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Petr Vozka

Comparison of alternative tillage systems

Supervisor: Prof. M.J. O'Dogherty

Co-supervisor: Prof. R.J. Godwin

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Abstract

The aim of the project was to compare the performance and the costs of alternative tillage systems and machinery, in both energy and economic terms. To determine the energy requirements of tillage implements, experimentation in field conditions and controlled laboratory was conducted. Costs of alternative implements and complete systems were analysed.

The field experiment was undertaken to determine the performance of tillage implements in real conditions. Draught force and area of disturbance of the implements were measured and specific resistance calculated. The implements involved in the experiment were 4 furrow mouldboard plough, 3 furrow disc plough, disc harrow and 7 winged tines. The mouldboard plough was operating at two different depths. Two tractors were used for execution of the implement and the wheel slip was measured.

The soil bin studies were conducted in additional evaluation of the implements. The laboratory conditions ensure the uniformity of each test. The experiment was carried out to determine draught force, area of disturbance and specific resistance. The experiment involved single furrow mouldboard plough, disc plough, disc harrow and winged tines. Winged tines were made up of four different wing widths.

Finally, an economic cost calculator was developed to compare the costs of different implements and tillage systems. Technical parameters and current prices of the implements were obtained from the manufacturers.

The results from the field experiment show that there is a similar draught force per unit implement for mouldboard and disc ploughs, while draught force of mouldboard plough is significantly higher. The tillage efficiency of all implements is similar, with a mean of specific resistance of 58 kN/m^2 and a range of 15 kN/m^2. In the soil bin the vertical force preventing penetration occurred for disc plough and disc harrow. The specific resistance of the mouldboard plough had the lowest value, while the specific resistance of disc plough was higher by a factor of 1.65. By increasing the wing width of the tines the draught force was increased but the specific resistance decreased. Comparing the

costs of complete tillage systems it was observed that minimum tillage decreases the operational cost per hectare by 30% compared to a conventional system based on ploughing. Direct drilling is the cheapest way to establish a crop, but if herbicide has to be applied the cost per hectare is similar to that of minimum tillage. The costs of different sizes (102, 162, 224 kW tractors) of alternative tillage systems are similar. Namely the cost of mouldboard plough is £ 80.33/ha with a range of £ +2.48/-1.93/ha, the cost of shallow mouldboard plough is £ 68.85/ha with a range of £ +2.02/-1.64/ha, the cost of stubble cultivator is £ 42.05/ha with a range of £ +2.02/-1.27/ha, the cost of direct drill is £ 20.76/ha with a range of £ +0.89/-0.75/ha and the cost of direct drill with herbicide application is £ 43.15/ha with a range of £ +0.41/-0.53/ha.

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1 Introduction

Tillage is generally regarded as the most fundamental operation in global agriculture and has a great influence on the performance of the crop production system. The aim of the tillage is to create the optimum environment from seed germination to root growth and to enable mechanization as well as soil and water management. The set of implements chosen for tillage depends on local customs, soil and crop types and the cultivation system used.

Ploughing has been a traditional method of primary soil cultivation during the past centuries all over the world. The mouldboard plough has one of the most complex shapes of tillage implements and has been developing for centuries. Its main advantage over other tillage tools is soil cultivation including soil inverting in order to bury weeds. Ploughing is very effective in controlling weeds, especially perennial weed species. Since the middle of last century various forms of shallow tillage have emerged in order to reduce energy consumption and to increase work rates. Mainly economic and environmental factors are the reasons why minimum tillage is popular in agriculture. Minimum tillage practises do not include the use of mouldboard ploughs and allow farmers to minimize costs and increase output. The combination of tines or discs and various kinds of harrows are the major types of implements used for secondary or minimum tillage. As the soil is not inverted, more organic matter is accumulating in the top soil layer, which needs more attention in terms of weed, pest and disease control.

Recent changes in economic and regulatory situations on the agricultural market and with respect to the environment compel farmers to review their tillage systems and to implement new techniques of soil cultivation. Work rate and the energy consumption are the basic measures of machine performance. Quality must be also considered, because it describes the ability to manage the system without wasted product. To complete any of the tasks in given time, timeliness is crucial in agriculture which is sensitive to season and bad weather. There is a diverse range of implements available, from ploughs to direct drills, to achieve today’s demands in soil cultivation and sowing.

For effective machinery management there is a need for information about energy requirements, work rates and cost of alternative tillage systems. A number of investigations have been carried out to evaluate the performance of the mouldboard plough, in terms of plough geometric factors, ploughing speed, the effect of ploughing speed and costs (Wheeler and Godwin, 1996; Saunders, 2002; Godwin et al., 2007). Forces acting on freely rotating discs have been examined (Godwin et al., 1987; Al-Ghazal, 1989). Studies were carried out to investigate the effect of tine geometry and multiple tines on implement forces (Godwin and Spoor, 1977; Godwin, 2007). There is a limited recent information on the comparable performance of mouldboard, disc and tine implements working under similar conditions.

1.1 Aim

The aim of this project is to compare the performance and the costs of alternative tillage systems and machinery, in both energy and economic terms.

1.2 Objectives

The objectives of the project are:

- To assess alternative tillage implements in terms of draught forces, disturbed areas and specific resistances in field and soil bin experiments.
- To compare the economic performance and work rates of conventional and reduced tillage systems.
- To propose alternative tillage systems, which best suit different farm sizes.

1.3 Project methodology

This project is aimed at undertaking experimental and theoretical research and to recommend energy and, therefore, cost efficient tillage system for different size of farms. The research programme can be divided into following steps:

- To conduct field experiments with alternative implements to determine their performance in real conditions in terms of draught force, disturbed area, specific resistance and work rates. The implements for the experiment are mouldboard and disc ploughs, a disc harrow and winged tines.
- To investigate draught force, disturbed area and specific resistance of alternative implements in controlled laboratory conditions. The experiment will ensure more uniform conditions than in the field and will include mouldboard and disc implements and winged tines of four different wing widths. Experiments for each implement will be replicated three times.
- To compare the costs of whole systems an economic calculator program (spreadsheet model) will be developed. Technical parameters and current prices of a limited number of tractors and implements will be collected.
- To conduct economic studies based on the collected data. Total costs of alternative tillage systems will be analysed.

2 Literature review

Tillage is one of the key operations in crop production, although it may be sometimes omitted due to recent developments in technology. It is used to nurture crops by mechanical, soil stirring actions. Tillage provides a suitable seedbed to grow crops, from seed germination to root growth, for fertilizer and pesticide incorporation, and weed and moisture control. Soil cultivation requires approximately half of the total energy and labour expended on farms, so it is important to adopt suitable tillage practices, monitor its costs and follow up new trends.

Agriculture in the beginning of civilization enabled people to turn from hunting to farming, to domesticate plants and animals and to settle in one spot. Settled agriculture originated in the fertile plains along rivers and led to development of ancient civilizations. To make the land cultivation work easier, a large variety of tools for breaking and stirring the soil was designed. The first wooden plough was developed and for the next 26 centuries remained practically unchanged.

In the 18th century steel was used in place of wood; wheel ploughs at that time had a cast-iron share and a rounded iron mouldboard. The introduction of the steam engine meant a rapid expansion in the use of ploughs. In the 1900's the tractor era as a source of power started slowly and enhanced crop yields and work rates. In the last century researchers focused on further increasing mouldboard plough performance in terms of understanding the forces acting on the plough body, efficiency of tractor power and optimalization of plough components and work speed. The data in *Table 1* outlines the key developments in agriculture with a strong impact on yield and work efficiency.

No-tillage and conservation cropping systems, which have evolved rapidly since the early 1960's, became a competition for the traditional plough system. A new approach to tillage was demanded to decrease the risk of erosion and soil degradation. These negative effects caused by intensive tillage and heavy machinery set in motion a trend of soil structure decline and loses of soil nutrition and organic matter. In dry areas extensive tillage resulted in degraded soil from wind and water erosion. In the Great Plains in the U.S. in the 1930's a combination of tillage and sustained drought caused

the „Dust Bowl“; one dust storm in 1935 carried approximately 350 million tons of soil in the air, of which some were dropped as far east as New York (Lal, 2007). Events, such as this, prompted the adoption of effective conservation plans for long-term agricultural sustainability. Tillage systems are continually evolving and the aim is still the same: sustainable technology with high productivity and no adverse effects on the environment.

Table 1. Chronological developments in agriculture (Lal, 2007)

Era	Locale	Technology
11000–9000 BC	Mesopotamia	Beginning of settled agriculture
9500–8800 BC	Sumerians	Use of supplemental irrigation
5000–4000 BC	Mesopotamia	Use of simple tools such as an "ard" or plough
3000–2000 BC	Indus Valley	Use of animal-driven plough
2500–2000 BC	Mesopotamia	The concept of fertility of cropland soils
900–700 BC	Greece	Use of animal manure
370–280 BC	Rome	Use of green manures
1 AD	Rome	Use of lime and saltpetre (KNO3)
1604–1668 AD	Germany	Impact of saltpetre on plant growth
1100–1200 AD	Moorish Spain	Soil quality
1803–1873 AD	Germany	Use of chemical fertilizers
1950–1970 AD	U.S. Corn Belt	Conservation tillage, no-till farming
1960s AD	Israel	Drip irrigation, fertigation
1980s AD		Biotechnology and GM crops
2000 AD		Deliver nutrients and water directly to plant roots, biomass-based H2 fuels, conservation tillage, land-saving technologies, precision farming, soil carbon sequestration

2.1 Tillage operations

All tillage practices are carried out to increase yield and improve soil conditions; any activity beyond that cannot be justified on the basis of tradition or habit. Each tillage operation is aimed to reach one of the following goals (Deere & Company, 1976):

- management of crop residue
- provide optimum soil aeration
- incorporation of fertilizers
- promote optimum moisture level

- insect control
- temperature control
- provide good seed-soil contact
- improvement of soil tilth
- erosion control

The various operations of soil cultivation can be classified as follows:

- *Primary cultivation* works the undisturbed soil to loosen it down to around 25 cm depth, buries trash and weeds by inversion, mixes it into the tilled layer or leaves it on the surface.
- *Secondary cultivation* prepares the relatively rough surface after primary cultivation for planting. It works the soil shallower to the required clod size and distribution and firms the soil to give good contact with the seed or plant and conserves moisture.
- *Seeding* is placing the seed or seedling at the correct depth and spacing in the soil. Some tillage practices combine shallow soil cultivation and crop establishment in one pass over field.

There are many tillage practices and a number of different titles. Three specific tillage systems can be determined by soil type and crop to be grown:

1) **Traditional tillage** refers to a sequence of operations performed to prepare a seedbed for a given crop. It is called traditional, because it has been evolving for centuries as a basic soil cultivation. This system involves usually stubble cleaning down to 8 cm depth, primary cultivation down to 25 cm depth (*Figure 1*) and secondary cultivation down to 10 cm depth. (SMI, 2002). Major types of implements used are tines or discs stubble cultivators, mouldboard, disc or chisel ploughs and tined seedbed cultivators or various kinds of harrows. Traditional tillage is suitable for organic farms, when weed control is one of the main problems, and also for poorly structured soils or soils prone to water logging.
2) **Minimum tillage** describes crop establishment systems that embrace fewer passes and minimal soil disturbance in comparison to traditional tillage. Crop residues well chopped by a combine harvester are usually incorporated without soil inversion into the top 10 cm of soil leaving a proportion on the surface (*Figure 2*). This type of cultivation also controls weed and pests such as slugs,

together with a reduction of energy inputs and labour requirements. Disc or tine stubble cultivators and power tillers are an example of implements for minimum tillage. Conservation or ecological tillage follows the trend of soil care systems for sustainable agriculture. These techniques are similar to minimum tillage, but their main aims are not only economical factors, but primarily improving soil structure and conditions.

3) Where a **no-tillage** system is used, no soil cultivation is done from harvest until sowing and no soil is moved into the seeding area. A narrow slot is created by discs, coulters or chisels for obtaining the desired seed placement. Direct drills usually have trash wheels to clear through the row area of the previous crop and extra weight for soil openers for adequate penetration. This system is useful where land is too steep for conventional tillage and where there is a short turnaround between crops. Residues left on the surface may help prevent crusting and erosion. Weeds represent the biggest problem of no-tillage systems, which often require a heavy use of herbicides or mechanical cultivation.

Figure 1. Two operations in traditional tillage system: stubble cultivation and ploughing

Figure 2. Tine stubble cultivator suitable for minimum tillage

2.2 Soil quality

Reducing tillage operations is a way of saving money and labour, but there are other factors, which need to be considered before adopting a particular technique. The properties of individual soils vary widely and are a limitation for tillage systems. No tillage system can be best suited for all types of soil, so that careful evaluation of soil conditions should be done before its selection. Soils classified as suitable for repeated direct drilling of either winter or spring crop are well-drained loam soils, while soils with slow internal drainage and periodic water logging conditions are not well-suited to no-tillage. The soils affecting by fluctuating ground water, often sandy and silty soils with low organic matter content can pose great problems if tillage is reduced. Compaction is also a problem for these soils and tillage (eg. subsoiling) may be required to recreate soil porosity. (Phillips, 1984). Appropriate soil and crop types for minimum tillage are shown in *Table 2*. As noted by Spoor, 1985 tillage implements should be used to achieve the desired soil conditions with the help of natural forces, rather than forced only by an implement. Soil structure pre-exists, therefore tillage has to be directed towards its improvement.

Table 2. Minimum tillage analysed as a function of soil type and crop (Kuhn, 2007)

Type of Crop	**Cereals, OSR, Pulse crops, Sunflower, Soya**		**Maize grain, Maize silage**		**Sugar Beet, Grass silage, Potatoes**	
Risk of compaction	Low		Medium		High	
Speed of drainage	Good	Average	Good	Average	Good	Average
Clays / Clay-loams / Chalky-clays / Chalk soils	Possible		Possible	Risky	Risky	
Silty-clays	Possible		Possible	Risky	Not Recommended	
Silts / Sandy-silts	Possible		Risky		Not Recommended	

The amount of vegetation- dead or alive- maintained on the surface protects the soil from water and wind erosion. It has been observed that a 30% soil covering of residue protects the soil against erosion and reduces significantly losses of agrochemicals and soil nutritients into water courses. The percentage of cover of the soil surface is more important than the amount of residue, so that to acquire uniformity of shredded or chopped residues of the previous crop is essential. Another possibility of improving natural fertility and limiting soil erosion is to establish a cover crop as soon as possible after harvest. Cover crop also helps smother any emerging weeds and eliminates any surplus soil nutrients. Before the following crop is sown, the cover crop must be chemically destroyed.

Soil disturbance caused by tillage systems affects soil biological activity. It is higher where minimum tillage is used, because more plant residues are left on the surface and in the top layer stimulate micro-organisms, which are dependent on the presence of oxygen and organic material. An increase of worm activity is also observed due to the undisturbed structure of a network of galleries and cracks (*Figure 3*). Rasmussen, 1999 examined the impact on soil quality of a ploughless tillage system and an increase in the number of all species of earthworms was observed. The porosity just beneath the depth of a ploughless system decreased, as well as the volume of macropores (drainable pores), while the volume of medium (waterholding) pores increased. Ploughless tillage due to plant residues left on or near the soil surface led to a higher water content, lower evapotranspiration and soil temperature and greater and more stable soil aggregates. In

summary, changing from a plough based system will improve soil structure, increase surface stability and retain nutrients in the soil.

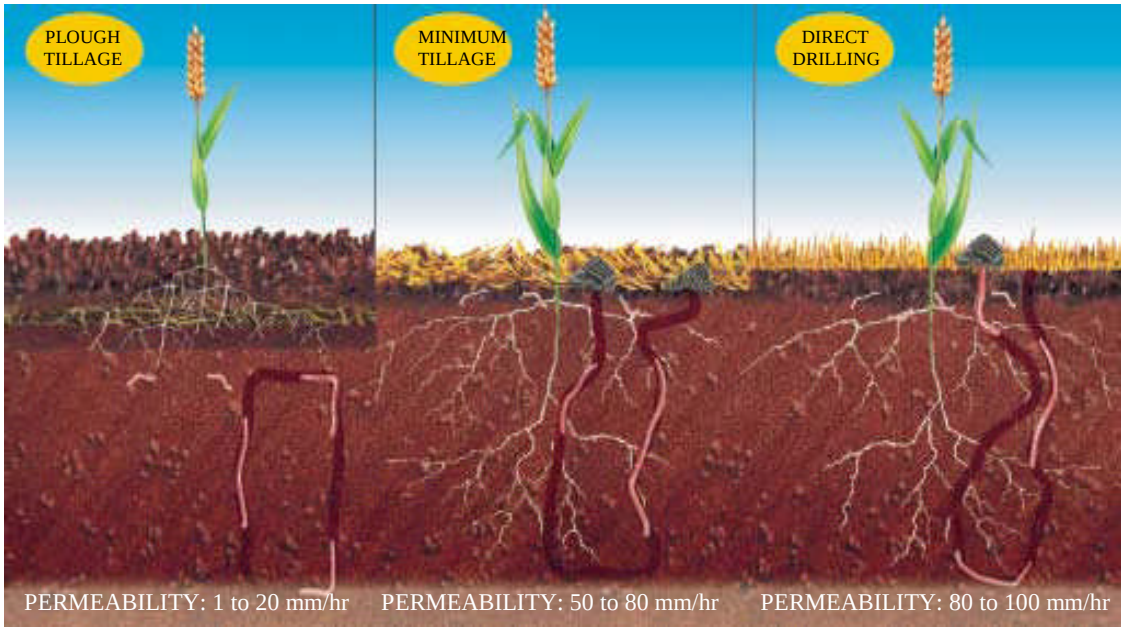


Figure 3. Various tillage systems and their effect on worm activity (Kuhn 2007)

Effective weed control is an advantage of plough based systems, because trash and weeds are buried relatively deeply and plant pests and diseases are also reduced. Where ploughing is omitted or done shallower, to around 12 cm, the cultivation system is more dependent on the use of herbicides. Controlling annual and perennial weeds can be dealt with satisfactorily by spraying before crop establishment, thus reducing the grass seed bank. To gain the benefit of reduced tillage, weed management must be maximised to control resistant weeds and prevent resistance developing. Also, rotational ploughing can reduce some hard to control perennials. In an organic production system, where a chemical control option is not available, a chisel or mouldboard plough, spring tines or discs are feasible implements for weed physical destruction. In minimum systems, crop residues on the surface create a favourable environment for the development of certain diseases and pests; therefore it is advisable to pay particular attention to crop rotation and planting resistant varieties. Kouwenhoven, 2002 reports, that perennial weeds were hard to control by ecoploughing down to 12- 14 cm depth; however a ploughing depth of 20 cm was acceptable. When weed infestation is severe, ploughing shallower than 20 cm is inadvisable and deep ploughing is necessary.

Cultivation types and their advantages and disadvantages are summarised in *Table 3*.

Table 3. List of cultivation types and their characteristics (SMI, 2002)

Cultivation type	Depth (cm)	Cost (£/ha)*	Time (min/ha)	Advantages	Disadvantages
Plough	15-35	85-120	150-220	• All soils • Buries trash/weed seeds • Creates fine seedbed • Uses existing equipment	• Low work rates • Many operations • High cost of establishment • Subsurface damage can occur
Reduced tillage	5-10	40-70	60-100	• High output • Few passes • Low cost of establishment • Soil moisture and nutrient retention	• Perceived higher horse power need • Perceived more grass weeds • Not suited to all types
Direct drill	0	30-45	25-40	• High output • Low cost of establishment • Moderate horse power needed compared to cultivator drills	• Specialist drill needed • Grass weed problems • Suitability for non direct drill crops

* 2000 prices

2.3 Principles of soil mechanics implements

All soil cultivation systems, except no-tillage, are based on the implements which are used to work the soil in order to prepare quality conditions for crop growing. Basic tillage implements can be distinguished by two major variables in their design:

- rake angle
- depth/width ratio

Rake angle is the angle between the implement's plane and the horizontal plane in the direction of travel. Horizontal and vertical forces acting on the implement increase with rake angle (*Figure 4*). These forces are considered for a simple tillage tool by Godwin, 2007 as follows:

- horizontal (draught) force is required to pull or push the implement through the soil

- vertical force is acting on the tool in a manner to assist or prevent penetration into the soil

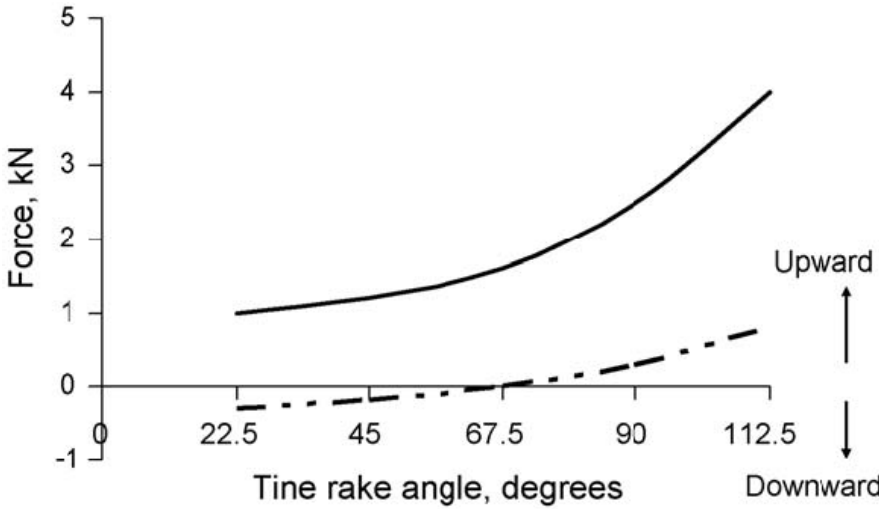
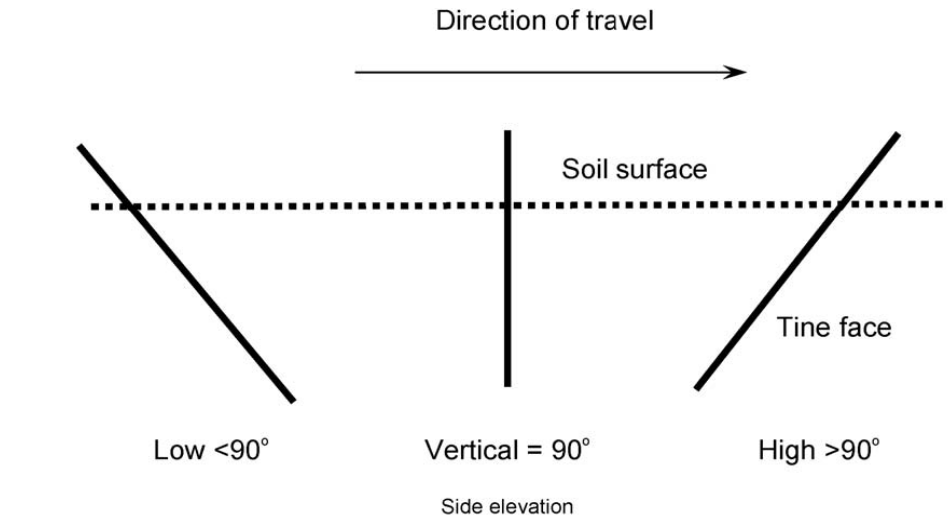


Figure 4. Effect of tine rake angle on draught (solid) and vertical (broken) forces (Godwin and Spoor, 1977)

The magnitude of the specific resistance is more significant than keeping the draught force small, because it represents soil disturbed area per unit of force (draught force/ soil disturbance; kN/m^2). For soil loosening operation the rake angle of the tool must be smaller than approximately 67.5º to assist penetration. For a compacting operation implement weight may be needed to counterbalance upward vertical forces. A list of operations and basic implements with optional rake angles is shown in *Figure 5*.



Operation:

Loosening	Sorting	Compacting
Cutting	Consolidating	Disintegrating
Inverting	Re-arranging	
Smoothing	Disintegration (some)	

Implements:

Chisel tines	Harrows	-	drag	Rollers
Plough shares		-	power	Scrubber boards
Bulldozer blades				Wheels

Figure 5. Tine rake angles for soil operations and basic implements (Godwin 2007)

The depth/ width ratio affects the pattern of soil failure. If it is greater than 6, the soil below the critical depth is fails laterally and the soil close to the surface fails in a crescent form. Results from Godwin and Spoor, 1977 illustrate a significant increase of the magnitude of the horizontal force with an increase in working depth. (*Figure 6*). The horizontal force was found to increase according to a square law with speed, by Wheeler and Godwin, 1996.

Work by Spoor and Godwin, 1978 and Godwin, 1984 show how the soil disturbance pattern is dependant upon the spacing of a pair of the tines operating at the same depth. Tine spacing affects draught force, disturbed area and specific resistance and recommended spacings are:

- 1.5x depth of work for single tines

- 2.0x depth of work for winged tines

Shallow tines operating ahead of winged tines reduce specific resistance and allow wider spacing (2.5x depth of work) of winged tines. For a relatively small increase in draught force leading tines work the soil in the zone of the deep tine and create additional disturbance.

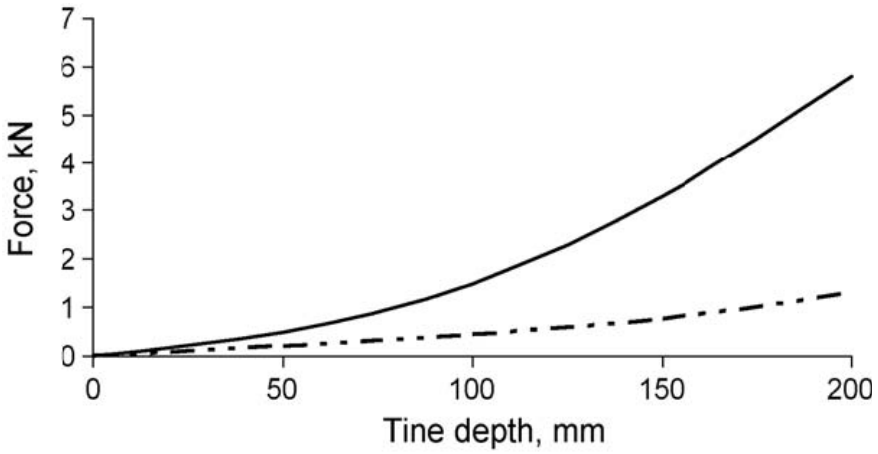


Figure 6. The effect of tine depth on the horizontal (solid) and vertical (broken) forces acting on a 90º rake angle tine (Godwin, 2007)

Research carried out on mouldboard ploughs includes the effect of the working depth and ploughing speed on the acting forces. Recently, the experimental results of Hakansson, 1998 led to a recommendation, that on clay and clay loam soils ploughing deeper than 20- 25 cm is not advantageous due to the high energy requirements, unless the weed situation is very serious. On sandy soils, where ploughing resistance is low, deep ploughing is less expensive than on heavier soils and may reduce the need for other treatments to control perennial weeds.

The conclusions from the research carried out by Saunders, 2002 were that depth had the greatest effect on draught force and speed had a lesser effect on the force. The major considerations from this are not to work deeper than necessary and to work at higher forward speed to increase work rate and achieve better machinery exploitation.

Complementary studies to Saunder's work were conducted by Balafoutis, 2003. In a series of experiments at a wider range of speeds it was confirmed that depth has the largest effect on draught force and most influences the final cost of ploughing.

Agricultural discs are widely incorporated in a range of tillage implements. Disc ploughs used for primary tillage have discs inclined rearwards for additional penetration, while disc harrows have the face of the discs positioned in the vertical plane (a tilt angle equal to zero). The angle of attachment of the disc to the direction of travel is called the disc or sweep angle and affects the forces acting on a disc. Godwin et al., 1987 examined the performance of a disc for different configurations of the disc angles. The forces acting on the disc arose from a passive reaction on the concave face and a scrubbing reaction on the convex face. Both the disc geometry and the disc angle influenced the magnitude of the reactions. It was observed that minimum draught force occurred in the range 20 - 30º for the disc angle and vertical force increased rapidly as the disc angle decreased below the clearance angle (angle between the plane of the disc face and the disc edge). The lowest specific resistance in the experiment occurred at approximately 25º of the disc angle.

Research carried out by O'Dogherty et al., 1996 showed the effect of overlap area when discs were working in a gang. It resulted in the reduction of the cut area at an increasing rate as disc spacing was reduced. The overlap of the soil cut area occurred over the practical ranges of disc angles and spacing. The area of uncut soil was between 7% and 20% of the nominal cut area of adjacent discs in a gang.

2.4 Tillage economics

Machinery costs are one of the key components distinguishing tillage systems. Those techniques which are less energy and time demanding can be advantageous to the farmers. More advanced, more efficient and thereby more expensive machines are being developed, but the yield targets also continue to increase. This, and other factors in today's agriculture, as higher prices for parts and energy together with decreasing product prices put more pressure on machine management to adopt smart policy of

owning and using farm machinery. It is, therefore, important to fully exploit expensive high-output machinery as well as to monitor their costs to improve their performance.

