, 3, 2) & ":" & Right(GPSTIMEVAR, 5),
            "######")
            'DATA_ARRAY(2) IS LATITUDE, BUT MUST BE CONVERTED TO
            DECIMAL DEGREES
            Lat.Text = Format(Left(DATA_ARRAY(2), 2) +
            (Right(DATA_ARRAY(2), Len(DATA_ARRAY(2)) - 2)) / 60,
            "##.########")
            'DATA_ARRAY(4) IS LATITUDE, BUT MUST BE CONVERTED TO
            DECIMAL DEGREES
            Lon.Text = Format(Left(DATA_ARRAY(4), 3) +
```

```
            (Right(DATA_ARRAY(4), Len(DATA_ARRAY(4)) - 3)) / 60, "-
            ##.########")
            Quality.Text = DATA_ARRAY(6) 'DISPLAY GPS QUALITY TO
            THE FORM
            Sates.Text = DATA_ARRAY(7) 'DISPLAY # OF SATELLITES TO THE
            FORM
            Elevation.Text = DATA_ARRAY(9) 'DISPLAY ELEVATION TO THE
            FORM
            Velocity.Text = DATA_ARRAY1(7) * 0.62137 'FROM VTG STRING
            AND CONVERT TO MPH AND DIPSLAY TO FORM
            Slip.Text = (1 - (GSRspeed.Text / Wheel.Text)) * 100
            'CALCULATES AND DISPLAYS SLIP

            'THE FOLLOWING CLASSIFIES GPS QUALITY
            If Sates.Text = 0 Then
                GPSLogger.DiffService = "NO CORRECTION"
            ElseIf Sates.Text = 1 Then
                GPSLogger.DiffService = "NON-DIFF GPS FIX"
            ElseIf Sates.Text = 2 Then
                GPSLogger.DiffService = "WAAS CORRECTION"
            End If

            'THE FOLLOWING WRITES THE DATA TO A TEXT FILE
            If (LogData.Value = 1) And (OPENFILE = True) Then
              Write #1, Lon.Text, Lat.Text, Sates.Text, Quality.Text,
              Elevation.Text, GPSTime.Text, Velocity.Text, Fuel.Text,
              COUNTER(1).Text, Wheel.Text, COUNTER(2), GSRspeed.Text,
              COUNTER(3), ENGspeed.Text, COUNTER(4), Slip.Text,
              Egttemp.Text, Torque.Text

            End If

       Wend

End Sub
```

```
'READS EGT THERMOCOUPLE
Private Sub Tempconvert_Timer()

    'Collect the data with cbAIn%()
    'Parameters:
    '   TempNum     :the number used by CB.CFG to describe this board
    '   Chan%       :the A/D and channel number; starts at 16
    '                calculated by (ADChan% + 1) * 16 + EXPChan%
    '   CBScale%    :the temperature scale (F, C or K)
    '   DataValue%  :the name for the value collected
    CBScale% = FAHRENHEIT  'DEFINES WANTED UNITS FOR TEMPERATURE
    Channel% = 0 'DEFINES CHANNEL NUMBER
    Options% = Filter

    Ulstat = cbTIn(TempNum, Channel%, CBScale%, TempValue!, Options%)
'CALLS A FUNCTION IN THE UNIVERSAL LIBRARY
    If Ulstat <> 0 Then Stop
```

```
    Egttemp.Text = TempValue!  'DISPLAYS EGT VALUE IN THE FORM

End Sub
```

```
'READS ANALOG SIGNAL FOR TORQUE

Private Sub tmrConvert_Timer()

    Chan% = 0
    Range = BIP10VOLTS 'DEFINES DESIRED VOLTAGE RANGE
    Ulstat = cbAIn(BoardNum%, Chan%, Range, DataValue%)
    If Ulstat <> 0 Then Stop
    Range = BIP10VOLTS
    Ulstat = cbToEngUnits(BoardNum%, Range, DataValue%, EngUnits!)
    If Ulstat <> 0 Then Stop

    'THE FOLLOWING DISPLAYS THE TORQUE TO THE FORM
    Torque.Text = EngUnits * (2022) 'MULTIPLY FOR CONVERSION FACTOR TO
    OBTAIN USABLE NUMBERS

End Sub
```

```
'THE FOLLOWING CONTROLS FUNCTIONS FOR THE COUNTER BOARD
Private Sub MSComm2_OnComm()
'MSComm2 ROUTINE DEFINES OPERATIONS ON NEW SERIAL MESSAGE FOR CNTR
BOARD

    On Error Resume Next

    If MSComm2.CommEvent = comEvReceive Or (MSComm2.CommEvent =
    comEvRing) Then 'CHECK FOR NEW MESSAGE RECEIVED
        BUFFER_LENGTH = MSComm2.InBufferCount
    Else
        BUFFER_LENGTH = 0
    End If

    While BUFFER_LENGTH > 5
        BUFFER_ARRAY = BUFFER_LEFTOVER & MSComm2.Input 'ADD NEW
        MESSAGE TO BUFFER
        START_POS = InStr(BUFFER_ARRAY, "%") 'DEFINE START OF MESSAGE
        STRING AT CHANNEL 1
        END_POS = START_POS + 7 'InStr(BUFFER_ARRAY, "!") 'DEFINE
        END OF MESSAGE STRING
        BUFFER_LENGTH = END_POS - START_POS 'Len(BUFFER_ARRAY)
        'BUFFERLENGTH SET EQUAL TO LENGTH OF MESSAGE

        If START_POS = 0 Then Exit Sub
        If END_POS = 0 Then Exit Sub

        DATA_STRING = Mid(BUFFER_ARRAY, START_POS + 1, END_POS –
        START_POS + 1) 'SPLIT DATA STRING
        DATA_ARRAY = Split(DATA_STRING, ",") 'SPLITS DATA STRING
        ACCORDING TO ","
```

```
        CounterID = DATA_ARRAY(0)
        Frequency = DATA_ARRAY(1)

        COUNTER(CounterID).Text = Frequency

        Fuel.Text = COUNTER(1) * 0.001902 'DISPLAYS FUEL CONSUMPTION TO
        THE FORM
        Wheel.Text = COUNTER(2) * 0.00415 'DISPLAYS WHEEL SPEED TO THE
        FORM
        GSRspeed.Text = COUNTER(3) * 0.0177 'DISPLAYS THE GROUND SPEED
        TO THE FORM
        ENGspeed.Text = COUNTER(4) * 1.3 'DISPLAYS ENGINE SPEED TO THE
        FORM

        BUFFER_LEFTOVER = Right(BUFFER_ARRAY, END_POS + 1) 'COLLECT
        UNUSED BUFFER

    Wend

End Sub
```