Machinery and equipment represent a substantial input in crop production and can make up 40% of the cost of the production of winter wheat (Markham, 1998). There is also a large amount of capital invested in machinery.
The main factors affecting machinery costs are:

- annual cropped area
- local soil conditions (heavy or light) and local climate (number of days available between harvest and drilling)
- tractor availability (average size and age of the tractors, contractor use)
- labour availability

To assure high efficiency, the full potential of each machine needs to be exploited. On smaller farms, which are usually over-mechanised, because the utilisation of the machines is low, the use of a contractor is a cost-effective option. A contracting service can reduce the number of operations and machines. Medium-sized farms can use contractors for a particular operation. In peak periods, short-term hire may also be attractive. On large farms mechanisation strategy needs to be carefully selected to allow optimizing of costs and minimizing labour and machine requirements (Forristal, 1995).

There are several options when a tractor or tillage implement is needed:

- purchase a new machine
- purchase a second-hand machine
- use a contractor
- short term hire
- joint purchase
- machinery ring

If we look at total costs for different tillage systems, the traditional system is the most expensive, because, simply, it moves more soil than the others. The less the soil is cultivated, the less expensive is the tillage system, even if the costs of pesticides are approaching those of a no-tillage system. (*Figures 7, 8*).

Possible savings depend on how much cultivation and, therefore, machinery use can be reduced. It is evident that every extra pass on the field means additional costs. Nix, 1987 suggested the following areas of possible savings on machinery costs:

- have less capacity- with the same labour, tractors, etc. increase the tillage area or with less labour, tractors and machinery to farm the same area
- later replacement- keeping machinery longer
- more careful maintenance- reduce repairs and prolong productive life cycle of machinery
- more careful consideration of whether to have your own machine or use the contractors

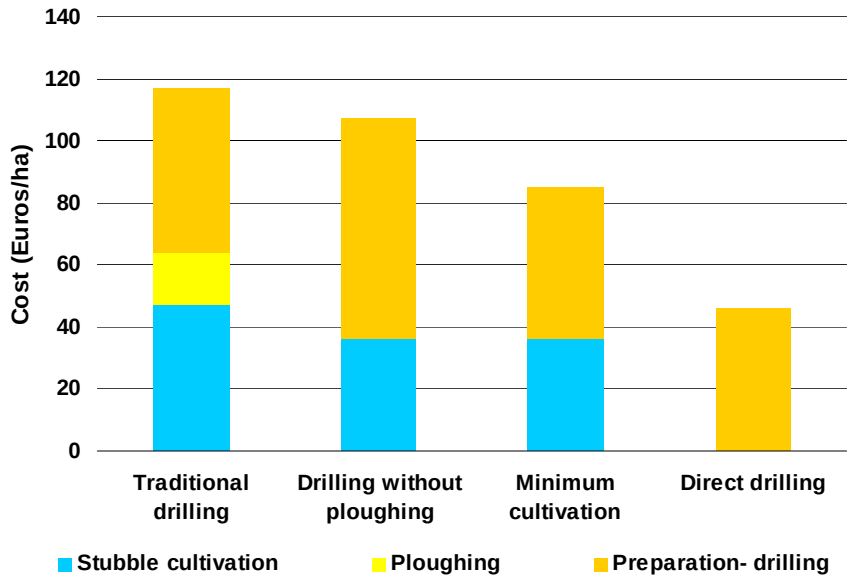


Figure 7. Comparison of machinery costs depending on the drilling technique used (Kuhn, 2007)

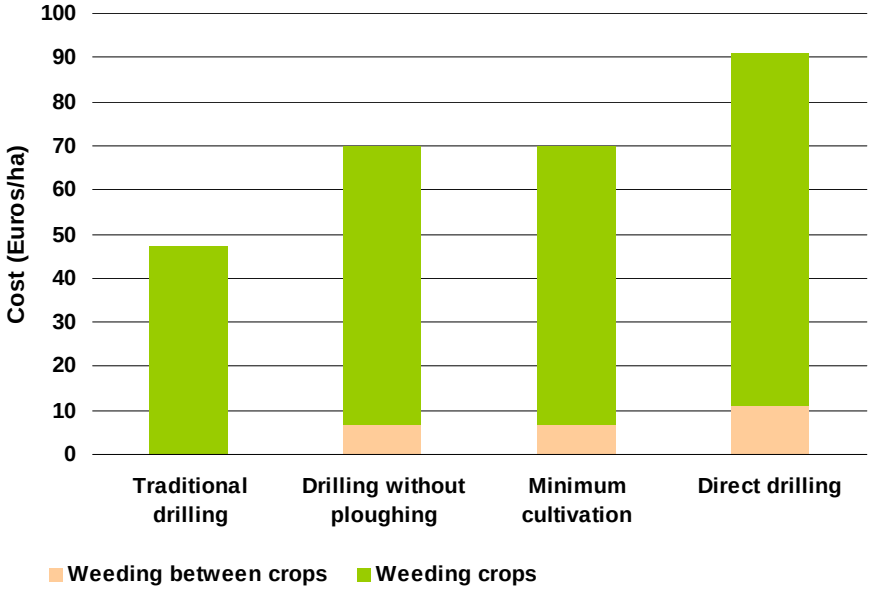


Figure 8. Comparison of weeding costs depending on drilling technique used (Kuhn, 2007)

System cost comparison made by Saunders, 2002 showed, that for areas less than 125 ha and with a 50 day working window, the standard plough is cheaper than discs and direct drilling. However, discs and direct drilling have the highest output and become cheaper for large areas, because the work rate of a direct drill is approximately 3 times higher than a standard plough. Increasing working width and speed of operation of mouldboard ploughs is mentioned as a way to reduce the cost of plough based systems.

2.5 Summary

In summary, tillage systems affect not only crop cultivation itself, but also many other parameters such as soil quality and soil organic matter in the long term, and weed and pests occurrence. In terms of energy and costs, all the research agrees that energy requirements increase significantly with working depth and that the costs of tillage are dependent on the area and number of passes worked. Therefore, a reduction in working depth and the number of tillage operations can be a way of reducing the draught force required by an implement. The research also shows that successful conversion to a system of reduced tillage depends on the demands on the availability of certain types of implements as well as on other factors, such as soil type, weather and type of crop.

Various comparisons of tillage systems are needed to determine optimal tillage implements for different farm sizes.

3 Field experiment

The results from the field and soil bin (chapter 4) experiments have been published in a paper presented at XXXII CIOSTA – CIGR Section V Conference 2007, which is attached as Appendix 1. The experimental work in the field and soil bin was jointly conducted with Bosrotsi, 2007.

3.1 Introduction

Tillage is regarded as a vital component of soil management and has great influence on crop production systems. The aim of tillage is to create the optimum environment for growing crops from seed germination to root growth, fertilizers and pesticides incorporation and to enable soil and water management practices to take place. An individual farmer chooses an implement for any of the tasks from wide range of different configurations on today's market. The soil cultivation system practiced and tillage implements used depend on local customs, soil and crop types, the weed and pests situation and the amount of plant residue from the previous crop.

A tillage tool is defined as an individual soil-engaging component, such as a plough body or single tine. A basic tillage implement consists of a single tool or group of tools, together with the associated frame, wheels, hitch, protection devices, and any power transmission components. For tillage implements, the tillage tools constitute the main process system, while the other components form the support system.

A variety of implements can be used to create a fine tilth. The major types of cultivation implements consist of mouldboard and disc ploughs, various kinds of harrows and the combinations of tines and discs. Mouldboard ploughs are widely used for land preparation all over the world because of their ability to create a fine seedbed and to bury trash and weeds. Disc ploughs are easy to use and have great versatility in land preparations. Tines are suitable for shallow or deep cultivation in both arid and semi-arid regions. The combinations of tines and discs in different configurations are used in minimum tillage systems.

The field experiment described below was conducted to aid a comprehensive understanding of the performance of alternative tillage implements in real conditions, considering their crucial role in the area of soil preparation. A range of popular implements, which represent the major types used in agriculture across Europe, was examined to determine their energy requirements. Further measurements were recorded in controlled laboratory conditions in order to eliminate the effect of variations in soil properties.

3.2 Procedure

The field experiment was conducted on the demonstration field of Cranfield University at Silsoe. The soil was Cottenham series, sandy loam type (King, 1969) with physical properties similar to the parameters of the soil used for the laboratory experiment (see *Table 10*). The measured soil moisture content was 13.62% and the mean cone penetration resistance (30º cone with 12 mm base diameter) was 0.85 MPa. The field site had been tilled and then set-aside.

The tractors used in the execution of the experiment were an MF 6180 (85.8 kW) and an MF 390 (56.4 kW) 4WD. The tillage implements involved were:

- A 4-furrow reversible Dowdeswell DP 10 mouldboard plough with a furrow width of 381 mm operating at depths of 200 mm (*mouldboard plough deep*) and 150 mm (*mouldboard plough shallow*).
- A 3-furrow Parmiter DPM Series disc plough (*disc plough*) with a furrow width of 305 mm, disc diameter 660 mm, disc angle 49º and tilt angle 22º.
- 7 Cousins winged tines, CM series, cultivator consisting of 235 mm wide full sweep bottoms, a rake angle of 25º, two tine spacings of 224 mm (*close tines*) and 336 mm (*wide tines*).
- Tandem abreast MF 280 disc harrow (*disc harrow*) comprised of a four gangs assembly. The front gangs are made up of 12 scalloped discs each of 508 mm diameter with a disc spacing of 235 mm and a gang angle 23º. The rear gangs consisted of 14 plain discs (of the same diameter as the front discs) with a disc spacing of 187 mm and a gang angle of 18º.

The total width, working depth and speed of the implements are summarized in *Table 4*.

Both mouldboard and disc ploughs were working at a depth of 200 mm, as it was considered as a standard ploughing depth used in agriculture. To determine, how depth affects draught force, shallow ploughing was included in the experiment. A depth of 150 mm was chosen representing the minimum depth, at which a standard mouldboard body could work, as found in previous studies. Winged tines and a disc harrow were considered as the implements for secondary or shallow primary cultivation; hence the depth of 100 mm was chosen. The measured depth of the disc harrow varied about a value of 60 mm, and extra weight ballast would be needed for additional penetration. It is necessary to note that the actual depth of all implements differed from the desired value due to the uneven surface of the field. The speed of work was maintained at 5 km/h for all implements.

Table 4. Width, working depth and speed of the implements in the field experiment.

Tractor type	Implement type	Width of the implement (mm)	Working depth (mm)	Speed of work (km/h)
MF 6180	Mouldboard plough deep	1524	200	5
MF 6180	Mouldboard plough shallow	1524	150	5
MF 390	Disc plough	914	200	5
MF 390	Disc harrow	2700	60	5
MF 390	Wide tines	2251	100	5
MF 390	Close tines	1579	100	5

To achieve a reasonable quality of work the setting and adjustment of all implements was done on adjacent plot. The preliminary measurements were carried out to investigate the rolling resistance of the two tractors. The rolling resistance is defined as the pull required to move a wheel across a horizontal surface. The rolling resistance of a wheel with a pneumatic tyre consists of two main components. The internal component is caused by loss of energy, which results from the continuous flexing of the tyre carcass as the wheel rotates in contact with the ground. The external component is equal to the energy which the wheel is expending in order to deform the soil surface (Crossley and Kilgour, 1983).

3.2.1 Wheel slip

Wheel slip may be seen as an indicator of the efficiency of conversion of potential forward movement of the tractor into actual forward movement. Slip is defined as the lost travel distance in relation to the theoretical travel distance (Crossley and Kilgour, 1983). Generally a driven wheel must always experience some wheel slip, which enables to propel itself forward. Excessive wheel slippage is a major problem, especially when ploughing with one wheel in the furrow. The furrow wheel usually gets enough traction, as a result of tractor tilt during ploughing, which exerts more weight on it. The land wheel may spin on trash, green plants or loose soil. Wheel slip of more than 15% should be reduced, because it causes unnecessary tyre wear and waste of time and fuel. The most common method of improving traction is to add weight (ballast) to the tractor front and to the drive wheels (Deere & Company, 1976). The tyre pressure is often reduced for field work in order to put a greater area of the tyre casing in contact with the soil surface. A greater area and number of the tyre tread bars helps to improve traction, but very low pressure can lead to damage of the tyre. The tyre pressures maintained during the field experiment are given in *Table 5*.

Table 5. Tyre pressures maintained during the field experiment

Tractor Type	Front wheel size	Rear wheel size	Wheel pressure front (kN/m^2)	Wheel pressure rear (kN/m^2)
MF 390	12.4/11-24 (cross ply)	18.4/11-30 (cross ply)	96.526	113.421
MF 6180	380/70 R28	480/70 R38	110.316	124.104

The procedure below was followed in order to determine the wheel slip of the tractor under load with alternative tillage implements:

- The 4WD was disengaged to enable the front and rear wheels to rotate independently.
- The sidewall of the tyre was marked.
- The ranging pole was erected on the spot where the mark on the tyre met the ground.
- The tractor was driven under load with the implement in a straight line.

- 10 complete rotations of the tyre were counted and another ranging pole was erected on the spot, where the mark on the tyre met the ground.
- The distance between the ranging poles was measured by measuring wheel.

To investigate the theoretical distance, both tractors were driven without an implement. The procedure was repeated at least three times with all the implements used in the field experiment.

3.2.2 Work rate

Work rate is used to assess an agricultural machine or implement. It determines the upper limit of the implement performance and is usually expressed as a rate over available time in a season or year. Witney, 1988 describes the overall rate of work as a performance of a machine over the complete operational cycle (productive work time plus routine interruptions for turning and product handling). The seasonal rate of work then includes major breakdowns, mealtimes, travelling from field to field and any other delays, which prevent the implement from working, while weather and soil conditions would be suitable.

Work rate, which was measured during the field experiment, accounted for the performance of the implement in productive work and turning. The following times were measured for conventional and reversible ploughs:

- Time, when the implement was working the soil over a distance of approximately 70 metres.
- Turning time, when the implement was raised from the soil until the moment when it was ready for next pass.

Work rate was calculated for different widths of ploughs over the range of areas. Working, turning time and time allowing to process a headland, an area providing room for turns, were included in the calculations.

3.2.3 Draught force

To determine the energy requirements, the gross draught force of each implement was measured. The distance of each test was approximately 70 metres. The field experiment was completely randomized with two replications. To ensure proper working conditions for both mouldboard and disc ploughs, an open furrow was created, into which the soil slice was turned. This requirement influenced the layout of the experiment (*Figure 9*).

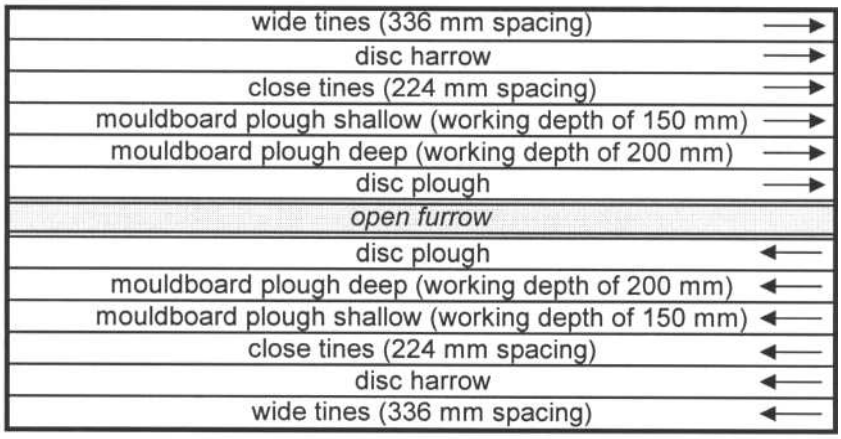


Figure 9. Layout of the field experiment

The tractor with the selected implement was drawn in two runs to determine the implement's gross draught force in both descending and ascending field applications. A 5 ton digital tension meter was located between the towing cables connecting the two tractors to display the actual draught force (*Figure 10*). This solution of using two tractors was chosen, because the tension meter could not be directly attached between a tractor and the implements. The net draught forces of the implements were calculated by subtracting the rolling resistance from the measured values of the draught force. The disturbed soil of the cross-sectional area of a single pass of the implement was excavated and a profile meter was used to measure the area of disturbance remaining. To indicate overall tillage efficiency, specific resistance was calculated. A statistical analysis was carried out on the force measurements including an analysis of variance and the least significant difference test at a 5% probability level.

Figure 10. Location of the digital tension meter between the tractors and detail of the digital tension meter

3.3 Results

The mean wheel slips of the tractors driven with all tested implements are presented in *Table 6*. The only excessive slippage was experienced during the preliminary measurements, when the implements were being set and adjusted with the tractors. A wheel slip of 35% measured for the tractor engaged with disc harrow was caused by negative weight transfer (see Appendix 2). Due to unsuitable engagement of the implement and the three-point linkage, the rear wheels of the tractor had not enough traction.

Table 6. Wheel slip of the tractors during the field experiment

Tractor type	Implement type	Wheel slip
MF 6180	Mouldboard plough deep	8%
MF 6180	Mouldboard plough shallow	5%
MF 390	Disc plough	12%
MF 390	Disc harrow	7%
MF 390	Wide tines	6%
MF 390	Close tines	7%

The work rates of three widths of plough are plotted in *Figure 11*. Work rates are based on the measured times for productive work, turning and processing a headland in the field experiment. A ten hour limit of work was considered, as other delays would need to be included in calculations, if an implement performance was observed over a longer period of time. After a rapid rise of work rate with area up to 3 ha, there was a much lower rate of increase which was the same for all plough widths. It illustrates the benefit of large fields on the tillage efficiency.

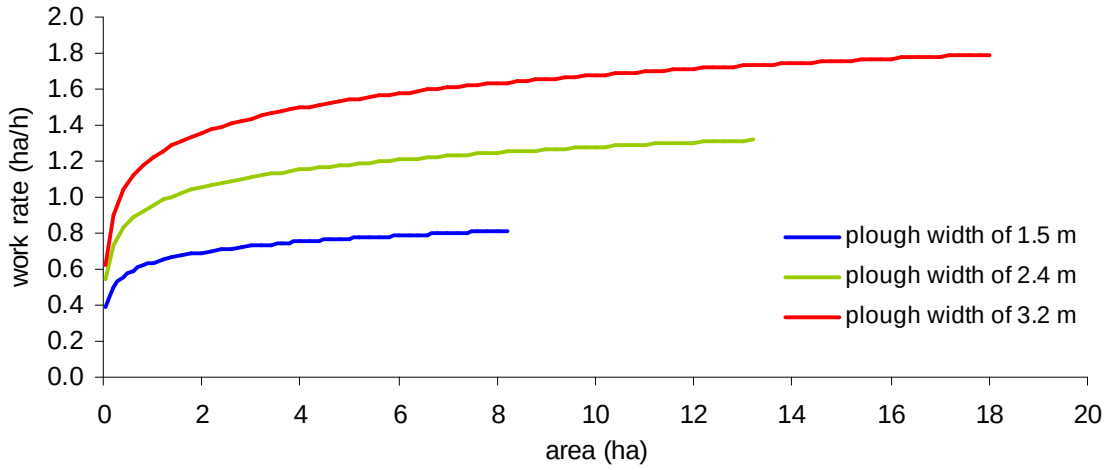


Figure 11. Work rates for different widths of plough

The draught forces of each implement measured in the field experiment are plotted in *Figure 12*. The draught force of the mouldboard plough is significantly higher than the draught force of the disc plough working at same depth. A reduced draught force of close tines can be seen in comparison to that of wide tines. The draught force per unit implement was calculated by dividing the draught force by the number of discs, tines or plough bodies. This enables to determine the draught force for different number of implement bodies, but it is not valid for comparison between different implements. *Figure 12* (down) shows the values obtained for the draught force per unit implement device.

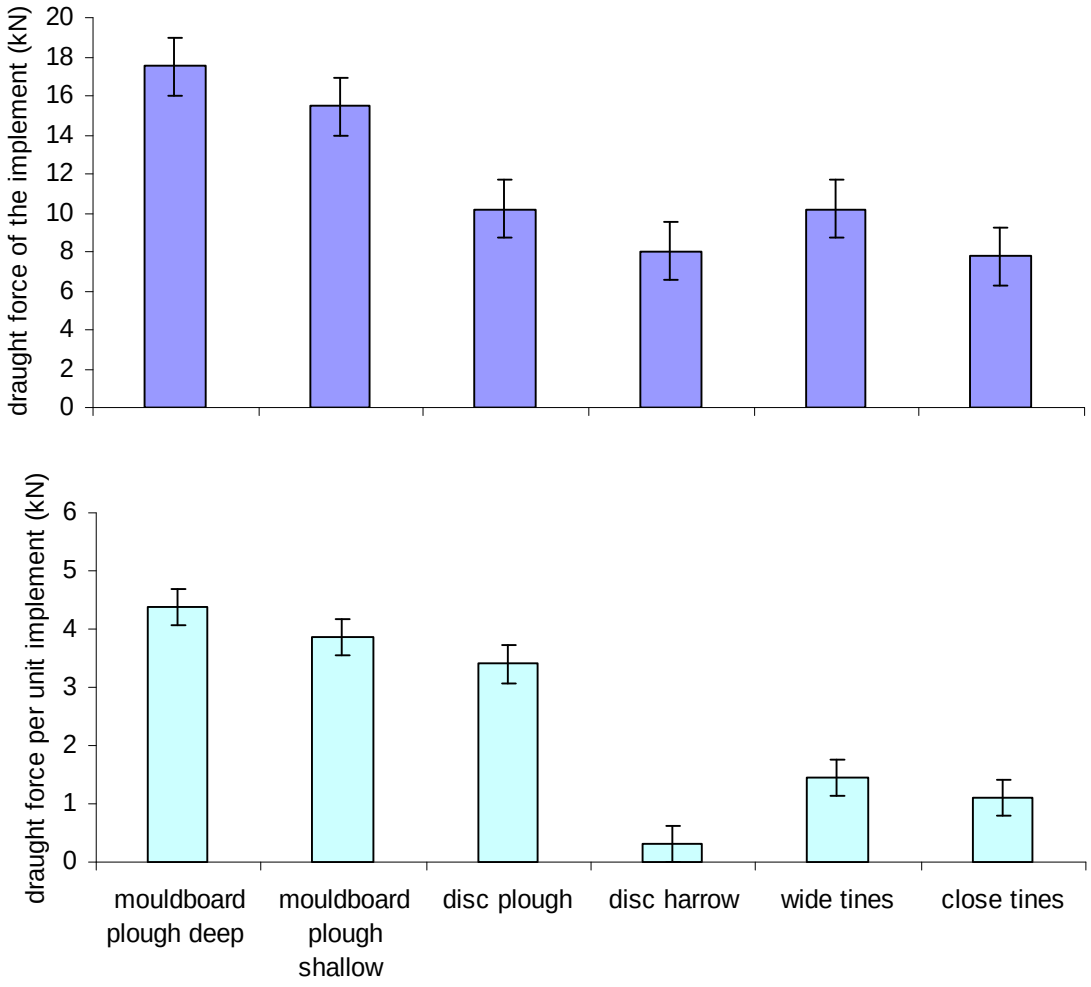


Figure 12. Draught force of the implement and draught force per unit implement of the field experiment (error bars indicate a confidence interval at 95% probability level)

The area of disturbance for the implements is shown in *Figure 13*. The area of disturbed soil decreases from that for the mouldboard plough deep to the tines. There is a slight difference in disturbed soil between close and wide tines and the difference in the soil

disturbance patterns is clear, demonstrating the effect of tine spacing (*Figure 14*). The soil profile of close tines shows evenly disturbed soil, while that of wide tines discloses a large amount of undisturbed soil between tines.

The specific resistance (the draught force requirement per unit area of disturbance) is presented in *Figure 13*. The specific resistance of all implements is broadly similar with a mean of 58.2 kN/m^2 and a range of +9/-6 kN/m^2, although the mouldboard and disc ploughs were working twice as deep as the tine implements and more than three times deeper than the disc harrow. Comparing the specific resistance of the mouldboard plough deep and the disc plough, the difference was only 1.6 kN/m^2, while the highest value among the implements studied occurred with the mouldboard plough shallow. The effect of tine spacing was demonstrated in the result that close tines gave a 20% reduction in specific resistance and a 26% reduction in draught force with a similar area of disturbance as for wide tines.

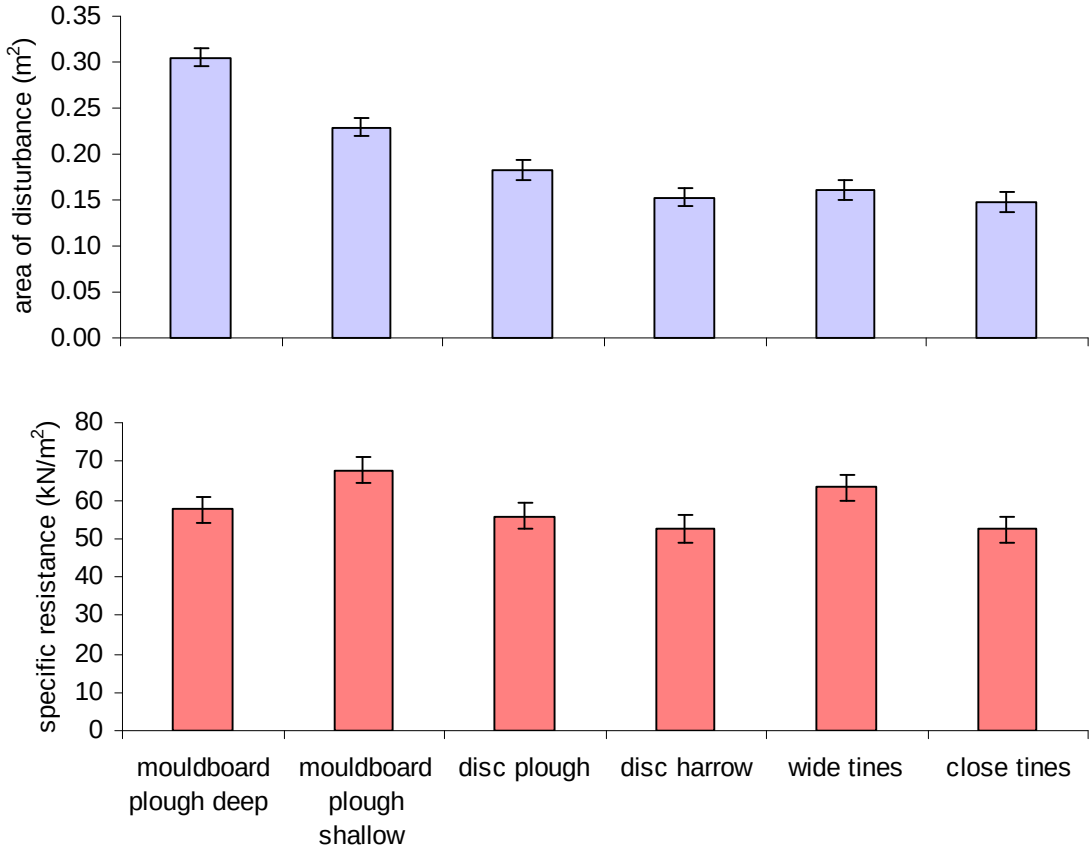


Figure 13. Area of disturbance and specific resistance of the implements in the field experiment (error bars indicate a confidence interval at 95% probability level)

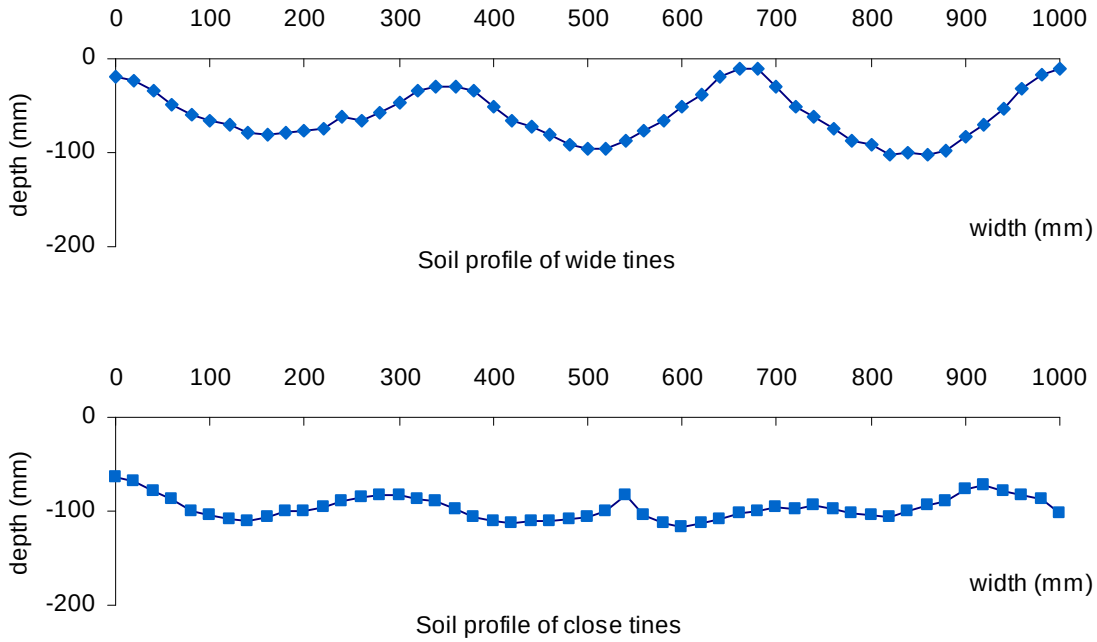


Figure 14. Soil profiles of the wide and close tines

A higher tillage efficiency is achieved when a tractor is fully exploited by an implement. To determine the optimum number of furrows of the mouldboard plough, the width of disc harrow and tine implement, two limits of the tractor must be considered. Firstly, the drawbar pull, which is dependant on the weight of the tractor, amount of slip expected and the type of soil on which the tractor is working. The second limitation is the useful drawbar power, which can be seen as a power of the engine reduced by losses in transmission, slip and rolling resistance. To determine the limit of the drawbar power and pull of the tractor reasonable assumptions have to be made. According to the work of Saunders, 2002, the limit of drawbar power can be assumed to be approximately 60% of the Power Take-Off (PTO) of the tractor working in conditions close to that in which the field experiment was conducted. The percentage of usable drawbar power is dependent on soil conditions. To calculate the maximum drawbar pull of the tractor, a Drawbar (DB) Pull/ Static Rear Axle Force (SRAF) ratio must be assumed. Saunders, 2002 used the tractor drawbar performance predictor, part of which can be seen in *Figure 15*, to determine the DB Pull/ SRAF ratio. The graph shows DB Pull/ SRAF plotted against the percentage wheel slip and the data are distinguished for three different soil categories, which are firm, tilled and soft or sandy soil. Saunders, 2002 came with two different values representing a range of operating

conditions giving a DB Pull/ SRAF of 0.52 and 0.72. These illustrate the situations where a tractor s working at 10% slip on firm soil and at 27% slip on tilled soil. The mean of two values gives the DB Pull/ SRAF ratio of 0.62 for a tractor working over a range of conditions. The formula for calculating the DB Pull than would be:

$$DB\ Pull = SRAF * 0.62$$

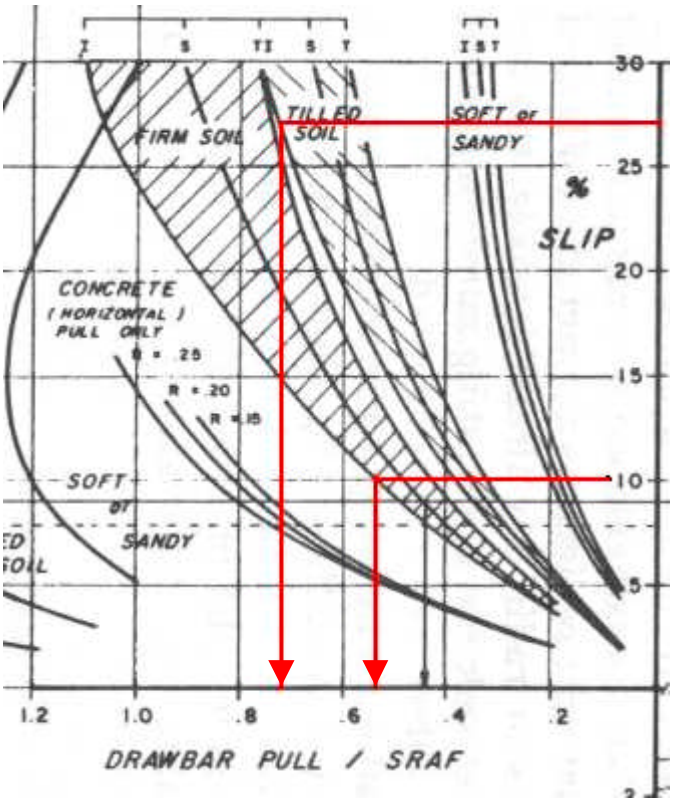


Figure 15. Tractor drawbar performance predictor (red lines indicate a range of operating conditions, for which a DB Pull/ SRAF ratio was calculated; Goering, 1992)

The standard production tractors, MF 6180 (85.8 kW) and MF 390 (56.4 kW), used for executing the field experiment, were chosen as an example to see the possible tillage implements configurations. As described earlier, two limiting factors, drawbar pull and drawbar power, of the tractors must be calculated to determine the range of implements. The MF 6180 and MF 390 have a maximum PTO power of 73.8 kW and 48.8 kW respectively (*Table 3*). The limit of drawbar power is than 44.3 kW and 29.3 kW for MF 6180 and MF 390, respectively. Static mass at the rear axle of 3634 kg for MF 6180 and

2480 kg for MF 390 can be related to SRAF of 35.7 kN for MF 6180 and 24.3 kN for MF 390. Using the formula above, the useful drawbar pull for MF 6180 is 22.1 kN and for MF 390 is 15.1 kN. The drawbar power and drawbar pull limits of the tractors enable the determination of the possible combinations of mouldboard and disc ploughs, disc harrow and tine implements over which the tractors are capable of operating.

Table 7. Characteristics of the tractors

	MF 6180	**MF 390**
Engine power (kW)	85.8	56.4
Maximum PTO power (kW)	73.8	48.8
Total static weight (kg)	4845	3307
Rear static weight (kg)	3634	2480

To predict the force requirements of alternative tillage implements, draught forces of the implements measured in the field experiment were taken into account. The maximum width of the implements, which the tractors are capable to operate, was calculated. The maximum width of the implement was limited by the maximum width in which the particular implement is available from the manufacture. Wider implements may have a different performance on the field due to necessary changes in their design (for example a disc harrow of over 3.7 m of width has a folding mechanism and is designed as a trailed implement). The working speed was considered as 5 km/h, the same as that maintained during the field experiment. Possible combinations of the implements and tractors used in the field experiment are shown in *Table 8*. These combinations are estimated in order to increase work rates.

Adding an extra furrow to the mouldboard plough increased the work rate by 26%. There is a power reserve when the mouldboard plough is working shallower. The low draught of the disc plough allowed an increase in its width by 100%, significantly increasing the work rate. According to the calculations, the MF 390 tractor would be capable of operating the wider disc harrow, but the limiting factor is the maximum width of the implement available in a mounted rigid version. The tine implements proposed increase the work rate by 49% and 92% for a wide tine spacing version and a close tine spacing version respectively.

Table 8. Possible tractor and implement combinations based on the field experiment

Tractor MF 6180	Field experiment			Calculated configuration		
	Measured draught force per unit implement (kN)	Number of furrows	Width of the implement (m)	Theoretical number of furrows *)	Theoretical width of the implement *) (m)	Increase of work rate (%)
Mouldboard plough (depth 200 mm)	4.38	4	1.52	5	1.91	27%
Mouldboard plough (depth 150 mm)	3.87	4	1.52	5	1.91	27%
Disc plough (depth 200 mm)	3.40	3	0.91	6	1.83	104%
Tractor MF 390	Measured draught force per unit width (kN/m)	Width of the implement (m)			Theoretical width of the implement *) (m)	Increase of work rate (%)
Disc harrow	2.98	2.70			3.7	39%
Wide tines	4.53	2.25			3.3	49%
Close tines	4.91	1.58			3.0	92%

*) Maximum width and number of furrow of the implement fully exploiting drawbar pull and drawbar power of particular tractor limited by the maximum width available for the implement in configuration used in the field experiment

3.4 Summary

A similar specific resistance of all implements studied during the field experiment was observed. The mean value was 58.2 kN/m^2 with a range of 15 kN/m^2. The mouldboard and disc ploughs showed similar values of specific resistance albeit the disc plough disturbed less soil. Relatively small differences in specific resistance of the implements demonstrate similar efficiencies in the field conditions. The specific resistance is affected by working depth and implement configuration.

The performance of tined implements showed the relationship between tine spacing and draught force, area of disturbance and specific resistance. The close tines with a tine spacing of 225 mm gave a 20% reduction in specific resistance, a 26% reduction in draught force and a similar area of disturbance compared with wide tines at a spacing of 335 mm.

The draught forces of the implements measured in the field experiment enabled the calculation of the maximum width of implements, which 56 kW and 86 kW tractors are capable of operating. Fully exploiting the available power of the tractors showed a significant increase in work rates. Adding an extra furrow to the mouldboard plough increased the work rate by 27%.

4 Soil bin experiment

4.1 Introduction

Following the field experiment, soil bin studies were executed to evaluate alternative tillage implements in controlled laboratory conditions. The geometrical parameters of the implements used in the soil bin were the same or similar to those of the implements in the field experiment. Similarity of the implements was necessary to enable additional evaluation and overall comparison. The soil bin experiment was carried out to determine draught force, area of disturbance and specific resistance of the selected implements.

4.2 Procedure

The experiments were undertaken in the Cranfiled University soil bin. The indoor bin consists of a rectangular sub-surface tank with a multi-purpose processor, which enables the creation of uniformly compacted soil conditions. The processor has the ability to excavate and spread the soil along the whole length of the bin and to roll it to ensure uniformity between replications. The soil is prepared in 50 mm layers, which are compacted by two passes of a roll. To monitor the soil conditions moisture content and soil bulk density were recorded for each soil bin fit in three replications (*Table 9*). All moisture content and bulk density results are given in Appendix 3. A core sampling method was chosen to obtain soil bulk density. A soil density ring of known volume was pressed into the soil. A full ring of soil was excavated and the soil carefully removed and weighed. The soil was then placed in an oven for 48 hours and weighed again. Soil bulk density was calculated using the values of wet and dry soil weight and the volume of the ring.

Table 9. Moisture content and bulk density during the soil bin experiment

	Moisture content (%)	Bulk density (kN/m^3)
Minimum	4.97	15.03
Maximum	7.32	18.67
Mean	6.37	16.48

The uniformity and strength of the soil was measured prior to each test using a cone penetrometer (30º cone with a 12 mm base diameter). The penetration resistance was recorded in three replications along the bin, each containing ten measurements across the bin. The mean penetration resistance was 1.88 MPa. The soil used for the experiment was sandy loam with typical properties illustrated in *Table 10*.

Table 10. Soil properties in the soil bin

Cohesion (kN/m^2)	11
Angle of shearing resistance (deg)	30
Soil-metal friction (deg)	20
Adhesion (kN/m^2)	0

The experiment was completely randomized with three replications and involved the following implements:

- A single furrow mouldboard plough (*mouldboard plough*) with a furrow width of 305 mm and a depth of 150 mm.
- A disc implement with a diameter of 607 mm in two settings maintained for the experiment: a disc angle of 46º, tilt angle of 21º, depth 150 mm and a width of furrow of 300 mm representing a disc plough (*disc plough*) and a disc angle of 22º, depth of 75 mm and a width of furrow of 260 mm representing a disc harrow (*disc harrow*).
- Winged tines made up of four different wing widths: 220 mm (*220 tine*), 170 mm (*170 tine*), 120 mm (*120 tine*) and a plain tine with no wing attached (*plaintine*). The four versions of the tined implement had a rake angle of 45º, a width of tine of 25 mm and were operated at a depth 150 mm.

The speed was set at 1.5 m/s (5.4 km/h) for all implements to correspond with the speed maintained during the field experiment.

The sequence of the implements examined in the experiment is given in *Table 11*. For the four versions of tine implement, the wings of the 170 tine were mounted on to a different tine to the others. The two tines were similar but not identical geometry. Wings mounted on the second tine were gradually adjusted from 220 mm to 120 mm and to a no wings version. Due to the furrow width of mouldboard plough, it was possible to do only one run per soil bin fit. To simulate the previous furrow, an open

furrow was created for the mouldboard as well as for the disc implements. This pre-cut was executed prior to the run and no data was recorded.

Table 11. Test procedure of the soil bin experiment

Soil bin fit number	Position of the implement in the soil bin			
1			170 tine	
2	220 tine		220 tine	
3	170 tine	170 tine		
4		220 tine		
5	120 tine	120 tine	120 tine	
6	plaintine	plaintine	plaintine	
7		mouldboard plough	*open furrow*	
8		mouldboard plough	*open furrow*	
9		mouldboard plough	*open furrow*	
10	disc plough	disc plough	*open furrow*	
11		disc plough	*open furrow*	
12	disc harrow	disc harrow	disc harrow	*open furrow*

A two dimensional Extended Octagonal Ring Transducer (EORT), as described by Godwin, 1975, was mounted between the implement and the processor. The EORT consists of a machined aluminium block, to which strain gauge bridges are attached in order to monitor horizontal and vertical forces and the resulting moment. The strain gauge bridges output voltages were directed to a data acquisition box to transfer it to a d.c. signal at a frequency of 100 Hz. A laptop computer connected to the data acquisition box was used for downloading the signals, which were processed in the software program DasyLab for further analysis (*Figure 16*). The EORT was calibrated for all three measurements (horizontal force, vertical force and moment) before the experiment. Calibration was conducted using known static loads and then recording the output voltage. The relationship between the voltage and the force was determined by plotting the measured values, as shown in Appendix 4.

A profile meter was used to measure the area of disturbance of a single pass of each implement, as illustrated in *Figure 17*. Specific resistance was calculated to compare the overall efficiency of the implements. Data from the experiment was statistically

analysed by analysis of variance and least significant differences calculated at the 5% probability level.

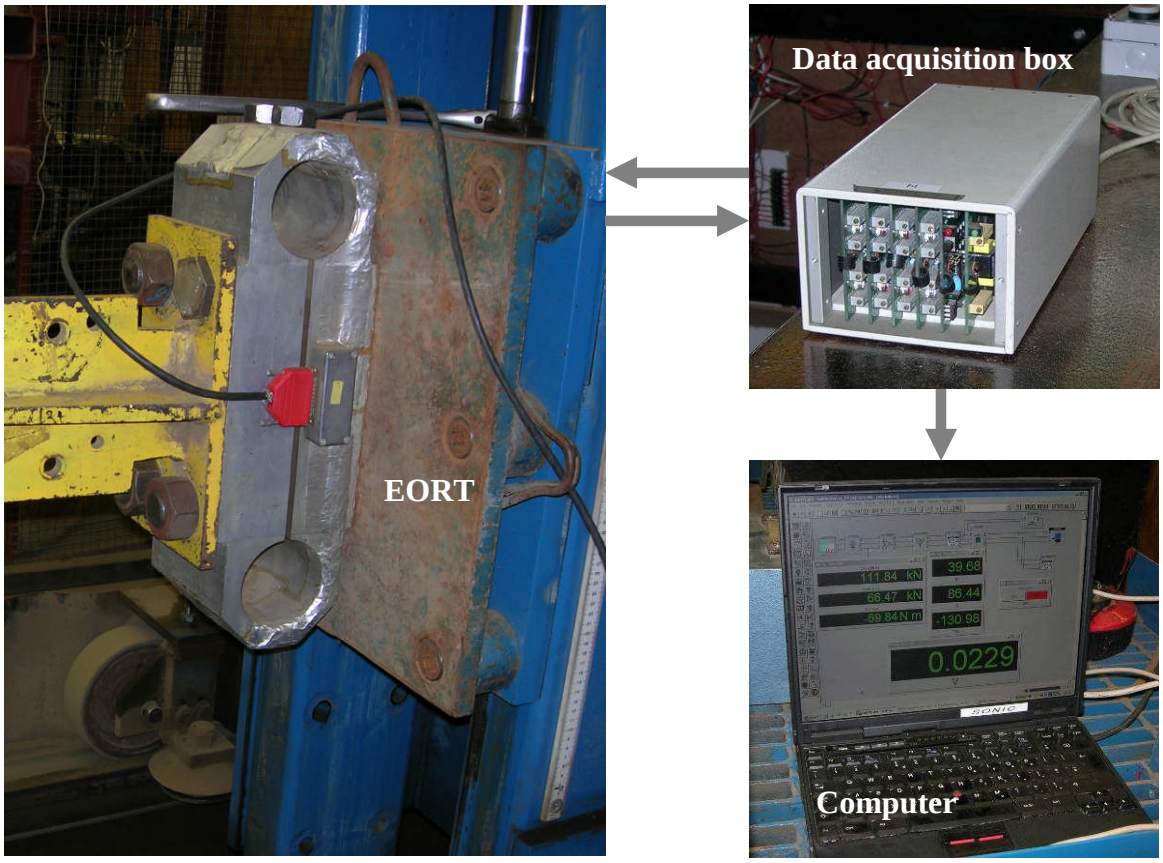


Figure 16. Configuration of force measuring devices in the soil bin

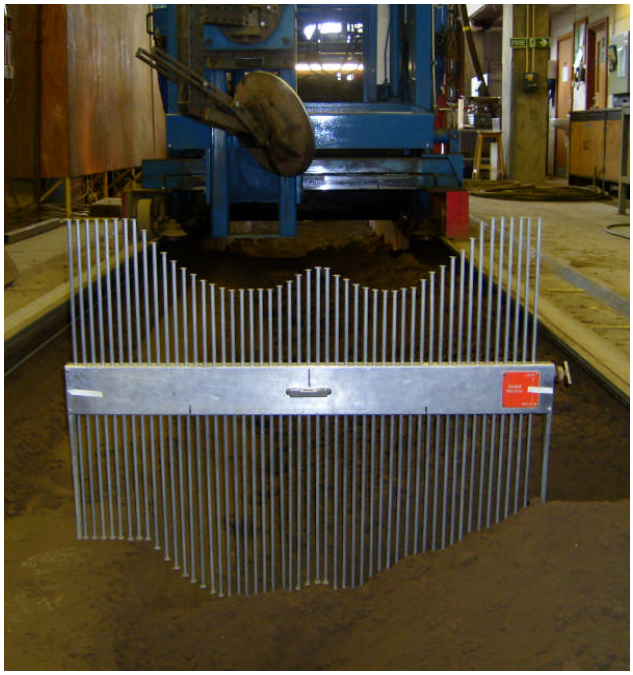


Figure 17. Soil profile meter during disc implement test

4.3 Results

The draught and vertical forces measured for all the implements in the soil bin are shown in *Figure 18*. The highest draught force occurred with the disc plough, while the draught force of the mouldboard plough was similar to the 170 tine. Negative values of vertical force indicate a downward reaction and good soil penetration and positive values represent an upward reaction, which means no positive penetration. Reducing the disc and tilt angles of the disc harrow compared to the disc plough resulted in significant increase in the upward vertical force. The draught force of the disc plough was nearly three times larger than that of the disc harrow, although the working depth was twice that of disc harrow.

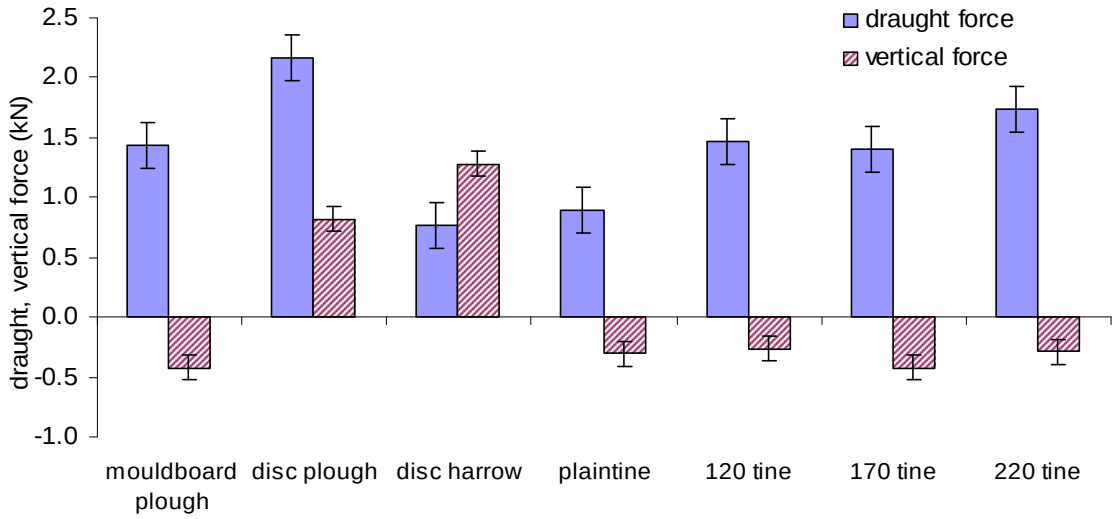


Figure 18. Draught and vertical forces for the implements of the soil bin experiment (error bars indicate a confidence interval at 95% probability level)

The area of disturbance was measured for all implements. Both the mouldboard and the disc plough disturbed most soil as shown in *Figure 19*. Although the disc harrow was working at half the depth of the disc plough, the area of disturbance was less than 30% of the area disturbed by the disc plough. Differences between the soil profiles of disc plough and disc harrow can be seen in Appendix 5. Values of specific resistance illustrate that the mouldboard plough had the lowest specific resistance, 40% lower than the disc plough (*Figure 19*). The disc harrow registered the highest specific resistance of all implements, due to small soil disturbance. The mean value of the specific resistance of all implements was 47 kN/m^2 with a range of +15/-17 kN/m^2. Excluding the

mouldboard plough the mean value was 50 kN/m^2 with a range of +12/-5 kN/m^2. The mouldboard plough had low draught force of 1.44 kN, high disturbed area of 0.047 m^2 and therefore low specific resistance of 30.4 kN/m^2.

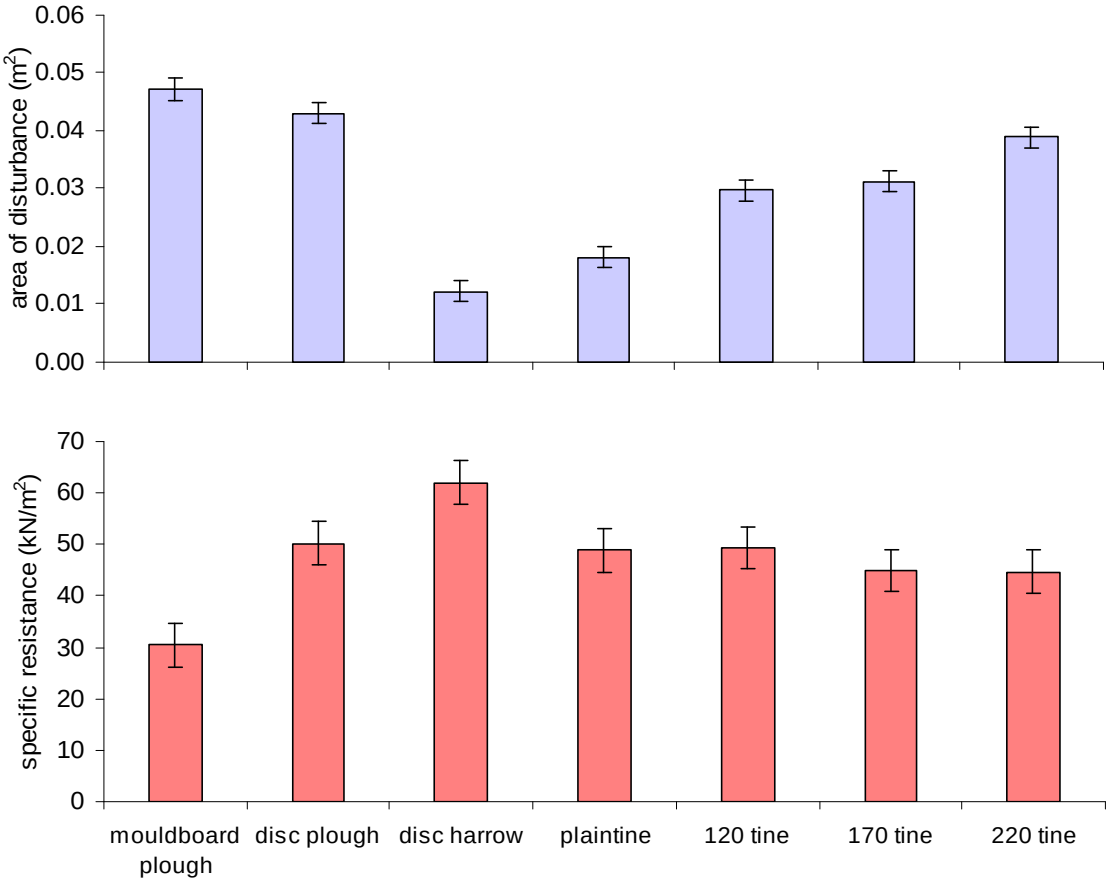


Figure 19. Area of disturbance and specific resistance of the implements performed in the soil bin experiment (error bars indicate a confidence interval at 95% probability level)

Adding the 220 mm wings increased the draught force compared with the plain tine by approximately 85% (*Figure 20*). There is a slight discontinuity for the 170 tine, where the wings were mounted on a second tine as described earlier. The vertical force acting downwards on all tines was similar with a mean of -0.32 kN.

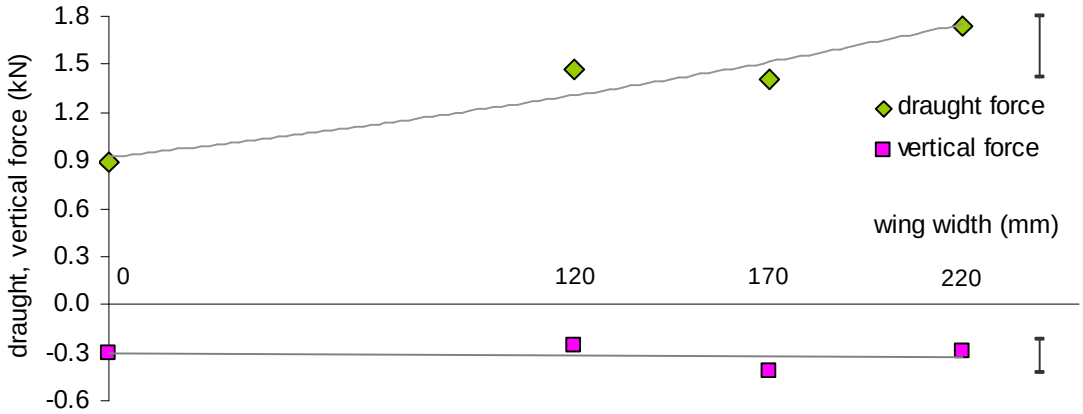


Figure 20. Draught and vertical forces of different wing width tines

Comparing the effect of wing width showed a clear tendency to increase the area of disturbance and decrease the specific resistance (*Figure 21*) as the width of the wing increases. The soil profile clearly shows the effect of wing width on the area of disturbance (*Figure 22*). The area of disturbance measured for the 220 tine was more than twice that of area disturbed by the plaintine. The results from the soil bin experiment showed that a winged tine has a lower specific resistance than a plaintine by approximately 10%.

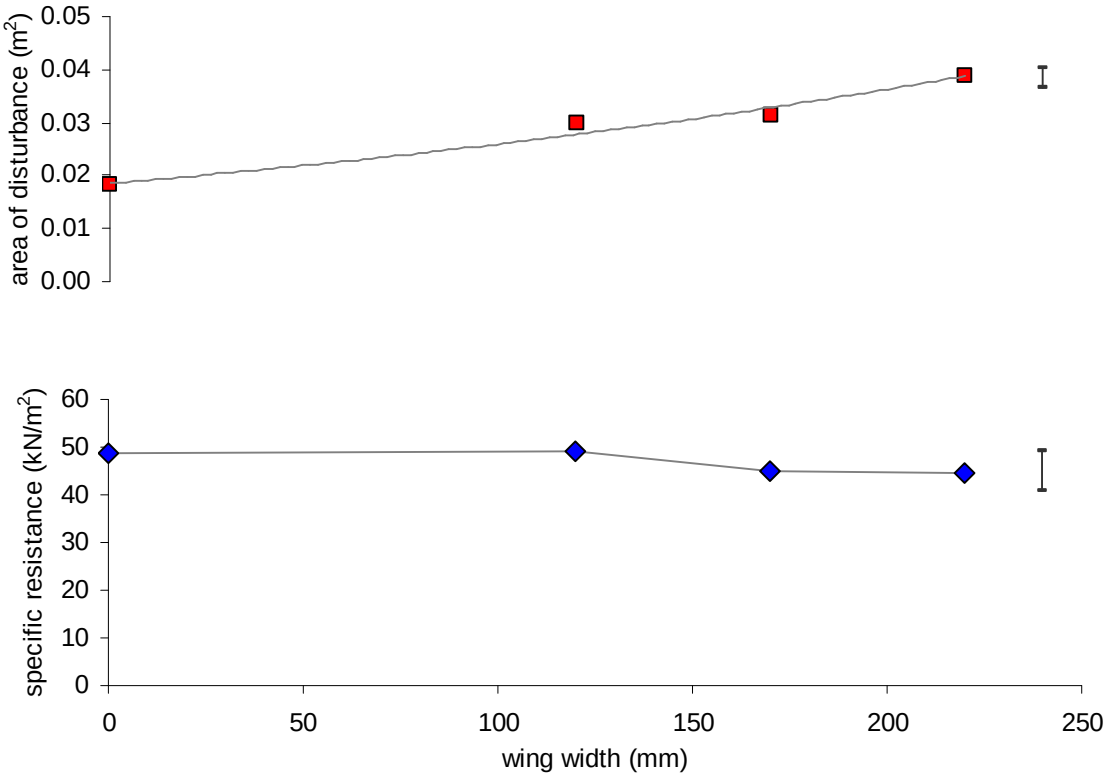


Figure 21. The area of disturbance and specific resistance for different wing width tines

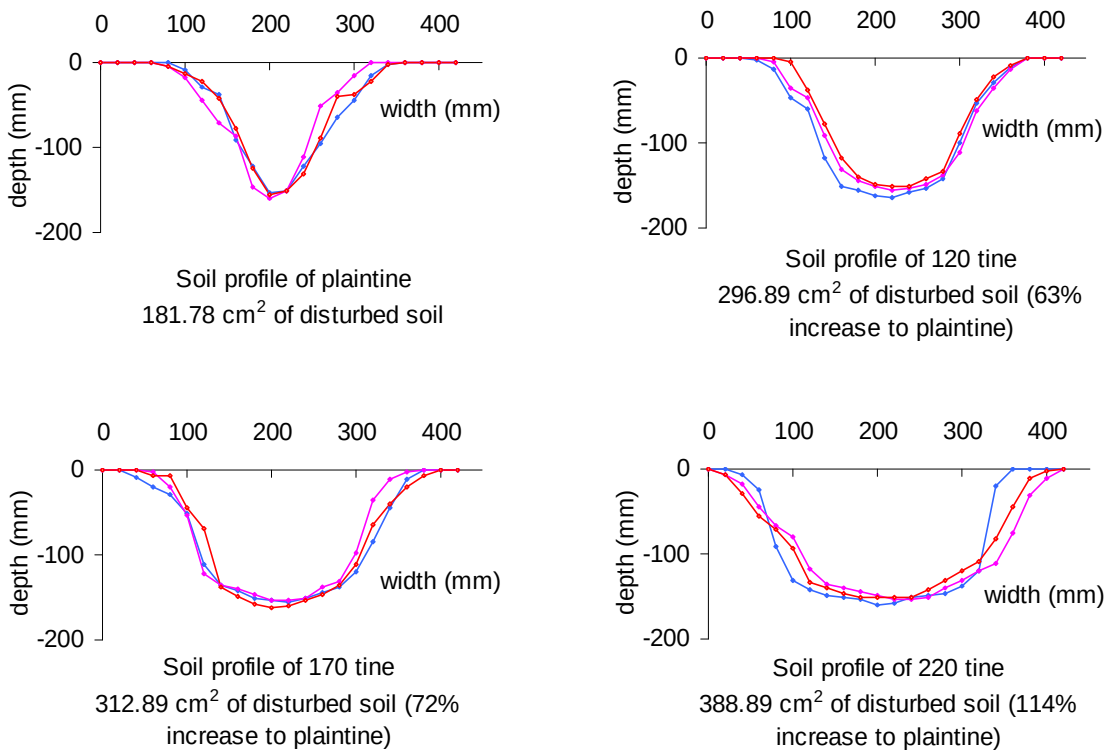


Figure 22. Soil profiles of different wing widths tines

The specific resistance of the comparable implements in the field and soil bin experiments is plotted in *Figure 23*. The specific resistance of the mouldboard plough in the field experiment was more than twice that of the mouldboard plough working at the same depth in the soil bin. The mouldboard plough in the field could have reached a hard soil pan created by previous tillage, which resulted in higher draught forces than expected from the soil forces measured for the other implements. The disc plough performed similarly in both experiments, though the depth of work in the soil bin was smaller. The specific resistance of winged tines was lower in the soil bin, although it must be noted that wing width was slightly smaller while the working depth was greater than in the field experiment. Comparing the disc harrow, the specific resistance in the soil bin was greater by approximately a factor of 1.2 compared to that in the field experiment as a result of a greater draught force measured in the bin. This shows the positive effect of multiple implements to reduce energy requirements.

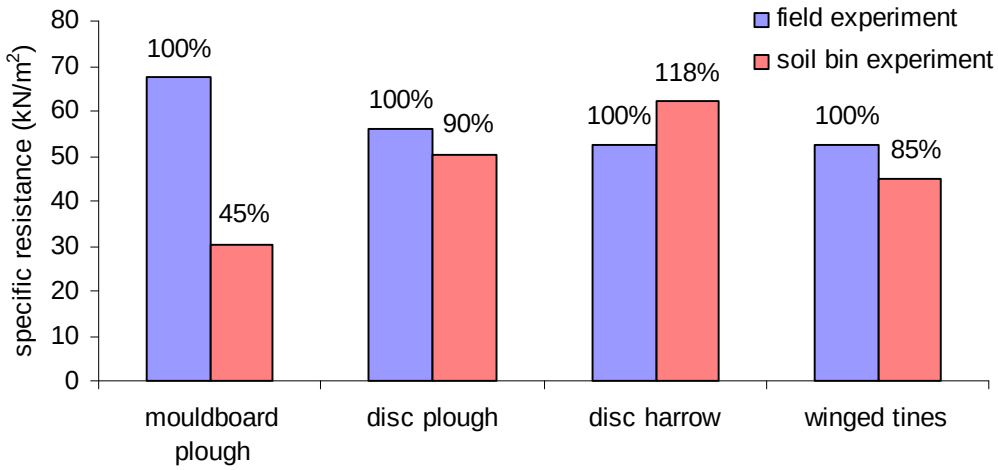


Figure 23. Specific resistance of the comparable implements in the field and soil bin experiments

4.4 Summary

Winged tines have a positive effect on tillage efficiency, as shown by the soil bin experiment. Increasing the wing width from a plain tine to 220 mm increased the draught force by approximately 85%, the area of disturbance by 114% and reduced the specific resistance by about 10%.

Disc implements produced an upward vertical force preventing penetration. The vertical force increased significantly, when disc and tilt angles were reduced. All other implements had downward vertical forces enabling good penetration into the soil.

The mouldboard plough had a relatively low draught force and therefore a low specific resistance. The specific resistance of the mouldboard plough in the soil bin was less than 50% of that the field.

5 Economic analyses

5.1 Introduction

Every business is focused on creating a profit. The same applies in the field of agriculture, where the aim is to get the greatest output at a minimum cost. A significant part of the total production costs represents the cost of owning and operating machinery. The actual costs of a machine are not known, until the machine is sold or scrapped. However, reasonable assumptions can be made about the 'life' and final value of the machine based upon historic depreciation data. The costs of operation can be estimated, when an accurate record of the costs of the machine is maintained. For systematic machine management, cost analysis and careful planning are crucial. According to Landers, 2000, the main reasons for monitoring costs are:

- good farm management is based on knowledge of the input costs of labour and machinery
- knowing current machinery costs enables to consider an alternative to ownership, as least costly method of obtaining farm machinery can be found
- new production techniques can be considered
- future changes in the farm business and fiscal policy

Earlier study (Markham and Chapman, 1998) shows that machinery costs can represent substantial part of the total costs of agricultural businesses. It is obvious that an attempt to minimize costs of farm production must be focused on possible savings in machinery fleet. Many tillage systems and machinery are available on the market and it is advantageous for the farmer to have the information about comparable systems. To investigate the optimum tillage system, alternative implements need to be compared. The economic comparison of the tillage systems tested during the field and soil bin experiments will be conducted.

5.2 Machinery costs

The total costs of a machine depends on many factors (how many years it is used, what is the yearly usage) and these consist of two components: fixed and variable costs. Fixed costs are occurring regardless of the machine use and variable costs depending upon the use of the machine. This distinction is possible only if a machine is operating in average conditions. Fixed costs, as depreciation and loss in value, are also dependant on machine utilization, because heavy usage reduces its operational life span. Conversely, some maintenance and repairs would be needed, even if the machine is slightly used. Proportion of major components of total machinery costs are shown in *Figure 24*.

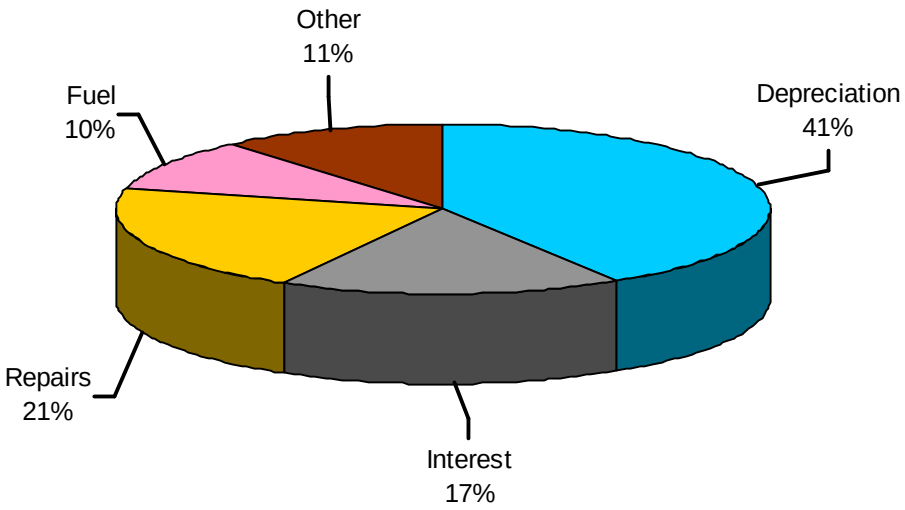


Figure 24. The machinery cost components from survey on Irish tillage farms (Forristal, 1995)

5.2.1 Fixed costs

Fixed costs of a machine include depreciation, costs of interest, taxes, insurance and shelter. Depreciation is usually the largest component of machine total costs. It measures the amount, by which the value of a machine decreases in time, whether it is used or not (Hunt, 2001). Machines depreciate due to several factors as follows:

- Older machines are worth less than a newer machine, even though the model changes do not significantly altered the function of the machine.
- As the machine is used, its parts become worn and reduce the performance and reliability of the machine. These parts can be replaced or repaired, but it can be more economical to replace the whole machine by a second one.
- A new, more efficient machine or practice available may reduce the value of the existing machine. When a machine becomes obsolete, it can be less economic to operate it as a result of a newer technology.

There are several methods of calculating depreciation. The most common methods are straight line method, declining balance depreciation and decremental depreciation (Witney, 1988).

The machine fixed costs include the interest on capital, which is invested in the machine. If the capital is borrowed, an expected inflation is included in the interest rates. A charge is made even if the capital is already owned, because money could be earned from an alternative investment. The costs when owned capital is invested are called opportunity cost of capital. Interest charges can be calculated as an equal yearly charge through the life of the machine. The real cost of borrowing can be reduced by both inflation and tax allowances (Witney, 1988).

The group of farm machinery, which is taxed, includes agricultural tractors. A self-propelled vehicle, which is used on public roads, attracts vehicle excise duty. Insurance of farm machines is not always common practise, but it is justifiable. It covers third-party liability, loss by fire or windstorm and theft. In some cases, the insurance of a tractor includes the covering of attached trailers. The insurance charges vary depending on coverage, but they are usually at 0.25% to 1% per year of the value of the machine (Hunt, 2001).

Machinery shelter increases resale value, as earlier surveys showed. Especially complex machinery, such as combine harvesters, is stored under a roof for at least part of the year. The shelter can be a roofed construction with open sides or enclosed building including workshop facilities. Depending on the type of the shelter, the annual storage

costs are equal to 0.5% to 1% of the machine purchase price (Hunt, 2001; Witney, 1988).

5.2.2 Variable costs

The variable costs of a machine as it name suggests vary with its use and they are expressed as costs per area worked or hour of operation. They are divided into maintenance and repair costs and costs of fuel and oil.

Maintenance is essential in an effort to guarantee the reliability of a machine. Expenses on maintenance represent the costs of the service usually specified by the manufacture. Regular maintenance contributes to high standard of machine performance and prolongs the physical life of the machine. Repair costs are the expenditure for parts and labour. Periodic replacement of wearing parts, such as tines, discs, chains and batteries, is dependant on the conditions, in which the machine is working and cannot be much influenced. Additional costs incur in case of accidental damage or neglecting maintenance. These costs are highly uncertain. Costs of repairs and maintenance can be expressed as a percentage of the price of the machine taking into account the annual use. Numerous surveys carried out on repair costs of various tractors and implements enable to compile a database, on which the estimated annual repair expenses of a machine can be based (Witney, 1988).

The cost of fuel and oil is included in variable costs. The demanded amounts of a power at a drawbar or power take-off of a tractor influence the fuel consumption. It varies considerably over the duty cycle, as the average fuel consumption is only two thirds of the fuel consumption for peak powers. The average engine loading during the year is approximately 55% of the maximum power of the tractor (Witney, 1988). The fuel consumption is based on the fuel requirements per hectare or per hour. Oil consumption is defined as the volume of the oil replaced at the recommended change intervals (Witney, 1988).

Fixed and variable costs give the overall costs of operation of a machine. Labour charges must be added depending on labour requirements of particular operation. The

average labour costs include National insurance contribution, employer's liability, overtime and benefits.

5.3 Machinery cost calculator

To compare alternative tillage systems a cost calculator based on Excel spreadsheet was developed based upon an earlier version by Saunders, 2002 and Home, 2003. The cost calculator contains the data about the popular tillage implements available on the market in Europe. It allows the modification of all variables to suit an individual farm situation. An implement, which is selected from a wide choice, can be matched with a tractor in power range of 50 to 360 kW. The calculator sheet display a maximum of five different field operations and presents the total costs of the implement and tractor. Additional information, such as working width and speed, work rate and time needed to complete a given task, can be also seen. All the variables involve in the calculator rely on the correct information, which were entered into both implement and tractor databases. As the calculator is quite complex, its components will be described separately.

5.3.1 Implement section

The machinery sheet consists of technical data and current prices of alternative tillage implements, which were obtained from major manufacturers. The database is structured to sections reflecting the primary function of the implement. These sections, such as mouldboard ploughs, power harrows of drills, contain a range of implements in different configurations. The variables, which apply to all the implements, are adjustable and consist of interest rate, financial life, opportunity cost of capital rate and shelter costs as shown in *Figure 25*. Financial life refers to a period of time, for which the capital is borrowed.

Interest rate	**7**	**% p.a.**
Finance life	**5**	**years**
Opportunity cost of capital	**5**	**% p.a.**
Shelter cost	**0.2**	**% of the implement purchase price**

Figure 25. Implement variables

Except the variables mentioned above there are other implement variables, but they are individual for every one. The machinery sheet also contains the calculation of fixed and variable costs. An example of the section of the machinery sheet containing data about five to seven furrow mouldboard ploughs is shown in *Figure 26*. The power requirements column next to the implement description indicates the appropriate size of the tractor to match the implement in average field conditions. The data were obtained in the field experiment and from the implements manufacturers' recommendations. The working width of the implement can be changed as Kverneland ploughs feature variable furrow width in a range of 30 – 50 cm. Spin buttons next to width column enables to change the working width, but do not allow either the minimum nor the maximum value to be exceeded. Working speed varies over the implements and influences the work rate. Time to complete the operation in hours and days is presented in next two columns. It is dependant upon the area entered on the calculator sheet. The capital costs obtained from the implement manufacture show the list price or the discounted price, where applicable. Residual value is based on depreciation calculated as the average fall in value in percent of the new price. Depreciation rates implemented from Nix, 2006 distinguish simple equipment from machines with many moving parts. Life before change is adjustable variable representing the length of productive life of the implement. The proportion of the capital borrowed to the capital owned invested in the machine is shown in column capital borrow. The actual values of fixed, variable and total costs are presented in last columns on the machinery sheet and the calculations are explained further.

TILLAGE IMPLEMENT	Power req.	Width		Speed	Work rate	Time to process the area		
>>PLOUGHS<<	hp	m		km/h	ha/h	hours	days	
KVER LS 5-furrow reversible mounted	115	2		6	0.9	400	40	...
KVER LB 6-furrow reversible mounted	130	2.4		6	1.08	334	34	...
KVER LB 6-furrow rev. mounted + Packomat	150	2.4		6	1.08	334	34	...
KVER PB 6-furrow reversible semi-mounted	165	2.4		6	1.08	334	34	...
KVER PB 7-furrow reversible semi-mounted	185	2.8		6	1.26	286	29	...

Continuation

	Purchase Price	Residual Value	Life Before Change	Capital Borrowed	Fixed Costs	Variable Costs	Total Costs
	£	£	years	%	£/ha	£/ha	£/ha
...	£12 829.5	£3 208	10	100	£4.00	£7.77	£11.77
...	£19 084.5	£4 772	10	100	£5.94	£9.80	£15.74
...	£24 034.5	£6 009	10	100	£7.48	£12.34	£19.82
...	£24 142.5	£6 036	10	100	£7.52	£12.40	£19.92
...	£26 397.0	£6 600	10	100	£8.22	£11.80	£20.02

Figure 26. Example of a section of the machinery sheet

The cost calculations are based on fundamental economics and generate the results for the calculator sheet. Fixed costs of each of the implement consist of depreciation, interest and shelter costs. Depreciation costs are calculated using straight-line method, which is a common practice to depreciate agricultural machinery. Depreciation costs equal to purchase price minus resale value over the years the implement is used.

$$Depreciation\ (£/\text{years}) = \frac{PurchasePrice\ (£) - ResaleValue\ (£)}{LifeBeforeChange\ (\text{years})}$$

Equation 1

The equation calculating interest costs takes into account the fact that the machine can be purchased by combination of borrowed and owned capital. The interest costs are determined as a compound of costs of borrowed money and costs of owned money invested in the machine.

$$Interest\ (£/year) =$$

$$= \frac{PurchasePrice\ (£) * InterestRate\ (\%) * \%ofCapitalBorrowed\ (\%) * FinanceLife\ (years)}{LifeBeforeChange\ (years)} +$$

$$+ \frac{PurchasePrice\ (£) * OppCostRate\ (\%) * (1 - \%ofCapitalBorrowed)\ (\%) * FinanceLife\ (years)}{LifeBeforeChange\ (years)}$$

Equation 2

Yearly shelter costs are expressed as a percentage of purchase price of the implement.

$$Shelter\ (£/year) = PurchasePrice\ (£) * ShelterCost\ (\%)$$

Equation 3

Implement yearly fixed costs are the sum of depreciation, interest and shelter costs. To get the cost per hectare value, the yearly costs must be divided by annual tilled area.

Variable costs of the machines are only composed of repairs and maintenance expenses, as it was assumed that apart from minor need for lubricants, none of the tillage implements require fuel or oil or additional material. Annual costs of repairs and maintenance are based upon the percentage of purchase price at various levels of use. Greater runtime per year the implement achieves, higher the costs are. The percentage of purchase price giving repair costs is based on Nix, 2006 and it is applied in two different rates, which vary upon implements configuration.

$$Repairs\&Maintenance\ (£/year) = PurchasePrice\ (£) * AnnualRepairCosts\ (\%)$$

Equation 4

Total costs are simply sum of fixed and variable costs and are presented as a cost per hectare.

5.3.2 Tractor section

The tractor sheet consists of a database of tractors in a power range of 50 to 360 kW, both 4WD and track versions. Technical specifications and current prices were obtained from a leading tractor manufacture (John Deere). The wide range of engine power of the

tractors fed into the database enables the optimum match with any implement following manufacturers' recommendations. Adjustable variables, same for all the tractors are presented in *Figure 27*. The assumed variables identical to the machinery variables are interest rate, financial life, opportunity cost of capital rate and shelter. Insurance and road licence are added, because tractors are usually taxed as road vehicles and are often insured. Price of diesel fuel can be also changed to reflect the floating price on the market.

Interest rate	**7**	**% p.a.**
Finance life	**5**	**years**
Opportunity cost of capital	**5**	**% p.a.**
Shelter cost	**0.2**	**% of the tractor purchase price**
Insurance and Road License cost	**1**	**% of the tractor purchase price**
Cost of fuel (diesel)	**0.35**	**£/l**

Figure 27. Tractor variables

Tractor sheet is similar to the machinery sheet with slight differences. Example of the data in the tractor sheet describing five different tractors is shown in *Figure 28*. As the tractor title includes the value of engine power in hp, the next column refers to a power in kW. Fuel consumption is based on agricultural surveys conducted in U.S. (Iowa State University, 2005). The value given is average fuel consumption for farm tractors through the year without reference to any specific implement and is dependant on maximum power of the tractor. Purchase price shows list price reduced by a discount, if available. The resale value was obtained using decremental depreciation as described by Witney, 1988. The advantage of this method is that the resale value of the tractor at age zero is identical with the purchase price and that resale value through the life of the tractor is an exponential function. It is obvious, because the greatest depreciation occurs during the first year of the tractor. The resale value is tied up with yearly usage, because it greatly influences the condition of the tractor. The depreciation age is used for calculation the resale value take into account heavier or lighter use. That means, that lightly used tractor of the same age as heavier used one will have higher resale value.

$$DepreciationAge\,(years) = \frac{1}{2} * \left[ActualAge\,(\text{years}) + \frac{AccumulatedUse\,(\text{h})}{AverageAnnualUse\,(\text{h/year})} \right]$$

Equation 5

The actual age variable accounts for the effect of ageing, while accumulated use/ average annual use ratio represents the utilization. The accumulated use is the total amount of hours, when the tractor was in operation, and the average annual use is taken as 1000 h/year. The age of the tractor, when it is replaced, was set to 8 years. The annual use of tractor was considered as 1000 hours in average, as it is, except tillage, used for other purposes through the year. Fixed, variable and total costs are calculated per year and per hour.

TRACTORS	Engine Power kW	Fuel Consumption l/h	Purchase Price £	Resale Value £	Life Before Change years	Annual Usage h/year	Capital Borrowed %	
JD 5820 4x4 88 hp	64.7	14.66	£31 020.3	£10 451	8	1000	100	...
JD 6230 4x4 100 hp	73.5	16.66	£39 483.0	£13 302	8	1000	100	...
JD 6330 4x4 110 hp	80.9	18.34	£41 199.3	£13 880	8	1000	100	...
JD 6430 4x4 120 hp	88.2	19.98	£44 387.1	£14 954	8	1000	100	...
JD 6630 4x4 130 hp	95.6	21.66	£50 639.4	£17 060	8	1000	100	...

Continuation

	Fixed Costs		Variable Costs		Total Costs	
	£/year	£/h	£/year	£/h	£/year	£/h
...	£4 300.6	£4.31	£8 382.3	£8.39	£12 682.8	£12.70
...	£5 473.8	£5.48	£9 864.3	£9.87	£15 338.1	£15.35
...	£5 711.8	£5.72	£10 677.8	£10.68	£16 389.6	£16.40
...	£6 153.7	£6.16	£11 592.9	£11.60	£17 746.6	£17.76
...	£7 020.6	£7.03	£12 769.3	£12.77	£19 789.9	£19.80

Figure 28. Example of the tractor database

Tractor fixed costs include depreciation, interest, shelter, insurance and road licence. Depreciation, interest and shelter costs are calculated using same equations as used for calculating costs of implements (Equations 1, 2 and 3). Annual insurance and road licence expenses are determined as a percentage of purchase price of the tractor. The equation is showed below.

$$Insurance\ \&\ RoadLicence\ (£/\text{year}) = PurchasePrice\ (£) * InsuranceAndRoadLicenceCost\ (\%)$$

Equation 6

Tractor variable costs include the repairs and maintenance costs, as well as costs of fuel and oil. The repairs and maintenance costs are based on estimated annual costs of spares and repairs as presented by Nix, 2006. The annual costs are calculated as a percentage of purchase price. The equation is identical with the one used for calculating machinery repairs and maintenance costs (Equation 4). Price of fuel is determined as fuel consumption multiplied by the price of litre of fuel. Oil costs are equal to approximately 15% of the fuel costs as U.S. Agricultural Census showed (Iowa State University, 2005).

$$Fuel\ \&\ Oil\ (£/h) = FuelConsumption\ (l/h) * FuelPrice\ (£/l) * [1 + OilConsumption\ (\%)]$$

Equation 7

The fixed, variable and total costs are then calculated as costs per year and per hour of operation, since tractor usage is expressed in hours per year.

5.3.3 Field Variables

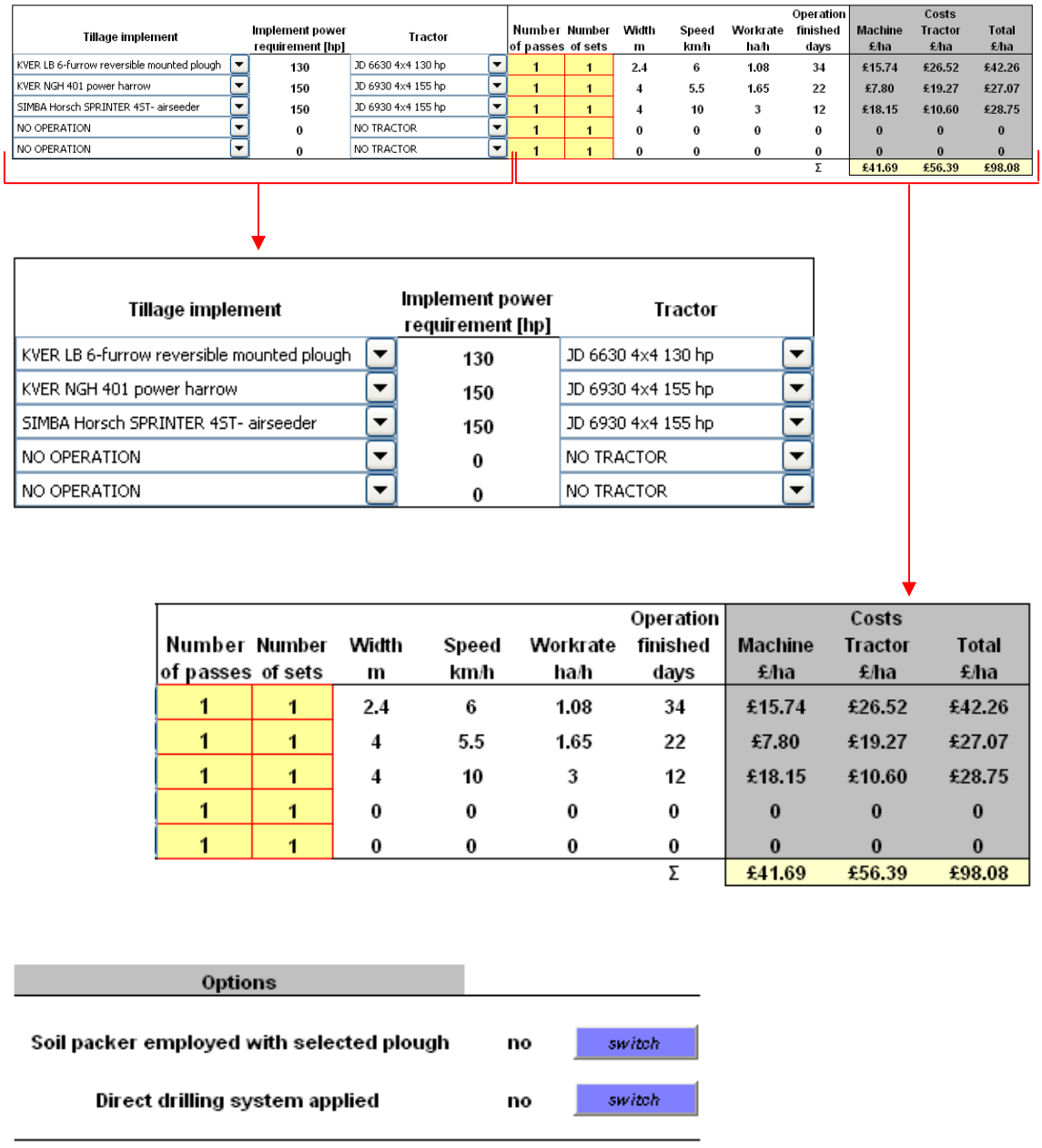
Prior to the implement and tractor selection the section including field and labour variables must be completed. As shown in *Figure 29*, all the variables need to be entered into the spreadsheet cells. This section contains tillage process area, field efficiency and hours worked per day. Labour cost variable is attached. It must be noted that the values in this section do apply across the selected implements and tractors. If the variables for the implements selected vary, it is necessary to evaluate the costs separately for each individual operation. Labour cost displayed is total hourly cost of regular workers based on typical annual labour cost (Nix, 2006). Labour cost includes national insurance contribution, employer's liability and average annual overtime.

Tillage Process Area	**360**	**ha**
Field Efficiency	**75**	**%**
Work Hours Per Day	**10**	**hours**
Labour Costs	**8.84**	**£/h**

Figure 29. Field variables and labour cost

5.3.4 Cost calculator

The cost calculator sheet displays the output of the cost calculations. There are presented machine, tractor and total costs for selected implement and tractor based on the field, implement and tractor variables and the data fed in the databases. The front screen of the cost calculator is shown in *Figure 30*. Five different operations can be undertaken one after another to enable to cost the whole system of soil preparation. Drop down boxes are used to select the type of the implement and tractor size for an appropriate field operation. The drop down boxes offer a complete range of implements and tractor sizes acquired from the database. When an implement is selected, recommended size of the tractor is indicated. Once an implement and tractor are selected, number of passes and sets can be entered. Two passes are necessary for some implements to do the task properly. To increase the work rate, additional set of implement and tractor may be needed. Width and working speed of the combination are displayed on the right hand side of the cost calculator. Work rate and number of days needed to work the area entered are also presented. The costs of the selected combination are automatically calculated and the machine, tractor and total costs are displayed. Tractor costs include labour cost. Additional options are available for ploughs and drills. The switch button is implemented to distinguish if soil packer is employed with a plough. When no tillage system is performed, the direct drilling system can be selected. As all the drills in the database can be used in variety of conditions, the direct drilling option represents the cost of additional power needed when direct drilling is applied.



Tillage implement	Implement power requirement [hp]	Tractor	Number of passes	Number of sets	Width m	Speed km/h	Workrate ha/h	Operation finished days	Costs Machine £/ha	Costs Tractor £/ha	Costs Total £/ha
KVER LB 6-furrow reversible mounted plough	130	JD 6630 4x4 130 hp	1	1	2.4	6	1.08	34	£15.74	£26.52	£42.26
KVER NGH 401 power harrow	150	JD 6930 4x4 155 hp	1	1	4	5.5	1.65	22	£7.80	£19.27	£27.07
SIMBA Horsch SPRINTER 4ST- airseeder	150	JD 6930 4x4 155 hp	1	1	4	10	3	12	£18.15	£10.60	£28.75
NO OPERATION	0	NO TRACTOR	1	1	0	0	0	0	0	0	0
NO OPERATION	0	NO TRACTOR	1	1	0	0	0	0	0	0	0
								Σ	£41.69	£56.39	£98.08

Tillage implement	Implement power requirement [hp]	Tractor
KVER LB 6-furrow reversible mounted plough	130	JD 6630 4x4 130 hp
KVER NGH 401 power harrow	150	JD 6930 4x4 155 hp
SIMBA Horsch SPRINTER 4ST- airseeder	150	JD 6930 4x4 155 hp
NO OPERATION	0	NO TRACTOR
NO OPERATION	0	NO TRACTOR

Number of passes	Number of sets	Width m	Speed km/h	Workrate ha/h	Operation finished days	Costs Machine £/ha	Costs Tractor £/ha	Costs Total £/ha
1	1	2.4	6	1.08	34	£15.74	£26.52	£42.26
1	1	4	5.5	1.65	22	£7.80	£19.27	£27.07
1	1	4	10	3	12	£18.15	£10.60	£28.75
1	1	0	0	0	0	0	0	0
1	1	0	0	0	0	0	0	0
					Σ	£41.69	£56.39	£98.08

Options		
Soil packer employed with selected plough	no	switch
Direct drilling system applied	no	switch

Figure 30. Front screen of the cost calculator

5.4 Procedure

The calculations of the costs of alternative tillage systems are beneficial for the farmer, because they show the cheapest system for an individual operation. Selection of the implements and tractors is dependent on the cultivated area and time availability. The area, which needs to be worked, is usually constant, but the number of days available for tillage operations varies upon the weather conditions and soil type. Number of workdays in Scotland in months, when autumn tillage is performed is given in *Table 12*. The number of workdays presented in the table when cultivation is possible has a probability level of 75%. For the costing examples a 35 day limit was chosen for a single operation or tillage system. This takes into account that August is not always available due to late harvesting and in November it is not a common practice to do primary cultivation, because crop should be establish earlier for smooth dormancy. A 10 hour working day was considered for all calculations. All compared implements and tractors are new.

Table 12. Number of workdays available in Scotland for autumn tillage (Witney, 1988)

Month	No. of field workdays on medium soil
August	25
September	23
October	19
November	18

5.5 Cost comparison

The cost comparison can be made for a single implement and tractor combination or for a complete tillage system as was described earlier. The calculated costs of different implements and alternative tillage systems are described in this section.

As it was calculated earlier, the 86 kW tractor used in the field experiment is capable to operate the 5 furrow plough, although the 4 furrow plough was used in the experiment. Costs of these two ploughs with the same tractor and working speed and depth are presented in *Figure 31*. The cost of the 5 furrow plough is lower from the area of

approximately 18 ha compare to that of the 4 furrow plough. The 5 furrow plough has higher work rate at the same speed as the 4 furrow plough, therefore this combination covers the given area in shorter time, which reduces the cost of operation of the tractor as it is calculated as cost per hour. The 4 furrow plough covers 269 ha in 35 working days, where the cost of £ 47.85/ha is 18% higher than the cost of 5 furrow plough. The 5 furrow plough has the cost of £ 39.36/ha at its maximum output. This example shows that the cost of ploughing can be reduced by utilizing the maximum available power of the tractor. The advantage of covering larger area must be also noted. The higher work rate of the 5 furrow plough to 4 furrow enabled to cover greater area per day as illustrated in *Figure 32*. In 35 working days the difference between two ploughs is 67 ha in favour of 5 furrow plough.

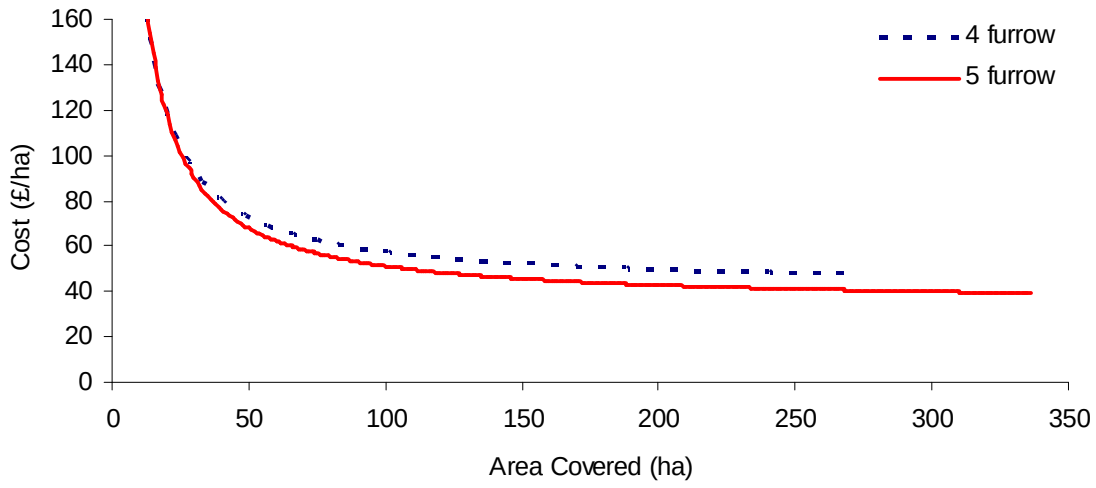


Figure 31. Operational costs of 4 and 5 furrow ploughs

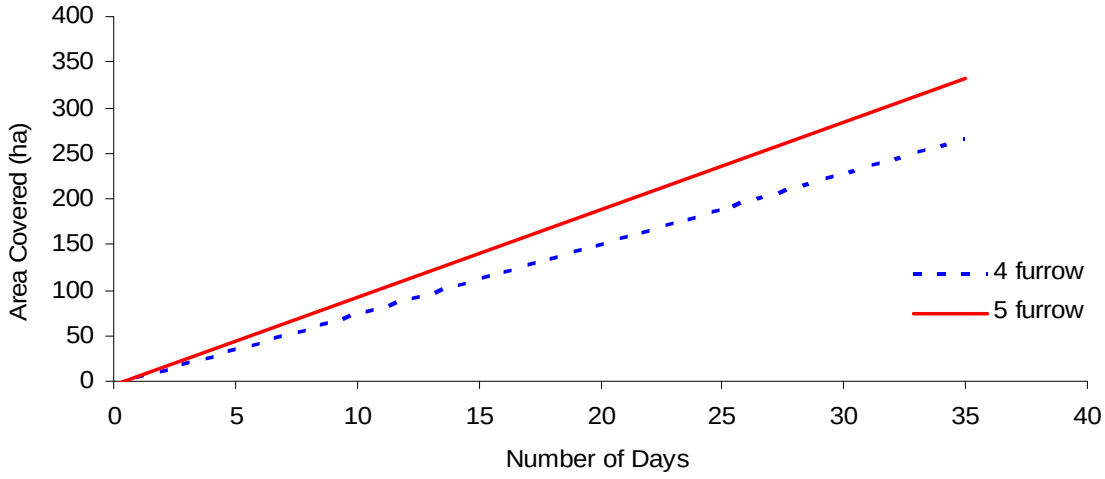


Figure 32. Area covered by 4 and 5 furrow ploughs

The next way to utilize all the power of the tractor is to increase the width of the plough. This can be done easily, because many of the modern mouldboard ploughs have the vari-width option. The vari-width option enables to change the width of plough manually before entering the field or during the operation from tractor's cab. Latter option is a great advantage, because the width of the plough can be adjusted depending on soil conditions by the tractor operator without leaving the cab. Mouldboard ploughs compared have vari-width option enabling a range of widths of furrow from 300 mm to 500 mm in 10 mm increments. Increasing the width of the furrow adds no extra capital cost to the operation. Costs of the tractor and 5 furrow plough with three different furrow widths are shown in *Figure 33*. Increasing the furrow width clearly reduces the cost of operation in all range of worked area. It also allows to work greater area in a given time limit. The plough with furrow width of 400 mm covers 315 ha, 24% more than 300 mm setting and 24% less than 500 mm setting. The 500 mm setting results in the lowest cost of £ 33.45/ha at the area of 395 ha.

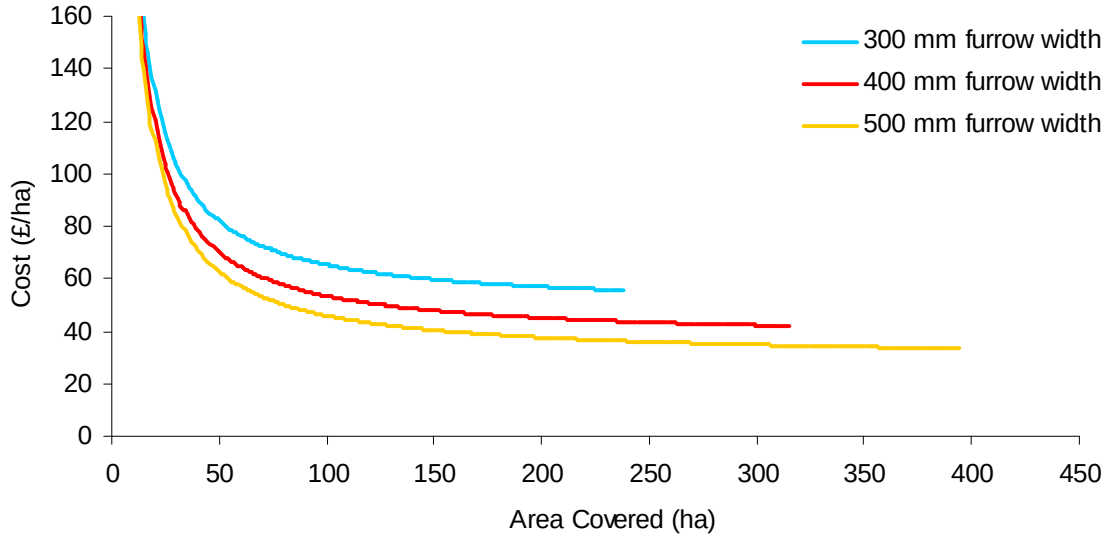


Figure 33. Operational costs of different furrow width

To determine the effect of work rate on the cost, mouldboard ploughs with different numbers of plough bodies were compared. In *Figure 34*, costs of 4, 6, 7 and 9 furrow ploughs are presented. The 4 and 6 furrow ploughs are in mounted version, while 7 and 9 furrow ploughs use semi-mounted configuration. The manufacturer recommended tractor sizes were matched with the ploughs. These combinations were operating at speed of 6 km/h. It can be clearly seen that the largest plough has the highest output.

The area covered by the 9 furrow plough is 567 ha, as expected this is more than twice the area covered by 4 furrow plough. The 4 furrow plough is the cheapest combination up to the area of 150 ha, where the 6 furrow plough becomes the cheapest. The 6 furrow plough has the lowest cost of £ 41.92/ha, in comparison to £ 46.82/ha and £ 46.63/ha of 7 and 9 furrow plough, respectively. The costs of 7 and 9 furrow ploughs are higher compared to the costs of 4 and 6 furrow ploughs in the area up to 250 ha, but they have higher output enables to cover greater area. The costs calculated compare favourably with those given for the 'general' case by Nix (2006).

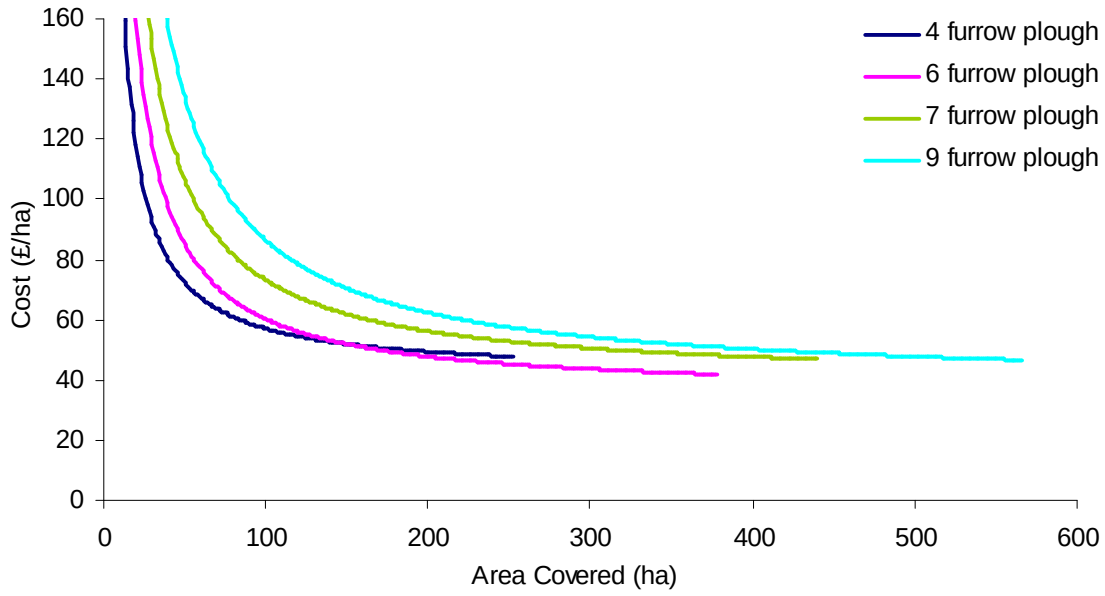


Figure 34. Operational costs of the plough with different number of furrows

There are two ways to cover greater area, than the existing plough combination is capable of. Either two smaller or one larger plough can be operated. The costs of two combinations of 5 furrow ploughs and one of 10 furrow plough are presented in *Figure 35*. The costs of the tractors are based on the yearly usage of 1000 hours. It means that when the tillage is done, the tractors are used elsewhere up to the limit of 1000 h/year. As can be seen, the cost of two 5 furrow ploughs is lower up to the area of 525 ha than that of 10 furrow plough. As they work at the same speed, the area covered is 630 ha for both. At this area the cost of two 5 furrow plough is £ 41.99/ha, which is 1% more than the cost of £ 41.52/ha of the 10 furrow plough. The main reason of this is that the purchase price of the 10 furrow semi-mounted plough is three times higher than that of

simple 5 furrow mounted plough. Breaking the costs at the area of 500 ha, the 5 furrow plough combinations have the cost of ploughs of £ 13.80/ha, cost of the tractors of £ 19.75/ha and labour cost of £ 9.82/ha, while the 10 furrow plough combination have the cost of plough of £ 19.78/ha, cost of tractor of £ 18.88/ha and labour cost of £ 4.91/ha. The advantage of 10 furrow plough combination compared to two 5 furrow ploughs is that to manage only one person and one combination is easier. The cost of two 5 furrow plough is similar compared to the cost of one 10 furrow plough in case that the tractors can be utilized on other tasks throughout the year. If the tractors are used only for tillage, the cost of two 5 furrow ploughs is significantly higher than that of 10 furrow plough as illustrated in *Figure 36*. In the range of the area from 52 to 630 ha, the cost of bigger plough is lower than the cost of two smaller ploughs and at 630 ha the difference in cost is approximately 35%. This example illustrates that keeping an extra tractor is cost ineffective, if it cannot be fully utilized.

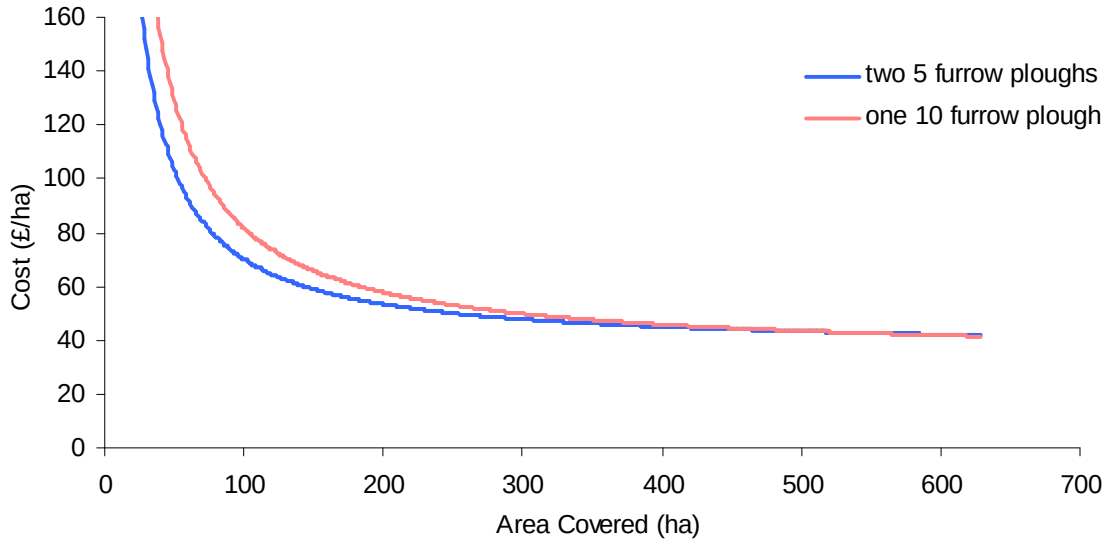


Figure 35. Operational cost of plough combinations, if the tractors are used elsewhere when tillage is done

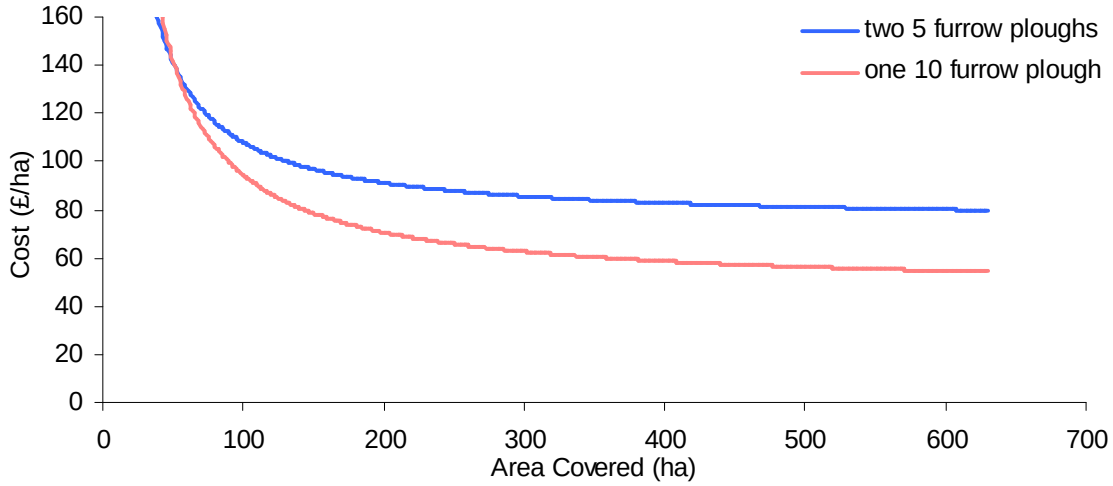


Figure 36. Operational cost of plough combination, if the tractors are used only for tillage

The cost of plough cultivation can be reduced by optimal machinery management. If the implement is kept longer in operation, the depreciation cost decreases. Proper maintenance and replacing wearing parts rather than all implement may be a way of cost savings. The effect of later replacement on the cost of operation can be seen in *Figure 37*. Three identical 5 furrow plough combinations with different productive life cycle are compared. The ploughs were replaced after 5, 8 and 10 years. The cost of plough kept for 10 years is always smaller than that of the plough kept for 8 years and the same relationship is between the plough replaced after 5 and 8 years. The costs for the area of 200 ha are £ 49.22/ha for 5 year, £ 46.25/ha for 8 year and £ 45.05/ha for 10 years operated ploughs. If it is possible to prolong the productive life of the implement, the cost of operation will be reduced compared to the implement, which is replaced earlier, but only marginally.

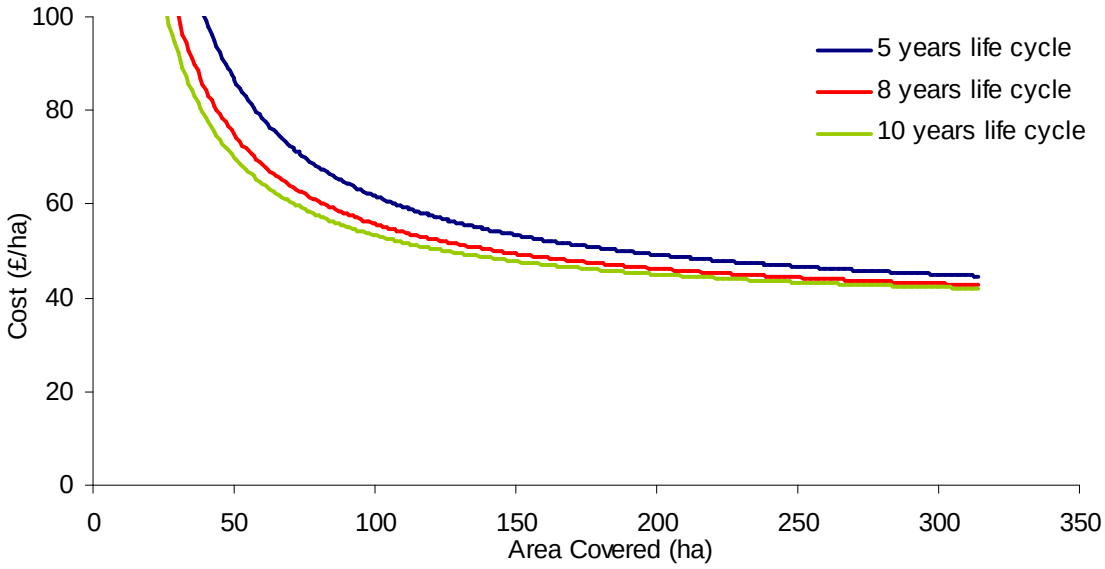


Figure 37. Operational costs of the ploughs with different time of replacement

Combination of mouldboard plough and soil packer, which is fitted to the main frame to the plough, is often advertised as a way of reducing tillage cost. Integrated soil packer usually consists of a packer unit, choice of tines and rear following harrow and helps to level the soil surface after ploughing. The great advantage of this practice is that the soil is prepared for drilling in one pass. The costs of 5 furrow plough with integrated soil packer and 5 furrow plough and soil packer working as a separate combinations were calculated. The costs of these two ways of soil cultivation can be seen in *Figure 38*. The cost of the separate plough and packer operations are broken into the costs of each of the individual operation. The benefit of reducing the number of field operations can be clearly seen. The soil packer integrated with the plough reduces the cost of field cultivation by 22% at 150 ha and by 20% at 300 ha compare to the plough and packer operated separately, but requires more powerful tractor. The cost of operation of the plough with integrated soil packer is always lower than in case that ploughing and soil consolidation is done in two operations. Reducing the number of passes over the field decreases the cost of tillage by £ 12.3/ha at the large tilled areas.

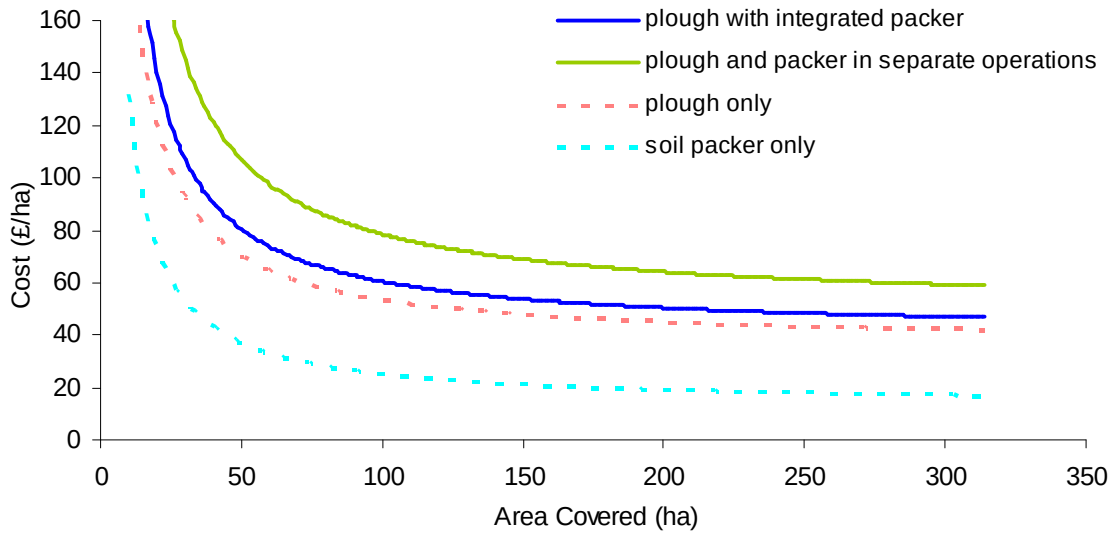


Figure 38. Operational costs of plough and packer in different setting

Combining different tillage tools in one implement became necessary in effort to reduce the time and labour requirement needed to establish the crop after the harvest. One pass cultivation implements are popular for their ability to prepare the seedbed in short time and at low operating costs. To calculate the cost of high output one pass implement, three widths of disc cultivator were chosen. The implement consists of tines, two rows of discs and rear roller. The operating cost of the implement is presented in *Figure 39* for the widths of 3.3, 4.5 and 6 m. The 3.3 m version covers 563 ha, 4.5 m version 766 ha and 6 m version 1025 ha in 35 day limit. At the area of 670 ha, the widest version becomes the cheapest with the cost of £ 39.20/ha, approximately 10% less than the cost of 4.5 m version at that area. The 6 m version has lower cost from the area of 198 ha compared to 4.5 m version, because the purchase price per metre width of the implement of the 6 m version is lower than that of 4.5 m version.

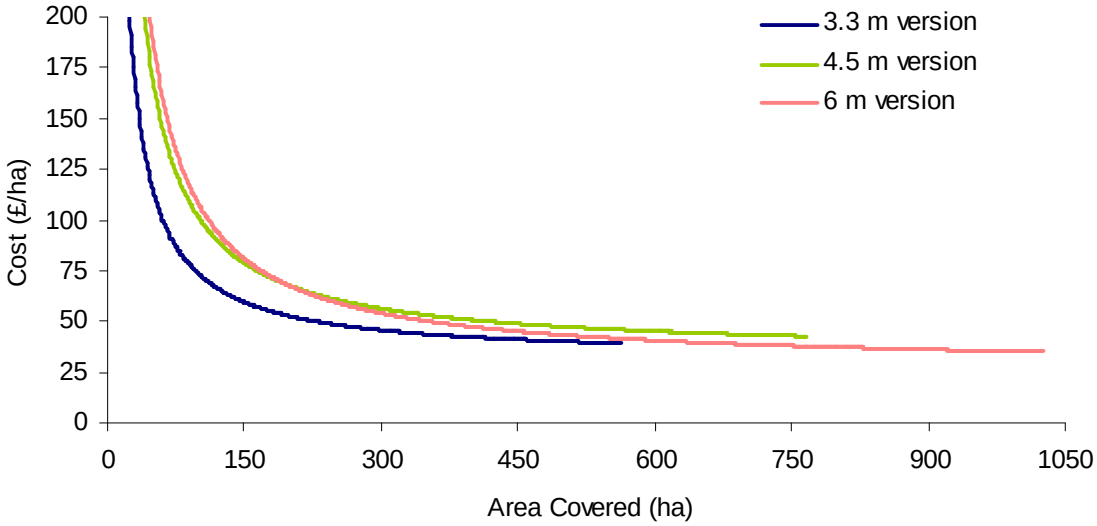


Figure 39. Operational costs of different widths of disc cultivator

The costs the 4.5 m version of the disc cultivator and one of the largest mouldboard ploughs available can be seen in Figure 40. The cost of 11 furrow mouldboard plough with width of 4.4 m is slightly lower than that of 4.5 m disc cultivator. At 693 ha, where the plough reaches the limit of 35 days, the cost is £ 40.81/ha for the plough and £ 43.65/ha for the disc cultivator. The costs of the comparable plough and one pass cultivator are similar, but after the ploughing an extra operation needs to be considered to level the soil surface. This can be performed by plough with integrated soil packer. The cost is £ 45.93/ha at 693 ha, about 5% more than the operating cost of the disc cultivator.

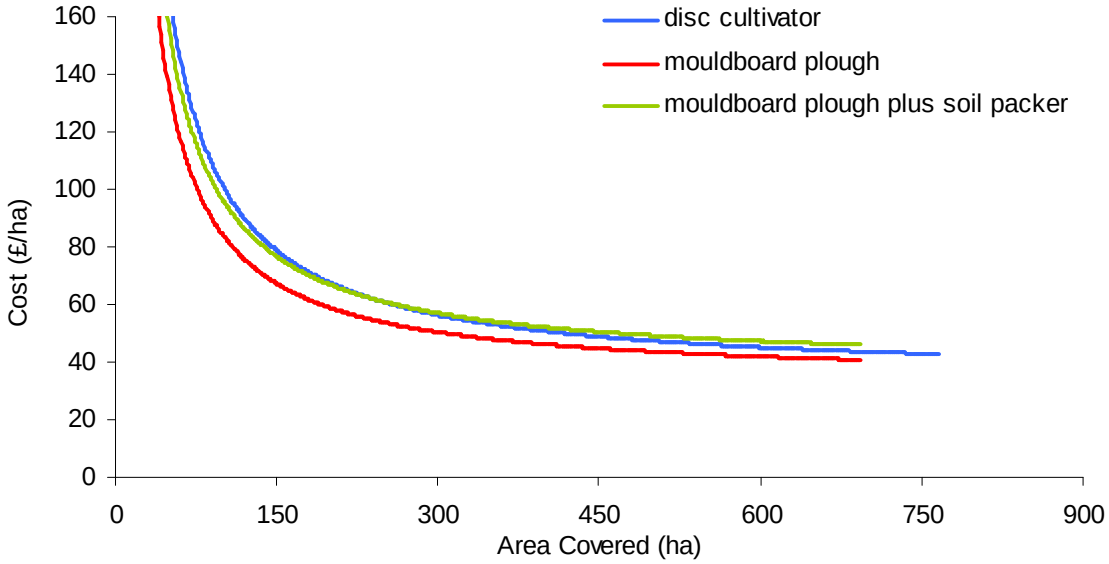


Figure 40. Comparison of the operational costs of mouldboard plough and disc cultivator

Finally, the complete tillage systems are included in the comparison. There is a large variety of implements, which can represent conventional system. Power harrow, tine cultivator or soil packer can follow the mouldboard plough. The combination of 6 furrow mouldboard plough with integrated soil packer and drill combination was chosen as it is the cheapest conventional system (*Figure 41*).

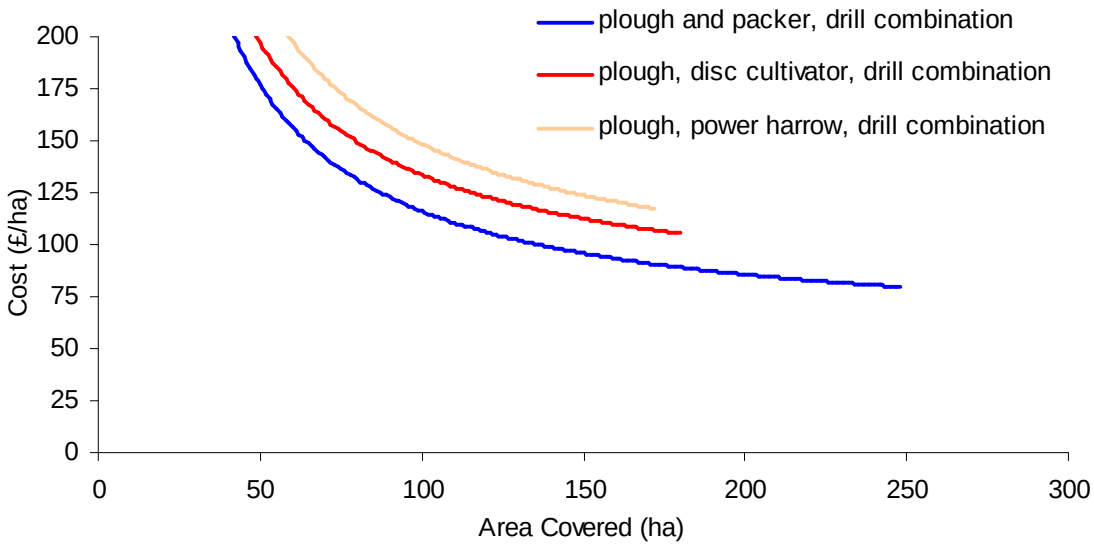


Figure 41. Comparison of the costs of different tillage systems based on ploughing

Shallow and faster ploughing was included as an alternative to standard plough cultivation. Minimum tillage is represented by a stubble cultivator and drilling combination. No-tillage practice is performed by a direct drill. The costs of the alternative tillage systems are presented in *Figure 42*. The operational costs at maximum output (35 day limit) of each tillage system are indicated. The 102 kW tractor was used for the cost calculations of alternative tillage implements. The standard plough system is the most expensive with low work rate. Its limit in 35 days is 248 ha. Faster shallow plough and drill has the maximum output of 302 ha. Positive effect of higher working speed results in the cost of approximately 9% lower than the cost of standard plough and drill at the maximum output. Minimum tillage further reduces cost and increases work rate. The cost of the minimum tillage at the area of 200 ha is £ 54.16/ha compared to £ 78.74/ha of shallow plough, £ 85.68/ha of standard plough and only £ 33.20/ha of no-tillage. The no-tillage is the cheapest system overall and covers the maximum area of 787 ha. The high work rate and only one pass over the field to establish the crop are the factors, which enables to reduce the operational cost to the possible minimum. Its cost at the area of 200 ha is 2.5 times lower than that of standard plough. As direct drilling practice is dependant on use of herbicides, the pre-cultivation spray is often performed. Adding the cost of chemicals and the application the cost of no-tillage increases. Up to 240 ha the no-tillage is the cheapest system, while than the minimum tillage becomes cheaper. At the maximum output of minimum tillage the cost is £ 44.07/ha compared to the cost of no-tillage with herbicide spray is £ 45.90/ha.

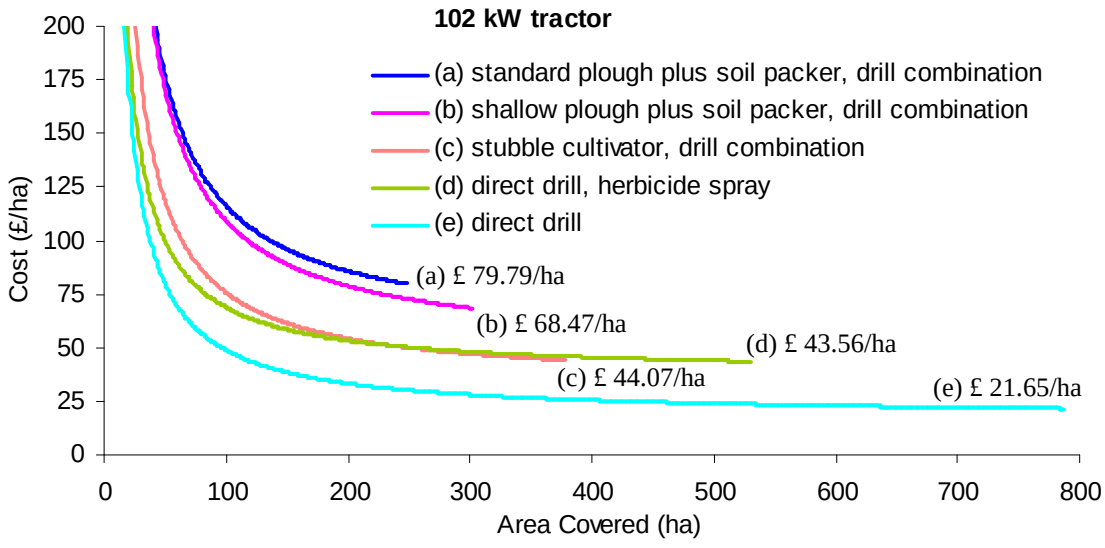


Figure 42. Cost comparison of alternative tillage systems (102 kW tractor)

The cost comparison of alternative tillage systems for larger tractors can be seen in *Figure 43* and *44*. The operational costs of each system, if 35 day limit is applied, illustrate similar relationships among the systems as those described for a 102 kW tractor.

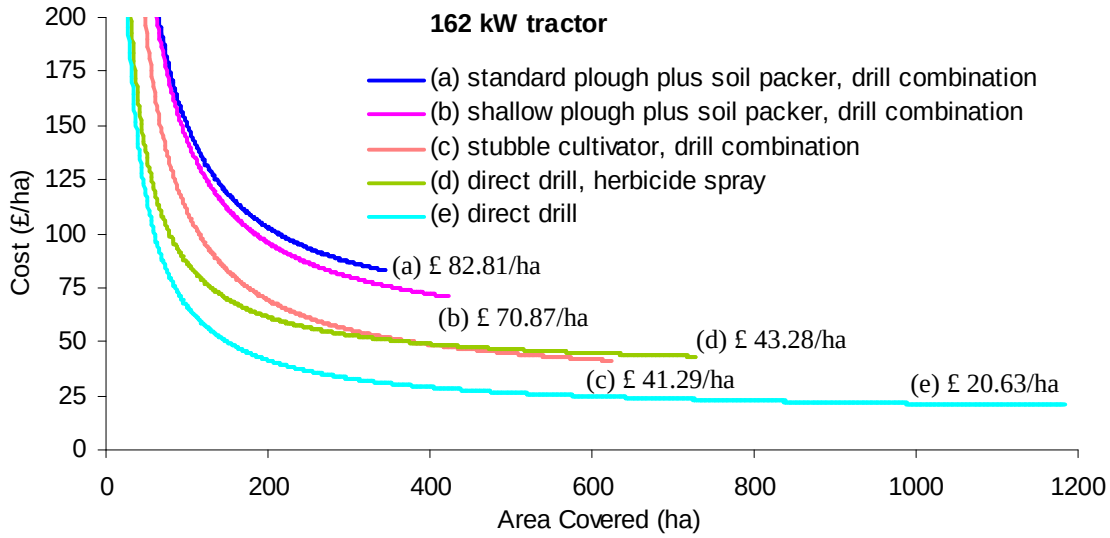


Figure 43. Cost comparison of alternative tillage systems (162 kW tractor)

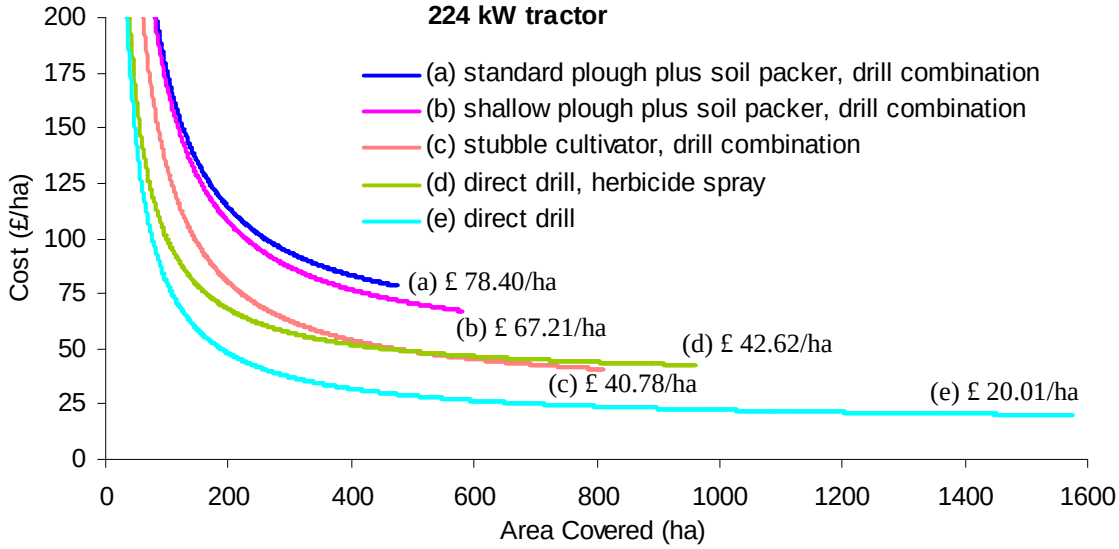


Figure 44. Cost comparison of alternative tillage systems (224 kW tractor)

5.6 Summary

Increasing the width of the implement increases the work rate and reduces the operational cost as the area increases. The cost of larger tillage combination is always higher than the cost of the smaller combination at the small area covered. The cost of 4 furrow plough at the area of 100 ha is £ 56.99/ha compared to the cost of 9 furrow plough of £ 86.85/ha. It must be noted that larger tillage combination enables to complete the task earlier, which is crucial especially if number of workdays is reduced. Generally, the operating costs reduce with area, but they are similar for all mouldboard plough at their maximum output.

Reducing the number of operations decreases the cost of tillage. The cost of the mouldboard plough with integrated soil packer is approximately 25% lower compared to the cost of two implements working separately.

Minimum and no-tillage systems of soil cultivation have higher output and lower operational costs than the conventional system irrespective of the depth of ploughing. Faster shallow ploughing reduces the cost compared to standard technique. At the area of 200 ha with a 102 kW tractor the cost of the shallow plough was approximately 8% lower than that of the standard plough. Significant cost savings are possible, if minimum cultivation is performed. The cost of minimum tillage decreases by 30% compared to conventional systems. No-tillage further reduces the cost and increases the output. As the herbicide is often applied to control the weeds in no-tillage system, the cost of direct drill with pre-cultivation spray is similar to that of minimum tillage. The difference in costs at 350 ha is only 3% in favour of minimum tillage.

6 Conclusions

The following conclusions can be made from comparisons of alternative tillage systems conducted in field and laboratory experiments and by the calculations of the costs of the various systems:

- Mouldboard and disc ploughs performed with similar specific resistance in the field, albeit the disc plough disturbed less soil. The mouldboard plough had the least specific resistance of all implements in the laboratory studies. The specific resistance of the disc plough was greater by a factor of 1.65.
- The mean value of specific resistance of 58.2 kN/m^2 and a range of 15 kN/m^2 of all implements in the field demonstrates similar field efficiency. The mean value of the specific resistance of the implements in the soil bin was 47 kN/m^2 with a range of +15/-17 kN/m^2. Excluding the mouldboard plough the mean specific resistance was 50 kN/m^2 with a range of +12/-5 kN/m^2. The mouldboard plough had a particularly low draught force of 1.44 kN, high disturbed area of 0.047 m^2 and therefore low specific resistance of 30.4 kN/m^2.
- Wing tines have the positive effect on tillage efficiency confirming earlier results by Spoor and Godwin, 1978 for deeper subsoiling equipment. Increasing the wing width from a plain tine to 220 mm increases draught force but reduces specific resistance. The winged tines had a lower specific resistance from the plain tine by approximately 10%.
- Tine efficiency was improved as the tine spacing of 335 mm was reduced to 225 mm. Closer tine spacing reduced the draught force requirements by 26% and disturbed a similar area to wide tine spacing. The performance of close and wide tines confirms the relationship between tine spacing and draught force, area of disturbance and specific resistance and agrees with the research conducted by Spoor and Godwin, 1978 and Godwin et al., 1984.
- Disc implements produced an upward vertical force preventing penetration into the soil. All other implements had downward vertical force which has positive effect on penetration.
- To use the maximum available power of 86 kW tractor, the 4 furrow plough used in the field could be replaced by 5 furrow plough. The work rate of 5 furrow plough is greater by 20% than that of 4 furrow plough at the same

working speed. The operational cost of 5 furrow plough of £ 40.61/ha at 269 ha is 18% lower than the cost of 4 furrow plough of £ 47.85/ha.

- Increasing the width of the implement increases the work rate and decreases the operating costs. When the implement is not maximally utilised, the smaller combination of tractor and implement can be cheaper. The cost of 4 furrow plough at the area of 100 ha is £ 56.99/ha compared to the cost of 9 furrow plough of £ 86.85/ha.
- No-tillage is the cheapest system comparing to the minimum tillage and conventional practice. The cost of tillage decreases as the standard plough is replaced by shallow faster plough. The cost of standard plough at the area of 200 ha is £ 85.68/ha compared to £ 78.74/ha of shallow plough, £ 54.16/ha of minimum tillage and £ 33.2/ha of no-tillage, all systems with same 102 kW tractor. If the cost of herbicide application is included in no-tillage system, the cost per hectare is similar to minimum tillage with a difference of only 3% in favour of minimum tillage. The costs in £/ha for all sizes of the various tillage systems based upon 102, 162, 224 kW tractors are approximately the same. Their average costs at maximum output and their ranges are: £ 80.33/ha and £ +2.48/-1.93/ha – mouldboard plough, £ 68.85/ha and £ +2.02/-1.64/ha – shallow mouldboard plough, £ 42.05/ha and £ +2.02/-1.27/ha – stubble cultivator, £ 20.76/ha and £ +0.89/-0.75/ha – direct drill and £ 43.15/ha and £ +0.41/-0.53/ha – direct drill with herbicide application.

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Appendices

Appendix 1 Paper presented at XXXII CIOSTA – CIGR Section V Conference in Nitra, Slovakia

Advances in labour and machinery management for a profitable agriculture and forestry

17. - 19. september 2007, Slovak University of Agriculture, Nitra, Slovakia

Performance of alternative tillage systems

P. Vozka[1], C. Bosrotsi[1], M.J. O'Dogherty[1], R.J. Godwin[1]

[1] Cranfield University at Silsoe, Silsoe, Beds MK45 4DT, UK

E-mail of corresponding author: p.vozka@cranfield.ac.uk

Summary

This paper reviews the basic energy demands of a range of alternative agricultural tillage systems. Tillage implements play a crucial role in the area of seed bed preparation whether the source is human, animal or mechanical power. To determine the effects of alternative tillage implements working at different depths, soil bin studies and on-farm experiment were conducted. The base of the experiment is to determne tillage implement performance in terms of draught force requirements, soil disturbance and specific resistance.

Key word: *draught force, tillage, soil disturbance, energy*

Introduction

Tillage is regarded as a key operation in global agriculture, and has a great influence on the performance of the crop production system. A variety of implements can be used to create the optimum environment to grow crops from seed germination to root growth, fertilizers and pesticides incorporation, as well as weed and moisture control. The set of implement which an individual farmer chooses for any of the task depends on local customs, soil type, weed and pests situation, crop type and the amount of plant residue from the previous crop. Mouldboard or disc ploughs and the combinations of tines or discs and various kinds of harrows are the major types of the cultivation implements. Mouldboard ploughs are widely used because of their ability to create a fine seedbed and burial of trash and weed seeds. Disc ploughs are easy to use and they have great versatility in land preparation. Tines are suitable for shallow cultivation in both arid and semi-arid regions.

A number of studies have been conducted to evaluate the draught force of mouldboard ploughs, taking into account the effect of soil properties, plough geometric factors, and the effect of ploughing speed (Wheeler and Godwin, 1996; Saunders, 2002; Godwin et al., 2007). Numerous studies were carried out to investigate force mechanics of discs (Godwin et al., 1987; Al-Ghazal, 1989). Investigations into the forces acting on differently designed tines were also made (Godwin and Spoor, 1977; Godwin, 2007). At present, there is limited recent information on the comparable performance of mouldboard, disc and tine implements working under the same conditions. The objective of this paper is to compare the performance of these implements both in controlled laboratory and in field conditions with the same Cottenham series, sandy loam soil (King, 1969).

Material and methods

The field experiment was conducted on the demonstration field of the Cranfield University at Silsoe. The soil was sandy loam type with moisture content of 13,62 % with

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the physical properties identical to the parameters of the soil used for the laboratory experiments (as specified below). The field experimentation examined the tractor field draught force and the performance for a range of implements. The tractors used in the execution of the field experiments were 125 hp and 85 hp 4WD tractors. The experiment was completely randomized with two replications. Forward speed was maintained at 5 km/h and the distance of each test was approximately 70 meters. The tillage implements involved were:

- A 4-furrow reversible mouldboard plough with a furrow width of 380 mm operating at depths of 200 mm (*mouldboard plough deep*) and 150 mm (*mouldboard plough shallow*).
- A 3-furrow disc plough (*disc plough*) with a furrow width of 305 mm, disc diameter 660 mm, disc angle 50°, tilt angle 22°, working at a depth of 200 mm.
- 7 winged tines consisting of 235 mm wide full sweep bottoms, rake angle 25°, two spacings of total implement width 1580 mm (*close tines*) and 2250 mm (*wide tines*), work depth 100 mm.
- Tandem abreast disc harrow (*disc harrow*) comprises of four gangs assembly. The front gangs are made up of 12 scalloped discs each of 508 mm diameter with disc spacing of 235 mm and gang angle of 23°. Rear gangs consist of 14 plain discs (of same diameter as front discs) with disc spacing of 187 mm and gang angle of 18° with a working depth of 60 mm.

The preliminary field measurements were carried out to investigate the rolling resistance of the two tractors. The tractor with the selected test implements was then drawn twice in each run to determine the implement gross draught force in both descending and ascending field application. A 5 ton digital tension meter was located between the towing cables connecting the two tractors to display the actual draught force.

In an addition to the field experiments a laboratory experiment was carried out under controlled conditions in the Cranfield University soil bin. The soil bin consists of a rectangular shape sub-surface tank with multi purpose processor which enables the creation of a uniformly compacted soil condition. The soil used for the experiment was a sandy loam with a moisture content and bulk density of 6,37% and 16,62 kN/m^3, respectively. The cohesion coefficient and angle of internal friction are typically 11 kN/m^2 and 30°, the angle of soil-metal friction 20°. The speed was set to 1,5 m/s (5,4 km/h) to correspond with the speed maintained during the field experiments. An extended octagonal ring transducer (Godwin, 1975) was attached to the processor to measure horizontal and vertical forces of the implement. The soil bin experiment was completely randomized with three replications and involved the implements listed below:

- A single furrow mouldboard plough (*mouldboard plough*) with a furrow width of 305 mm and a depth 150 mm.
- A disc implement with a diameter of 607 mm, with two settings was maintained for the experiment: a disc angle of 46°, tilt angle 21°, depth 150 mm, width of furrow 300 mm representing a disc plough (*disc plough*) whiles a disc angle of 22°, depth 75 mm, width of furrow 260 mm representing the disc harrow (*disc harrow*).
- Winged tines made up of four different wing widths: 220 mm (*220 tine*), 170 mm (*170 tine*), 120 mm (*120 tine*) and a plaintine with no wing attached (*plaintine*). The four versions of the tine implements used for the experiment were operating at a depth of 150 mm and a rake angle of 30° including the width of tine 25 mm.

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The statistical analysis was carried out on force measurements for both field and laboratory experiments including analysis of variance and the least-significant difference test (lsd) at a 5% probability level.

Results and Discussion of Results

The draught forces of each implements and the draught force per unit implement from the field experiment are plotted in *Figure 1*. While draught force of the deep mouldboard plough is significantly higher than the draught force of the disc plough, there is a little difference in their draught force per unit implement. Draught forces per unit implement of wide tines and the close tines are not significantly different. The draught force per unit implement of disc harrow has the lowest value, as a result of its shallower working depth.

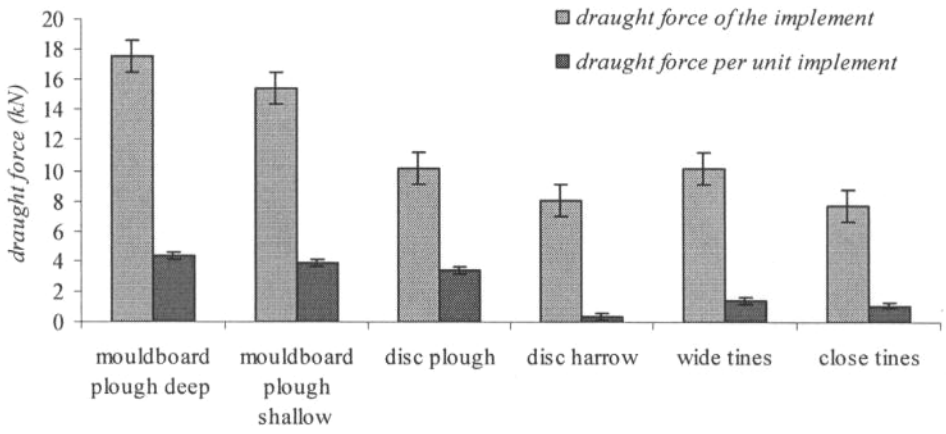

Figure 1: Draught force of the implements and draugh force per unit implement of the field experiment (error bars indicate confidence interval at 95% probability level).

The disturbed soil of the cross-section area of a single pass of the implements was escavated and a profile meter was used to determine the area of disturbance as shown in *Figure 2* for the wide and close tines. Specific resistance, which is defined as the draught force requirement per unit area of soil disturbance, was calculated to indicate overall tillage efficiency. The area of disturbance is decreasing from mouldboard plough deep to close tines, as shown in *Figure 3*. Specific resistance of all implements is similar – with a mean of 58 kN/m^2 and a range of 15 kN/m^2 – though mouldboard and disc ploughs were working twice as deep as tine implements and more than three times deeper than disc harrow.

Draught and vertical forces of the implements measured in the soil bin are shown in *Figure 4*. Negative values of vertical force indicate downward reaction, while positive values represent upward reaction, which means poor soil penetration. Reducing the disc and tilt angles of disc harrow implement resulted in significant rise of vertical force compare to disc plough. The highest draught force value occurred with the disc plough, while draught force of mouldboard plough was similar to the 170 tine. There is approximately 50% rise in draught force from plaintine to 220 tine.

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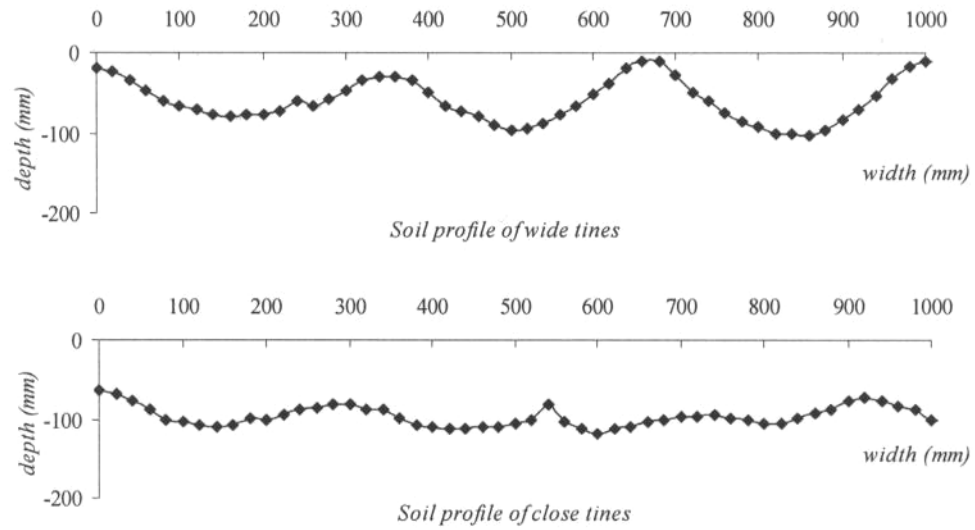

Figure 2: Soil profiles of the wide and close tines

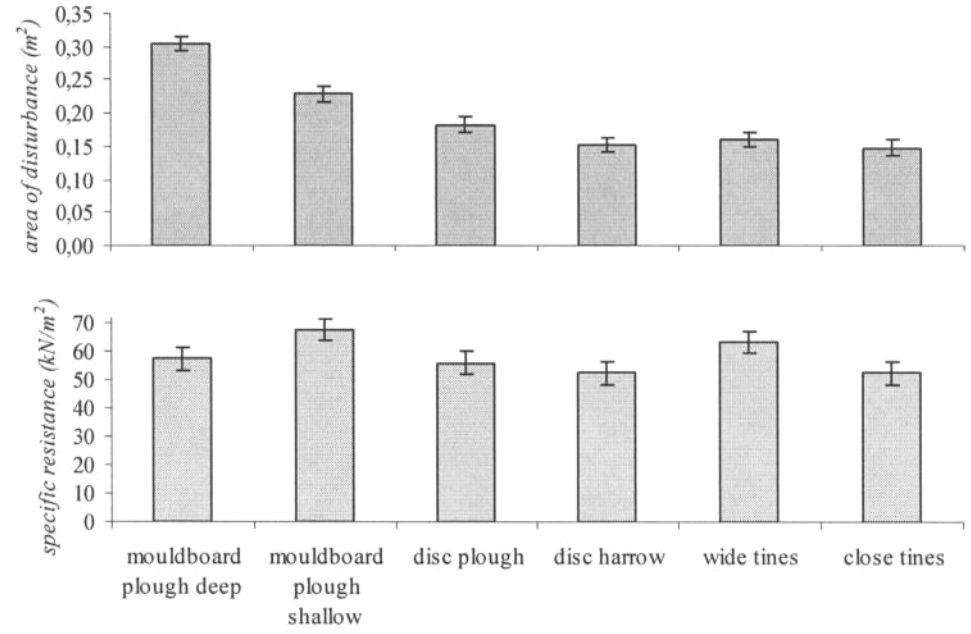

Figure 3: Area of disturbance and specific resistance of the implements of the field experiment (error bars indicate confidence interval at 95% probability level).

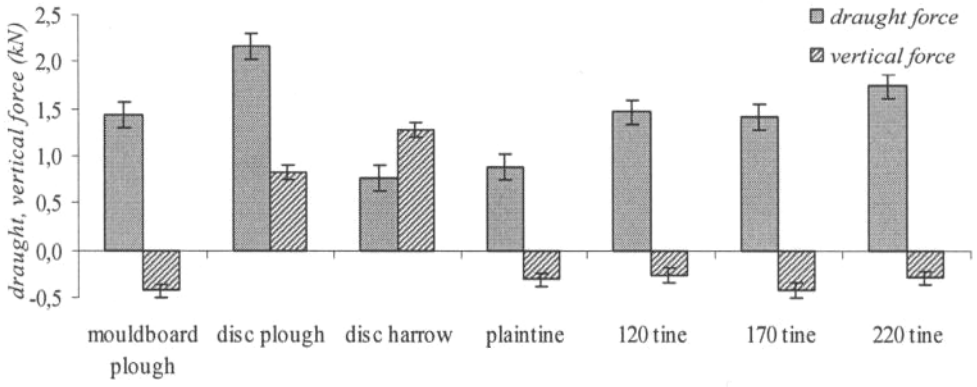

Figure 4: Draught and vertical forces for the implements of the soil bin experiments (error bars indicate confidence interval at 95% probability level).

The area of disturbance was measured for all of the test implements. When using a plough body, an open furrow was created into which the soil slice was turned. Both the mouldboard and the disc plough disturbed most soil as shown in *Figure 5*. Values of specific resistance illustrate that the moulboard plough had the lowest specific resistance, 40% lower than the disc plough. Although the disc harrow was working at half the depth of the disc plough, the area of disturbance was less than 30% of the area disturbed by disc plough. As a result, it registered the highest specific resistance of all implements.

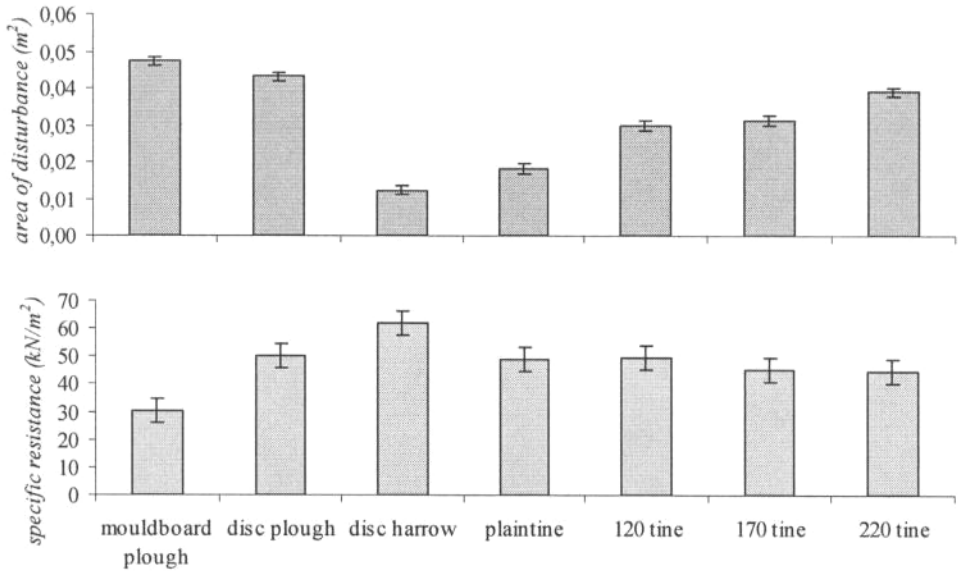

Figure 5: Area of disturbance and specific resistence of the implements performed in the soil bin experiments (error bars indicate confidence interval at 95% probability level).

Increasing the wing width from the plaintine to 220 mm tine increased the draught force (*Figure 6*). There is a slight discontinuity for the 170 tine, where the wings were mounted onto a second tine with similar but not identical geometry to the others. Comparing the effect of wing width shows the clear tendency to increase the area of disturbance and decrease the specific resistance as the width of the wing tine increases. This confirms earlier studies conducted by Spoor and Godwin, 1978 that a winged tine has a lower specific resistance than the plaintine of approximately 10%.

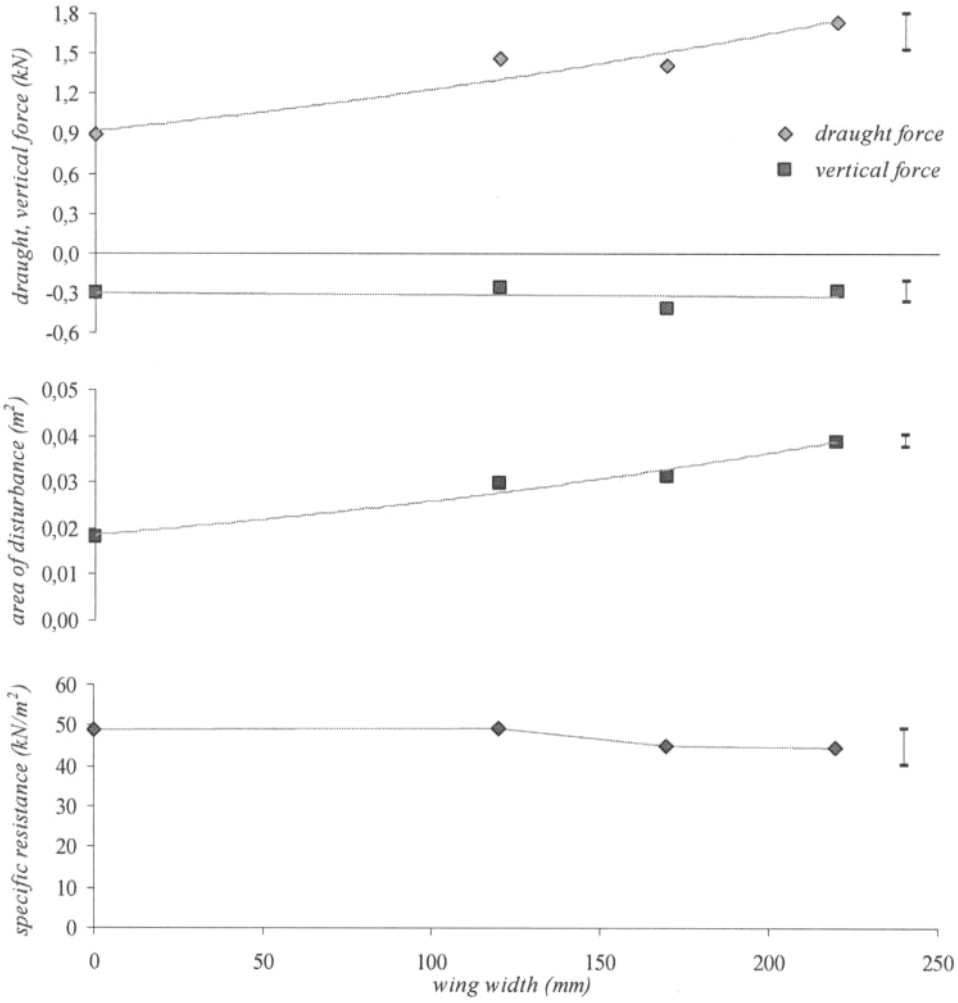

Figure 6: Draught and vertical forces, area of disturbance and specific resistance of different wing width tines from the soil bin experiements (confidence interval at 95% probability level).

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The specific resistance of the mouldboard plough in the field experiment was more than twice the magnitude of the mouldboard plough working at same depth in the soil bin (see *Figure 7*). The biggest difference of all implements between the values of specific resistance on the field and in the soil bin illustrates that mouldboard plough not only disturbs soil but also turns it and that is more influenced by the soil conditions. Disc plough performed similar in both experiments, though the depth of work was different. Comparing disc harrow, specific resistance calculated from the field was 85% of the value from the soil bin. The close spaced tines had lower specific resistance in the field than the wider spaced tines as a result of a lower draught force and a similar area of disturbance, albeit with a none uniform depth of disturbance (see *Figure 2*). This shows the positive effect of multiple implements on reduced energy requirements as demonstrated by Godwin et al., 1984.

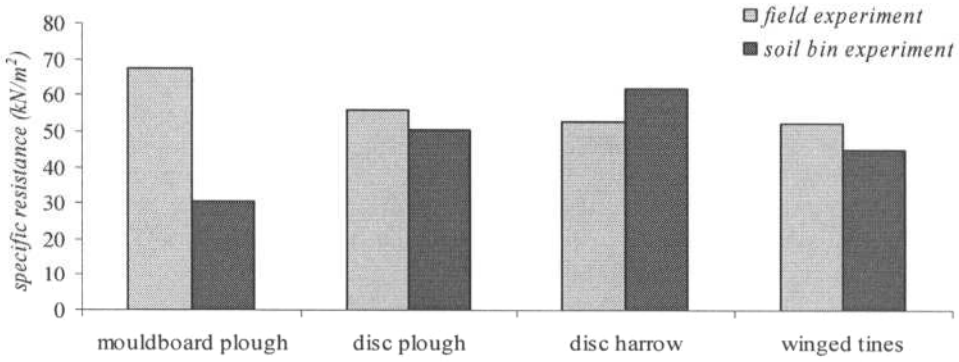

Figure 7: Specific resistance of the comparable implements in the field and soil bin experiments.

Conclusion

Winged tines have the positive effect on tillage efficiency. Incresing wing width increases draught force but reduces the specific resistance by about 10%.

The effect of tines spacing in the field showed that close tines with tine spacing of 225 mm gave a 20% reduction in specific resistance from wide tines with tine spacing of 335 mm. Close tines reduced the draught force requirements by 26% and disturbed a similar area to wide tines. The performance of close and wide tines confirms the relationship between tine spacing and draught force, disturbed area and specific resistance (Godwin et al., 1984) and recommended practical spacing for good soil loosening of approximately 2x depth of work for winged tines (Spoor and Godwin, 1978).

Mouldboard and disc plough studies on the field showed similar specific resistance albeit the disc plough disturbed less soil. In the laboratory the area of disturbance of moudboard and disc plough was similar, but the specific resistance of disc plough was greater by a factor of 1,65.

Disc implements produced an upward vertical force preventing penetration. All other implements had downward vertical force enabling penetration into the soil.

The mean value of the specific resistance of all implements studied in the field experiment was 58 kN/m^2 with a range of +9/-6 kN/m^2, and 47 kN/m^2 and +15/-17 kN/m^2, respectively in the soil bin experiment. With the exception of the mouldboard plough the mean value of the specific resistance in the soil bin was 50 kN/m^2 with a range of +12/-5 kN/m^2. The mouldboard plough had a particularly low draught force, high disturbed area and therefore low specific resistance. This comparison shows that alternative tillage implements at the depth range studied have a similar specific resistance.

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Appendix 2 Results from the field experiment

Field experiment: day 1 (16.4.2007) Settings and adjustments on adjacent plot

	Tractor. implement	Distance [m]	Time [s]	Speed [m/s]	Wheel slip
Wheel slip preliminary measurements	MF 6180	49.1	88.00	0.56	Zero
	MF 390 *towed distance*	45.4	164.80	0.28	Zero
	MF 390+disc plough	41.0	21.15	1.94	0.10
	engaged	36.8	24.42	1.51	0.19
					avg 0.14
	MF 390+disc plough	40.0	26.77	1.49	0.12
	not engaged	44.2	29.80	1.48	0.03
	driven				avg 0.08
	MF 6180+mouldb plough	42.7	33.65	1.27	0.13
	engaged	42.3	33.63	1.26	0.14
					avg 0.14
	MF 6180+mouldb plough	48.5	37.44	1.30	0.01
	not engaged	47.6	36.82	1.29	0.03
	driven				avg 0.02
	MF 390+disc harrow	33.9	38.00	0.89	0.25
	engaged	*negative weight transfer*			
	MF 390+disc harrow	41.3	33.60	1.23	0.09
	engaged	42.5	35.80	1.19	0.06
	after adjustment	43.1	33.10	1.30	0.05
					avg 0.07

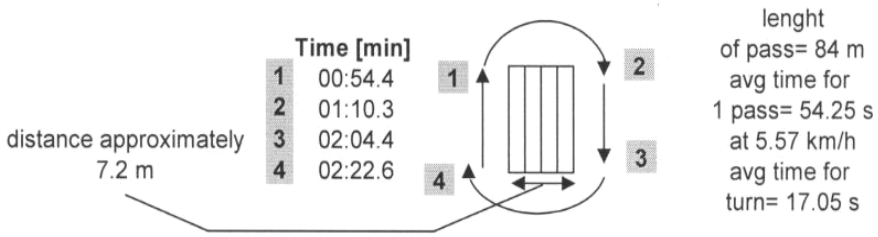
		Draught force [kN]		
Draught force-rolling resistance of the tractors	**MF 390**	3.64	2.90	**Average**
		3.80	3.20	**3.35**
		2.93	3.64	
	MF 6180	4.12	3.90	**Average**
		3.70	4.00	**3.68**
		2.70		

Field experiment: day 2 (17.4.2007)
University test plot

Wheel slip	Tractor & implement	Distance [m]	Time [s]	Speed [m/s]	Wheel slip
	MF 390+disc plough	40.3	35.9	1.12	0.11
disc plough		40.3	33.1	1.22	0.11
depth 200 mm		39.6	34.8	1.14	0.13
speed 5 km/h		39.5	35.1	1.13	0.13
				avg	**0.12**

Draught force	Draught force [kN]			
	down		*and back*	
	12.98	12.98	13.66	13.12
	13.14	13.24	11.76	14.34
	14.40	12.02	12.84	13.10
	12.02	13.50	12.50	14.76
	13.72	15.60	13.44	13.68
	13.20	13.12	13.28	14.20
	12.70	16.04	14.46	13.26
	13.16	13.40	13.24	14.04
	13.50	13.18	15.56	13.30
	13.54	12.96	14.78	14.14
	avg	**13.42**	**avg**	**13.67**
	total avg	**13.55**		

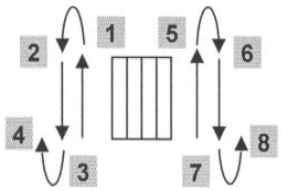
Work rate



Wheel slip	MF 6180+mouldb plough	Distance [m]	Time [s]	Speed [m/s]	Wheel slip
		44.5	34.5	1.29	0.09
mouldboard		45.3	34.1	1.33	0.08
plough deep		45.6	35.8	1.27	0.07
depth 200 mm		45.7	36.9	1.24	0.07
speed 5 km/h				**avg**	**0.08**

Draught force	Draught force [kN]			
	down		*and back*	
	23.04	22.68	19.98	19.96
	22.10	22.26	21.60	20.56
	21.48	22.18	20.10	19.84
	20.78	20.68	19.28	20.82
	21.08	23.48	**avg**	**20.27**
	20.52		**total avg**	**21.18**
	avg	**21.84**		

Work rate



	Time [min]		Time [min]	
1	00:49.2	5	00:51.4	
2	01:17.2	6	01:16.0	
3	01:59.8	7	02:06.9	
4	02:27.0	8	02:34.3	
	lenght 83.5 m		89.6 m	

avg time for pass= 45.9 s, resp. 51.15 s at 6.55 km/h, resp. 6.31 km/h
avg time for turn= 26.8 s

Wheel slip	MF 6180+mouldb plough	Distance [m]	Time [s]	Speed [m/s]	Wheel slip
		45.7	38.2	1.20	0.07
mouldboard		46.4	36.3	1.28	0.05
plough shallow		47.7	32.1	1.49	0.03
depth 150 mm		46.5	31.7	1.47	0.05
speed 5 km/h				**avg**	**0.05**

Draught force		**Draught force [kN]**			
		down		*and back*	
		20.22	19.70	18.50	17.88
		20.06	22.00	17.22	19.68
		21.16	19.32	19.04	18.58
				17.24	19.32
				19.48	17.26
				18.10	20.38
				18.50	19.20
		avg	**20.41**	**avg**	**18.60**
		total avg	**19.14**		

Wheel slip	MF 390+winged tines	Distance [m]	Time [s]	Speed [m/s]	Wheel slip
		42.4	33.2	1.28	0.07
close tines		41.8	34.0	1.23	0.08
depth 100 mm		42.1	38.4	1.10	0.07
speed 5 km/h		42.4	38.2	1.11	0.07
				avg	**0.07**

	day 3 (18.4.2007)	**Draught force [kN]**			
		down		*and back*	
		9.56	10.62	10.74	8.78
		12.80	10.10	9.64	10.74
		12.14	12.46	11.96	9.42
		10.46	13.52	10.40	12.52
		11.14	10.60	11.78	
		11.66	12.06		
		avg	**11.43**	**avg**	**10.66**
		total avg	**11.10**		

Wheel slip	MF 390+disc harrow	Distance [m]	Time [s]	Speed [m/s]	Wheel slip
		43.0	31.2	1.38	0.05
disc harrow		42.0	29.4	1.43	0.07
depth 60 mm		42.6	29.7	1.43	0.06
speed 5 km/h		41.2	30.8	1.34	0.09
(higher speed=				**avg**	**0.07**
ridge in the					
middle)		**Draught force [kN]**			
		down		*back*	
		9.76	9.90	11.24	11.76
		10.18	11.58	12.18	11.46
		10.98	11.10	12.04	11.70
		10.54	11.90	12.22	12.16
		11.26	10.94	10.54	11.60
		10.80	11.36	11.62	11.78
		11.12	11.74	11.86	12.08
		11.54	12.34	12.14	11.16
		avg	**11.07**	**avg**	**11.72**
		total avg	**11.39**		

Wheel slip	MF 390+winged tines	Distance [m]	Time [s]	Speed [m/s]	Wheel slip
		44.4	28.3	1.57	0.02
wide tines		42.4	27.7	1.53	0.07
depth 100 mm		40.7	34.2	1.19	0.10
speed 5 km/h				**avg**	**0.06**
		Draught force [kN]			
		down		*back*	
		14.44	15.10	9.70	14.04
		14.70	13.20	13.66	12.96
				13.64	14.00
		avg	**14.36**	**avg**	**13.00**
		total avg	**13.54**		

	mouldboard plough deep	mouldboard plough shallow	disc plough	disc harrow	wide tines	close tines
Mean net draught force (kN) *)	**17.50**	**15.46**	**10.20**	**8.04**	**10.19**	**7.75**
1st rep mean (kN)	18.16	16.73	10.07	7.72	11.01	8.08
2nd rep mean (kN)	16.59	14.92	10.32	8.37	9.65	7.31
Area of disturbance (m^2)	**0.305**	**0.229**	**0.183**	**0.153**	**0.161**	**0.148**
Specific resistance (kN/m^2)	**57.41**	**67.63**	**55.80**	**52.53**	**63.26**	**52.37**

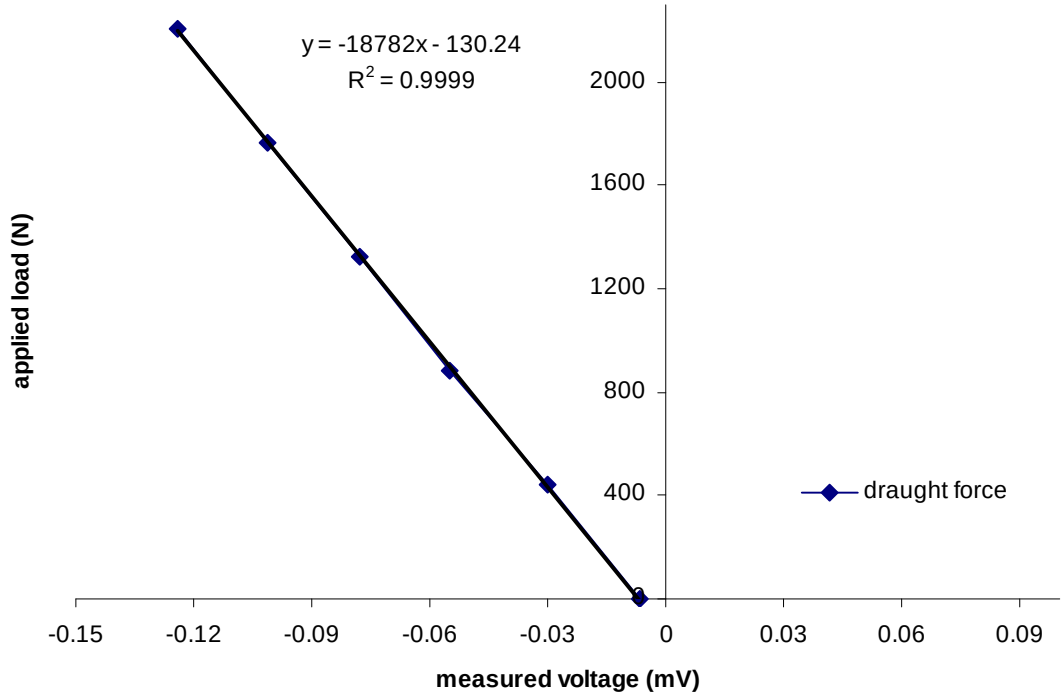
*) The net draught force was calculated subtracting tractor rolling resistance from measured implement draught force.

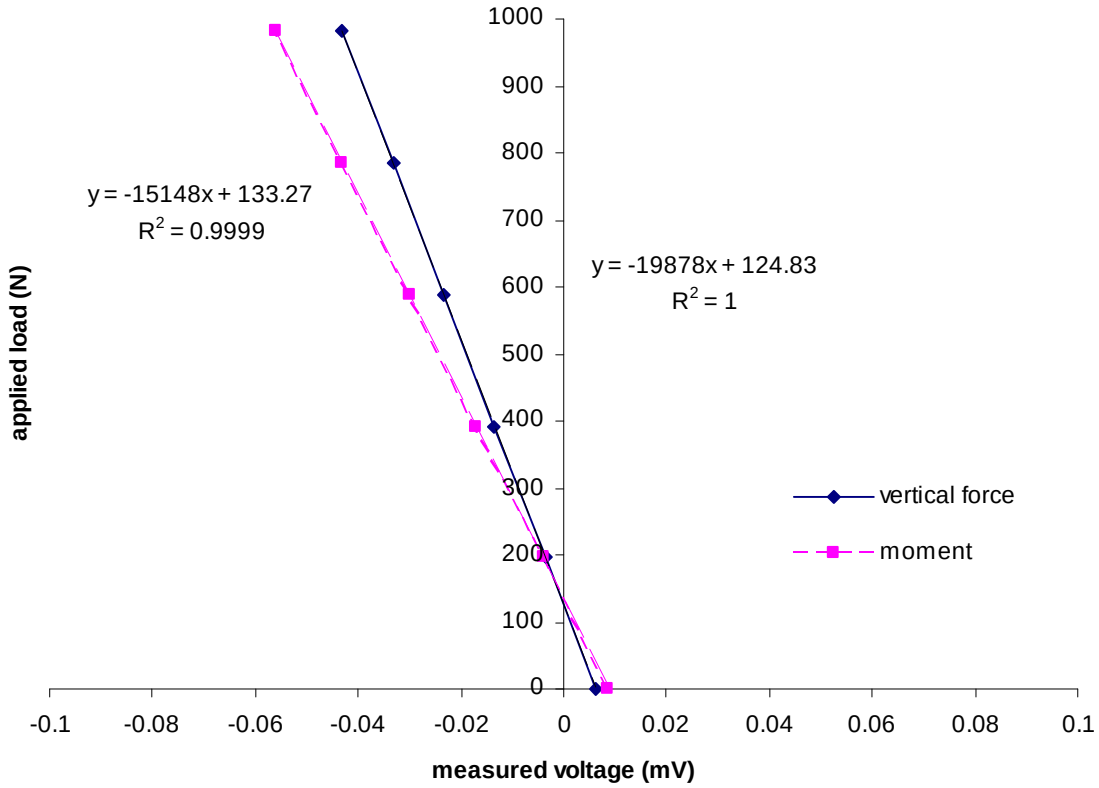
Appendix 3 Moisture content and bulk density results from the soil bin

Soil bin number/ replication	Moisture content d.b. %	Bulk density kN/m^3	Soil bin number/ replication	Moisture content %	Bulk density kN/m^3
1/1	6.92	16.39	7/1	5.93	16.60
1/2	6.50	15.25	7/2	6.03	15.32
1/3	7.06	18.67	7/3	6.40	17.12
2/1	6.57	18.33	8/1	6.01	15.70
2/2	6.14	16.08	8/2	6.44	15.37
2/3	4.97	15.66	8/3	6.15	16.28
3/1	5.89	15.71	9/1	6.23	15.92
3/2	5.98	15.03	9/2	7.16	18.36
3/3	6.16	16.26	9/3	7.08	17.55
4/1	6.59	15.85	10/1	6.71	16.82
4/2	6.28	15.05	10/2	6.95	17.51
4/3	6.23	15.89	10/3	6.93	17.92
5/1	6.85	17.59	11/1	6.68	16.45
5/2	6.20	16.40	11/2	6.17	16.08
5/3	6.02	15.49	11/3	6.37	16.09
6/1	6.18	16.21	12/1	6.49	16.93
6/2	6.21	16.26	12/2	6.74	16.80
6/2	5.86	16.49	12/3	6.53	17.93

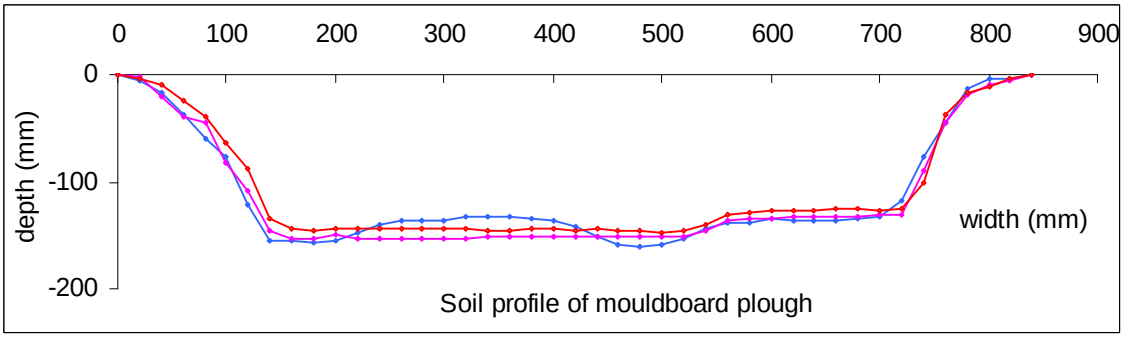
Average moisture content	6.37%
Average bulk density	16.48 kN/m^3

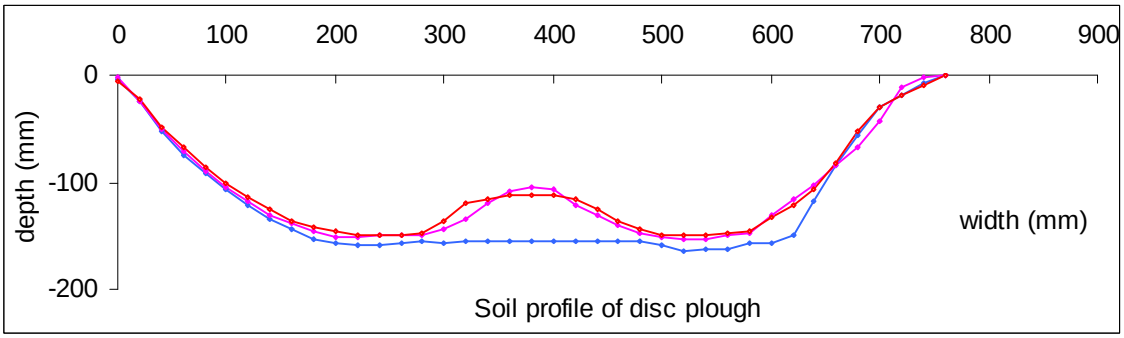
Appendix 4 Calibration graphs for horizontal and vertical forces and resulting moment (soil bin experiment)

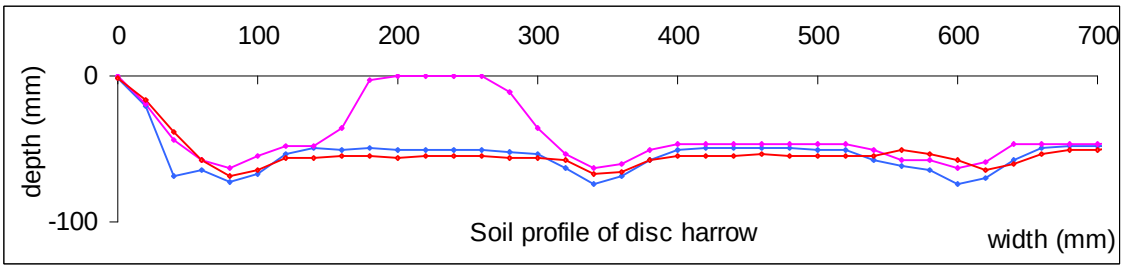


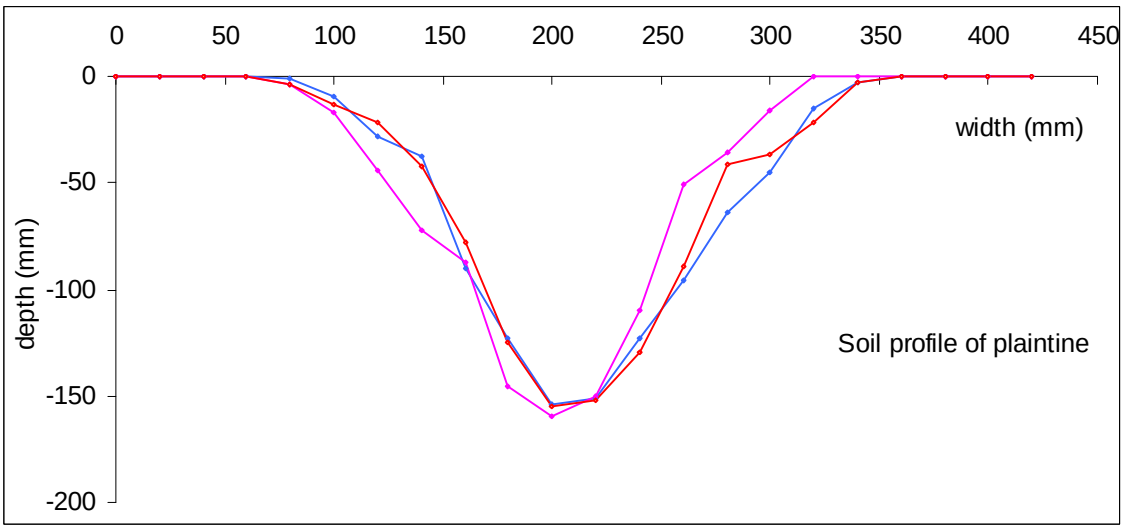


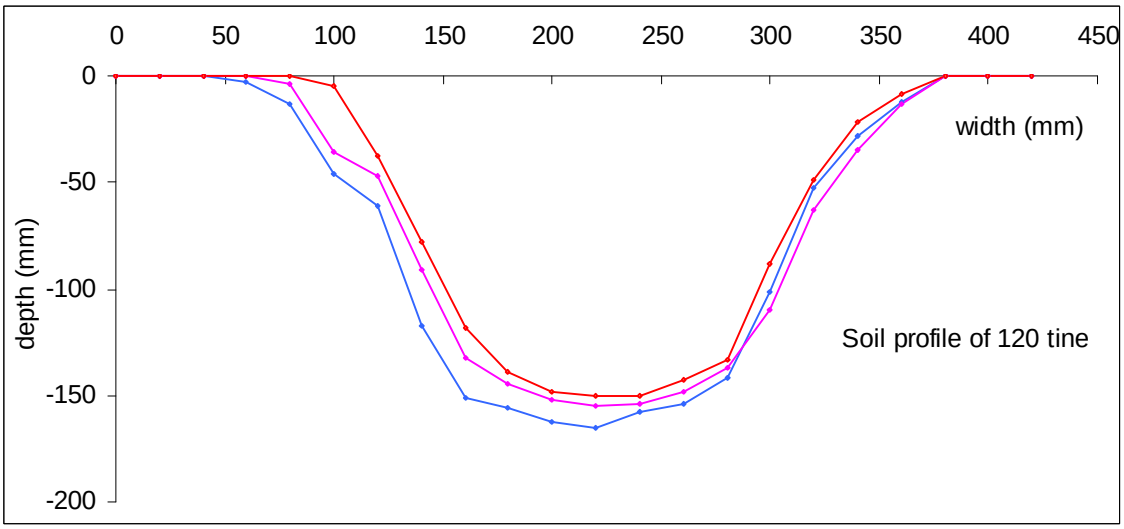
Appendix 5 Soil profiles of the implements in the soil bin experiment

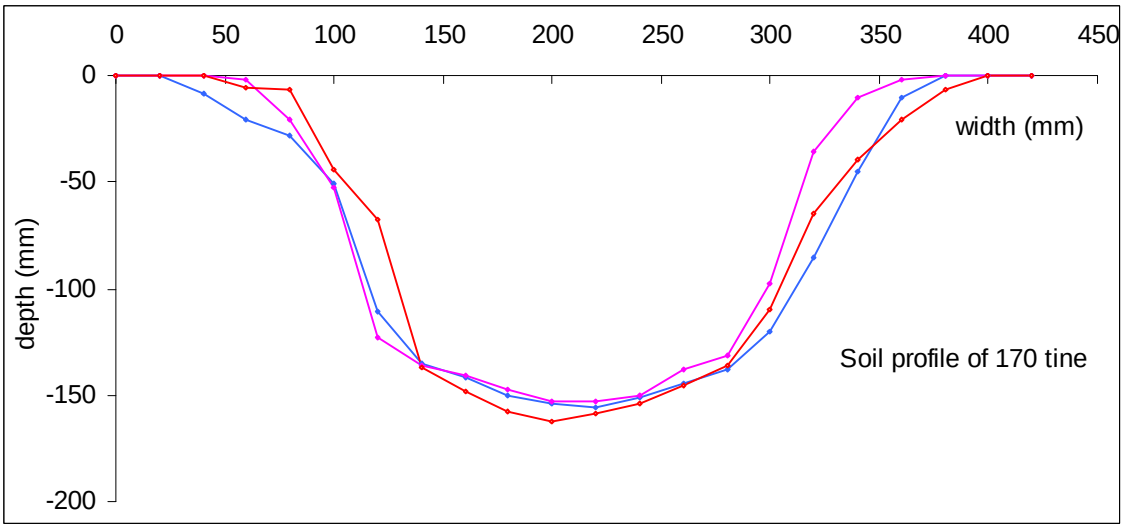









0
50
100
150
200
250
300
350
400
450
0
-50
-100
-150
-200
depth (mm)
width (mm)
Soil profile of 120 tine


0
50
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450
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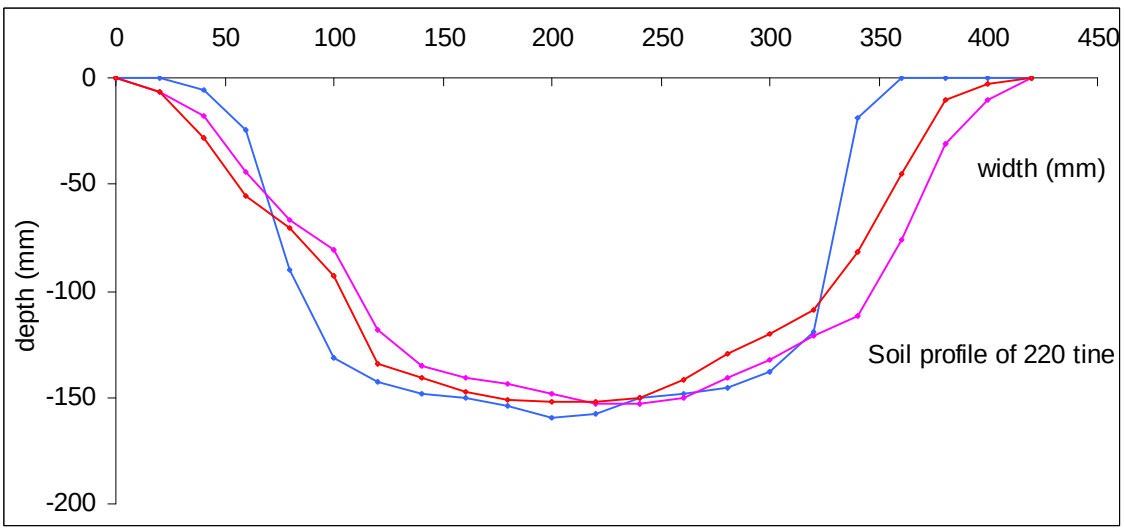
-50
-100
-150
-200
depth (mm)
width (mm)
Soil profile of 170 tine


0
50
100
150
200
250
300
350
400
450
0
-50
-100
-150
-200
depth (mm)
width (mm)
Soil profile of 220 tine

Appendix 6 Results from the soil bin experiment

Draught force, vertical force and resulting moment

plaintine	draught (kN)	vertical (kN)	moment (Nm)
L	1.03	-0.35	731.42
M	0.88	-0.31	620.92
R	0.76	-0.26	541.07
average	0.89	-0.31	631.13

120 tine	draught (kN)	vertical (kN)	moment (Nm)
M	1.55	-0.30	1130.72
L	1.56	-0.26	1152.71
R	1.29	-0.23	945.05
average	1.46	-0.26	1076.16

170 tine	draught (kN)	vertical (kN)	moment (Nm)
L	1.60	-0.47	1153.34
M	1.29	-0.41	910.19
R	1.33	-0.38	923.32
average	1.41	-0.42	995.62

220 tine	draught (kN)	vertical (kN)	moment (Nm)
L	1.82	-0.27	1338.79
R	1.64	-0.29	1196.30
M	1.77	-0.31	1280.30
average	1.74	-0.29	1271.80

MP	draught (kN)	vertical (kN)	moment (Nm)
1	1.63	-0.39	1441.44
2	1.34	-0.46	1121.22
3	1.34	-0.43	1133.39
average	1.44	-0.43	1232.02

DP	draught (kN)	vertical (kN)	moment (Nm)
1	2.17	0.89	1661.92
2	2.40	0.92	1884.06
3	1.92	0.66	1476.33
average	2.16	0.82	1674.10

DH	draught (kN)	vertical (kN)	moment (Nm)
1	0.69	1.11	775.88
2	0.79	1.34	900.10
3	0.80	1.38	922.34
average	0.76	1.28	866.11

first column:
R, L, M - position in the soil bin: Right, Left, Middle
MP - mouldboard plough, DP - disc plough, DH - disc harrow
1, 2, 3 - replication number

Area of disturbance measured using profile meter and planimeter

Area of disturbance (cm^2)

plaintine		test run 1	test run 2	test run 3
	rep I	188	182	194
	rep II	184	184	178
	rep III	180	170	176
			average	181.78
120 tine		test run 1	test run 2	test run 3
	rep I	292	366	306
	rep II	266	342	290
	rep III	260	302	248
			average	296.89
170 tine		test run 1	test run 2	test run 3
	rep I	320	336	310
	rep II	298	306	286
	rep III	316	314	330
			average	312.89
220 tine		test run 1	test run 2	test run 3
	rep I	384	444	374
	rep II	402	380	372
	rep III	386	386	372
			average	388.89
mouldboard plough		test run 1	test run 2	test run 3
	rep I	478	474	464
	rep II	496	468	464
	rep III	472	486	448
			average	472.22
disc plough		test run 1	test run 2	test run 3
	rep I	442	420	412
	rep II	432	430	414
	rep III	476	438	410
			average	430.44
disc harrow		test run 1	test run 2	test run 3
	rep I	148	130	140
	rep II	150	94	148
	rep III	108	80	108
			average	122.89

	mouldboard plough	disc plough	disc harrow	plaintine	120 tine	170 tine	220 tine
Specific resistance (kN/m^2)	30.40	50.28	62.03	48.86	49.34	45.00	44.76

Appendix 7 Statistical analysis of the results

Data analysis by software Statistica

1) Field experiment

Draught force

Univariate Tests of Significance for draught (kN) (field.sta)
Sigma-restricted parameterization
Effective hypothesis decomposition

	SS	Degr. of Freedom	MS	F	p
Intercept	1608.462	1	1608.462	2226.630	0.000000
Treatment	165.344	5	33.069	45.778	0.000106
Error	4.334	6	0.722		

Treatment; LS Means (field.sta)
Current effect: F(5, 6)=45.778, p=.00011
Effective hypothesis decomposition

	Treatment	draught (kN) Mean	draught (kN) Std.Err.	draught (kN) -95.00%	draught (kN) +95.00%	N
1	DP	10.19500	0.600989	8.72443	11.66557	2
2	MP deep	17.37500	0.600989	15.90443	18.84557	2
3	MP shallow	15.82500	0.600989	14.35443	17.29557	2
4	DH	8.04500	0.600989	6.57443	9.51557	2
5	close tines	7.69500	0.600989	6.22443	9.16557	2
6	wide tines	10.33000	0.600989	8.85943	11.80057	2

Tukey HSD test; variable draught (kN) (field.sta)
Approximate Probabilities for Post Hoc Tests
Error: Between MS = .72237, df = 6.0000

	Treatment *)	{1} 10.195	{2} 17.375	{3} 15.825	{4} 8.0450	{5} 7.6950	{6} 10.330
1	DP		0.001322	0.004493	0.247961	0.156574	0.999977
2	MP deep	0.001322		0.514802	0.000446	0.000397	0.001449
3	MP shallow	0.004493	0.514802		0.000911	0.000751	0.005081
4	DH	0.247961	0.000446	0.000911		0.997670	0.207837
5	close tines	0.156574	0.000397	0.000751	0.997670		0.131037
6	wide tines	0.999977	0.001449	0.005081	0.207837	0.131037	

*) grey number indicates significant difference between treatments

Tukey HSD test; variable draught (kN) (field.sta)
Homogenous Groups, alpha = .05000
Error: Between MS = .72237, df = 6.0000

	Treatment	draught (kN) Mean	1	2
5	close tines	7.69500	****	
4	DH	8.04500	****	
1	DP	10.19500	****	
6	wide tines	10.33000	****	
3	MP shallow	15.82500		****
2	MP deep	17.37500		****

Draught force per unit implement

Univariate Tests of Significance for draught per unit implement (kN) (field.sta)
Sigma-restricted parameterization
Effective hypothesis decomposition

	SS	Degr. of Freedom	MS	F	p
Intercept	70.85880	1	70.85880	2075.941	0.000000
Treatment	28.24480	5	5.64896	165.497	0.000002
Error	0.20480	6	0.03413		

Treatment; LS Means (field.sta)
Current effect: F(5, 6)=165.50, p=.00000
Effective hypothesis decomposition

	Treatment	draught per unit implement (kN) Mean	draught per unit implement (kN) Std.Err.	draught per unit implement (kN) -95.00%	draught per unit implement (kN) +95.00%	N
1	DP	3.400000	0.130639	3.080337	3.719663	2
2	MP deep	4.345000	0.130639	4.025337	4.664663	2
3	MP shallow	3.955000	0.130639	3.635337	4.274663	2
4	DH	0.310000	0.130639	-0.009663	0.629663	2
5	close tines	1.095000	0.130639	0.775337	1.414663	2
6	wide tines	1.475000	0.130639	1.155337	1.794663	2

Tukey HSD test; variable draught per unit implement (kN) (field.sta)
Approximate Probabilities for Post Hoc Tests
Error: Between MS = .03413, df = 6.0000

	Treatment *)	{1} 3.4000	{2} 4.3450	{3} 3.9550	{4} .31000	{5} 1.0950	{6} 1.4750
1	DP		0.016178	0.145957	0.000252	0.000318	0.000529
2	MP deep	0.016178		0.388358	0.000249	0.000250	0.000257
3	MP shallow	0.145957	0.388358		0.000249	0.000257	0.000285
4	DH	0.000252	0.000249	0.000249		0.037816	0.005765
5	close tines	0.000318	0.000250	0.000257	0.037816		0.410382
6	wide tines	0.000529	0.000257	0.000285	0.005765	0.410382	

*) grey number indicates significant difference between treatments

Tukey HSD test; variable draught per unit implement (kN) (field.sta)
Homogenous Groups, alpha = .05000
Error: Between MS = .03413, df = 6.0000

	Treatment	draught per unit implement (kN) Mean	1	2	3	4
4	DH	0.310000				****
5	close tines	1.095000	****			
6	wide tines	1.475000	****			
1	DP	3.400000		****		
3	MP shallow	3.955000		****	****	
2	MP deep	4.345000			****	

Area of disturbance

Univariate Tests of Significance for Disturbance (field.sta)
Sigma-restricted parameterization
Effective hypothesis decomposition

	SS	Degr. of Freedom	MS	F	p
Intercept	0.695021	1	0.695021	10859.70	0.000000
Treatment	0.055547	5	0.011109	173.58	0.000000
Error	0.000768	12	0.000064		

Treatment; LS Means (field.sta)
Current effect: F(5, 12)=173.58, p=.00000
Effective hypothesis decomposition

	Treatment	Disturbance Mean	Disturbance Std.Err.	Disturbance -95.00%	Disturbance +95.00%	N
1	DP	0.183000	0.004619	0.172936	0.193064	3
2	MP deep	0.305000	0.004619	0.294936	0.315064	3
3	MP shallow	0.229000	0.004619	0.218936	0.239064	3
4	DH	0.153000	0.004619	0.142936	0.163064	3
5	close tines	0.148000	0.004619	0.137936	0.158064	3
6	wide tines	0.161000	0.004619	0.150936	0.171064	3

Tukey HSD test; variable Disturbance (field.sta)
Approximate Probabilities for Post Hoc Tests
Error: Between MS = .00006, df = 12.000

	Treatment *)	{1} .18300	{2} .30500	{3} .22900	{4} .15300	{5} .14800	{6} .16100
1	DP		0.000159	0.000283	0.006373	0.001936	0.049337
2	MP deep	0.000159		0.000159	0.000159	0.000159	0.000159
3	MP shallow	0.000283	0.000159		0.000159	0.000159	0.000159
4	DH	0.006373	0.000159	0.000159		0.968479	0.817261
5	close tines	0.001936	0.000159	0.000159	0.968479		0.400397
6	wide tines	0.049337	0.000159	0.000159	0.817261	0.400397	

*) grey number indicates significant difference between treatments

Tukey HSD test; variable Disturbance (field.sta)
Homogenous Groups, alpha = .05000
Error: Between MS = .00006, df = 12.000

	Treatment	Disturbance Mean	1	2	3	4
5	close tines	0.148000	****			
4	DH	0.153000	****			
6	wide tines	0.161000	****			
1	DP	0.183000		****		
3	MP shallow	0.229000			****	
2	MP deep	0.305000				****

Specific resistance

Univariate Tests of Significance for Specific resistance (New1)
Sigma-restricted parameterization
Effective hypothesis decomposition

	SS	Degr. of Freedom	MS	F	p
Intercept	123291.3	1	123291.3	7214.693	0.000000
Treatment	1349.1	5	269.8	15.789	0.000000
Error	512.7	30	17.1		

Treatment; LS Means (New1)
Current effect: F(5, 30)=15.789, p=.00000
Effective hypothesis decomposition

	Treatment	Specific resistance Mean	Specific resistance Std.Err.	Specific resistance -95.00%	Specific resistance +95.00%	N
1	DP	55.71038	1.687647	52.26375	59.15702	6
2	MP deep	56.96721	1.687647	53.52058	60.41385	6
3	MP shallow	69.10480	1.687647	65.65817	72.55144	6
4	DH	53.01788	1.687647	49.57124	56.46451	6
5	close tines	52.16518	1.687647	48.71854	55.61181	6
6	wide tines	64.16314	1.687647	60.71651	67.60978	6

Tukey HSD test; variable Specific resistance (New1)
Approximate Probabilities for Post Hoc Tests
Error: Between MS = 17.089, df = 30.000

	Treatment *)	{1} 55.710	{2} 56.967	{3} 69.105	{4} 53.018	{5} 52.165	{6} 64.163
1	DP		0.994710	0.000186	0.865841	0.675821	0.015264
2	MP deep	0.994710		0.000360	0.570683	0.359546	0.053182
3	MP shallow	0.000186	0.000360		0.000135	0.000134	0.329139
4	DH	0.865841	0.570683	0.000135		0.999200	0.000886
5	close tines	0.675821	0.359546	0.000134	0.999200		0.000401
6	wide tines	0.015264	0.053182	0.329139	0.000886	0.000401	

*) grey number indicates significant difference between treatments

Tukey HSD test; variable Specific resistance (New1)
Homogenous Groups, alpha = .05000
Error: Between MS = 17.089, df = 30.000

	Treatment	Specific resistance Mean	1	2	3
5	close tines	52.16518	****		
4	DH	53.01788	****		
1	DP	55.71038	****		
2	MP deep	56.96721	****	****	
6	wide tines	64.16314		****	****
3	MP shallow	69.10480			****

Soil bin experiment

Draught force

Univariate Tests of Significance for draught (kN) (suma2)
Sigma-restricted parameterization
Effective hypothesis decomposition

	SS	Degr. of Freedom	MS	F	p
Intercept	41.72190	1	41.72190	1736.690	0.000000
Treatment	4.12636	6	0.68773	28.627	0.000000
Error	0.33633	14	0.02402		

Treatment; LS Means (suma2)
Current effect: F(6, 14)=28.627, p=.00000
Effective hypothesis decomposition

	Treatment	draught (kN) Mean	draught (kN) Std.Err.	draught (kN) -95.00%	draught (kN) +95.00%	N
1	plaintine	0.890000	0.089487	0.698069	1.081931	3
2	120 tine	1.466667	0.089487	1.274736	1.658597	3
3	170 tine	1.406667	0.089487	1.214736	1.598597	3
4	220 tine	1.743333	0.089487	1.551403	1.935264	3
5	MP	1.436667	0.089487	1.244736	1.628597	3
6	DP	2.163333	0.089487	1.971403	2.355264	3
7	DH	0.760000	0.089487	0.568069	0.951931	3

Tukey HSD test; variable draught (kN)
(soil_bin.sta)
Approximate Probabilities for Post Hoc Tests
Error: Between MS = .02402, df = 14.000

	Treatment *)	{1} .89000	{2} 1.4667	{3} 1.4067	{4} 1.7433	{5} 1.4367	{6} 2.1633	{7} .76000
1	plaintine		0.006401	0.015027	0.000296	0.009784	0.000174	0.938929
2	120 tine	0.006401		0.998873	0.360184	0.999979	0.001294	0.001138
3	170 tine	0.015027	0.998873		0.180046	0.999979	0.000649	0.002454
4	220 tine	0.000296	0.360184	0.180046		0.258483	0.059359	0.000191
5	MP	0.009784	0.999979	0.999979	0.258483		0.000902	0.001661
6	DP	0.000174	0.001294	0.000649	0.059359	0.000902		0.000174
7	DH	0.938929	0.001138	0.002454	0.000191	0.001661	0.000174	

*) grey number indicates significant difference between treatments

Tukey HSD test; variable draught (kN) (soil_bin.sta)
Homogenous Groups, alpha = .05000
Error: Between MS = .02402, df = 14.000

	Treatment	draught (kN) Mean	1	2	3
7	DH	0.760000		****	
1	plaintine	0.890000		****	
3	170 tine	1.406667	****		
5	MP	1.436667	****		
2	120 tine	1.466667	****		
4	220 tine	1.743333	****		****
6	DP	2.163333			****

Vertical force

Univariate Tests of Significance for vertical (kN) (suma2)
Sigma-restricted parameterization
Effective hypothesis decomposition

	SS	Degr. of Freedom	MS	F	p
Intercept	0.066305	1	0.066305	9.5763	0.007917
Treatment	8.674762	6	1.445794	208.8148	0.000000
Error	0.096933	14	0.006924		

Treatment; LS Means (suma2)
Current effect: F(6, 14)=208.81, p=.00000
Effective hypothesis decomposition

	Treatment	vertical (kN) Mean	vertical (kN) Std.Err.	vertical (kN) -95.00%	vertical (kN) +95.00%	N
1	plaintine	-0.306667	0.048041	-0.409704	-0.203629	3
2	120 tine	-0.263333	0.048041	-0.366371	-0.160296	3
3	170 tine	-0.420000	0.048041	-0.523038	-0.316962	3
4	220 tine	-0.290000	0.048041	-0.393038	-0.186962	3
5	MP	-0.426667	0.048041	-0.529704	-0.323629	3
6	DP	0.823333	0.048041	0.720296	0.926371	3
7	DH	1.276667	0.048041	1.173629	1.379704	3

Tukey HSD test; variable vertical (kN) (soil_bin.sta)
Approximate Probabilities for Post Hoc Tests
Error: Between MS = .00692, df = 14.000

	Treatment *)	{1} -.3067	{2} -.2633	{3} -.4200	{4} -.2900	{5} -.4267	{6} .82333	{7} 1.2767
1	plaintine		0.994140	0.645390	0.999975	0.588082	0.000174	0.000174
2	120 tine	0.994140		0.305931	0.999613	0.265817	0.000174	0.000174
3	170 tine	0.645390	0.305931		0.503331	1.000000	0.000174	0.000174
4	220 tine	0.999975	0.999613	0.503331		0.449080	0.000174	0.000174
5	MP	0.588082	0.265817	1.000000	0.449080		0.000174	0.000174
6	DP	0.000174	0.000174	0.000174	0.000174	0.000174		0.000312
7	DH	0.000174	0.000174	0.000174	0.000174	0.000174	0.000312	

*) grey number indicates significant difference between treatments

Tukey HSD test; variable vertical (kN) (soil_bin.sta)
Homogenous Groups, alpha = .05000
Error: Between MS = .00692, df = 14.000

	Treatment	vertical (kN) Mean	1	2	3
5	MP	-0.426667	****		
3	170 tine	-0.420000	****		
1	plaintine	-0.306667	****		
4	220 tine	-0.290000	****		
2	120 tine	-0.263333	****		
6	DP	0.823333		****	
7	DH	1.276667			****

Area of disturbance

Univariate Tests of Significance for Disturbance m2 (suma2)
Sigma-restricted parameterization
Effective hypothesis decomposition

	SS	Degr. of Freedom	MS	F	p
Intercept	0.020856	1	0.020856	9299.362	0.000000
Treatment	0.002955	6	0.000492	219.581	0.000000
Error	0.000031	14	0.000002		

Treatment; LS Means (suma2)
Current effect: F(6, 14)=219.58, p=.00000
Effective hypothesis decomposition

	Treatment	Disturbance Mean	Disturbance Std.Err.	Disturbance -95.00%	Disturbance +95.00%	N
1	plaintine	0.018178	0.000865	0.016323	0.020032	3
2	120 tine	0.029689	0.000865	0.027834	0.031543	3
3	170 tine	0.031289	0.000865	0.029434	0.033143	3
4	220 tine	0.038889	0.000865	0.037034	0.040743	3
5	MP	0.047222	0.000865	0.045368	0.049077	3
6	DP	0.043044	0.000865	0.041190	0.044899	3
7	DH	0.012289	0.000865	0.010434	0.014143	3

Tukey HSD test; variable Disturbance (soil_bin.sta)
Approximate Probabilities for Post Hoc Tests
Error: Between MS = .00000, df = 14.000

	Treatment *)	{1} .01818	{2} .02969	{3} .03129	{4} .03889	{5} .04722	{6} .04304	{7} .01229
1	plaintine		0.000175	0.000174	0.000174	0.000174	0.000174	0.004050
2	120 tine	0.000175		0.837389	0.000201	0.000174	0.000174	0.000174
3	170 tine	0.000174	0.837389		0.000488	0.000174	0.000175	0.000174
4	220 tine	0.000174	0.000201	0.000488		0.000282	0.051538	0.000174
5	MP	0.000174	0.000174	0.000174	0.000282		0.049902	0.000174
6	DP	0.000174	0.000174	0.000175	0.051538	0.049902		0.000174
7	DH	0.004050	0.000174	0.000174	0.000174	0.000174	0.000174	

*) grey number indicates significant difference between treatments

Tukey HSD test; variable Disturbance m2 (soil_bin.sta)
Homogenous Groups, alpha = .05000
Error: Between MS = .00000, df = 14.000

	Treatment	Disturbance Mean	1	2	3	4	5
7	DH	0.012289			****		
1	plaintine	0.018178				****	
2	120 tine	0.029689	****				
3	170 tine	0.031289	****				
4	220 tine	0.038889		****			
6	DP	0.043044		****			
5	MP	0.047222					****

Specific resistance

Univariate Tests of Significance for Specific resistance (New2)
Sigma-restricted parameterization
Effective hypothesis decomposition

	SS	Degr. of Freedom	MS	F	p
Intercept	142116.3	1	142116.3	3663.092	0.000000
Treatment	5105.2	6	850.9	21.931	0.000000
Error	2172.6	56	38.8		

Treatment; LS Means (New2)
Current effect: F(6, 56)=21.931, p=.00000
Effective hypothesis decomposition

	Treatment	Spec res Mean	Spec res Std.Err.	Spec res -95.00%	Spec res +95.00%	N
1	plaintine	49.00066	2.076236	44.84146	53.15986	9
2	120 tine	49.65397	2.076236	45.49477	53.81317	9
3	170 tine	45.01979	2.076236	40.86059	49.17899	9
4	220 tine	44.84941	2.076236	40.69021	49.00861	9
5	MP	30.42475	2.076236	26.26555	34.58396	9
6	DP	50.27404	2.076236	46.11484	54.43324	9
7	DH	63.24525	2.076236	59.08605	67.40445	9

Tukey HSD test; variable Specific resistance (New2)
Approximate Probabilities for Post Hoc Tests
Error: Between MS = 38.797, df = 56.000

	Treatment *)	{1} 49.001	{2} 49.654	{3} 45.020	{4} 44.849	{5} 30.425	{6} 50.274	{7} 63.245
1	plaintine		0.999990	0.822336	0.792191	0.000135	0.999491	0.000325
2	120 tine	0.999990		0.696402	0.659936	0.000135	0.999992	0.000543
3	170 tine	0.822336	0.696402		1.000000	0.000261	0.560602	0.000136
4	220 tine	0.792191	0.659936	1.000000		0.000289	0.522805	0.000135
5	MP	0.000135	0.000135	0.000261	0.000289		0.000135	0.000135
6	DP	0.999491	0.999992	0.560602	0.522805	0.000135		0.000986
7	DH	0.000325	0.000543	0.000136	0.000135	0.000135	0.000986	

*) grey number indicates significant difference between treatments

Tukey HSD test; variable Specific resistance (New2)
Homogenous Groups, alpha = .05000
Error: Between MS = 38.797, df = 56.000

	Treatment	Spec res Mean	1	2	3
5	MP	30.42475		****	
4	220 tine	44.84941	****		
3	170 tine	45.01979	****		
1	plaintine	49.00066	****		
2	120 tine	49.65397	****		
6	DP	50.27404	****		
7	DH	63.24525			****