

CRANFIELD UNIVERSITY

Peter Shanahan

Assessment of an innovative soil aerator on soil physical disturbance and reducing runoff on compacted grassland

School of Applied Science

Land Management

Thesis for the award of Masters of Science

2009

Supervisors: Dr. R. W. Simmons and Dr. M. J. Hann

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**This thesis is submitted in partial fulfilment of the requirement for
the Degree of Masters of Science in Land Management**

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Dedicated to the memory of Roger Clay

i. Abstract

Poor grassland management practices increases compaction and reduces infiltration leading to increasing risk of poaching and runoff generation. On-site impacts of grassland compaction include the loss of topsoil structure which also reduces soil ecosystem functioning. In addition, ongoing diffuse water pollution from compacted grassland limits the ability of the UK's authorities to meet EU water quality guidelines such as the Water Framework Directive and address flood risks in areas of extensive grassland management (e.g. Boscastle, 2004).

This study investigates the effects of an innovative ground-driven rotary soil aerator at alleviating soil compaction and reducing overland flow (designed by Mr. Roger Clay, Herefordshire). The magnitude of soil disturbance from slotting was assessed at the Cranfield University Soil Dynamics Test Centre soil-bin. Draught and vertical force requirements and tillage efficiency were also determined for varying depth and horizontal and vertical angle combinations using an Extended Octagonal-Ring Transducer (EORT). The effect of various slotting treatments on runoff was then investigated on a steep compacted permanent pasture in Herefordshire using erosion plots and simulated rainfall.

From the soil-bin assessment, soil disturbance was most efficient (lowest specific draught) at 100 mm depth, a vertical angle of 18° and with increasing horizontal angle (0° to 10°). The draught requirement for a single bladed disc at 18° vertical ranged from 0.88 to 1.24 kN (90-126 kg force) and a maximum vertical force or ballast requirement of 257 kg force per bladed disc.

Slotting treatments reduced runoff by 75% as compared with the non-slotted control.

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1 Introduction

Soil aerators, ground-driven bladed discs towed by tractor units, have mainly been developed by the sports surface and recreational grassland industries to quickly improve soil aeration, root development and maintain accessibility during wet periods by reducing surface crusting on worn patches (Cockerham, 2008). They have also been adopted for agricultural use on pasture or conservation crops to improve productivity of compacted soils by increasing soil aeration (Crawford and Douglas, 1993). Manufacturers of soil aerators make further claims towards improving grassland management through increasing soil infiltration, reducing compaction and reducing surface runoff. There is however little published evidence, with the exception of the investigations by Crawford and Douglas, (1993), Fortune *et al.*, (1999) and Vliet *et al.*, (2006), that such uses of mechanical aerators improves grassland as described by manufacturers.

This report evaluates a single, innovative type of soil aerator which has been designed and built at an organic dairy farm in Herefordshire, UK. This aerator will be evaluated for its potential to improve permanent pasture through increased soil aeration; disrupting compacted soil; and reducing surface runoff with its associated soil erosion risk and environmental pollution effects.

To meet the aim of this report the following three objectives were undertaken during the summer of 2009: 1) Investigate the forces the soil aerator generates as it engages with soil; 2) Evaluate variances in soil disturbance by the soil aerator under varying configurations of soil engagement and penetration; and 3) assess the practical application of the aerator on sloping grassland by investigating the effects aeration slots have on surface runoff.

2 Literature Review

2.1 Soil erosion and conservation

2.1.1 Background

This study evaluates the role of an innovative ground-driven bladed disc soil aerator at improving permanent pasture through increasing soil aeration, reducing surface compaction, increasing infiltration and reducing surface runoff thus ameliorating potential offsite environmental impacts from grassland.

2.1.2 Extent of soil erosion in the UK and Europe

Soil provides vital supporting, provisioning, regulatory and cultural ecosystem services (Millennium Ecosystem Assessment, 2005). The erosion of soil, principally by water and wind, has been accelerated by poor land management (e.g. intensive arable farming, compaction of grassland and loss of protective forest cover) thus limiting the functioning of soil through sediment loss, loss of organic carbon and nutrients. Maintaining soil functionality and ecosystem services is critical in order to address the pressures of climate change and increasing demands for food and potable water from a rising human population. Food security is an increasingly important driver for soil management in Europe and the UK.

Appropriate soil management to address soil erosion in Europe is highlighted by van-Camp *et al.*, (2004) and the development of a European Union Soil Framework Directive with principles of polluter-pays, precautionary approach and rectification of pollution at source. van-Camp *et al.*, (2004) identify three priority areas:

- Erosion
- Contamination (local and diffuse)
- Organic matter decline

Further, five 'soil threats': biodiversity, sealing, compaction, floods and landslides, and salinisation are also highlighted. Of importance for this study, van-Camp *et al.*, (2004) identify the relationship between soil erosion, soil compaction and flood risk and water quality across Europe.

With the risk of soil erosion being of such significance, an EC Soil Erosion Working Group was tasked with assessing appropriate levels of intervention at local, national, regional, and EU scales (Sánchez *et al.*, 2004). Their assessment of ten European countries, including the UK, using geospatial data (Pan European Soil Erosion Risk Assessment, PESERA, Jones *et al.*, 2004) found that soil erosion varies across Europe but is widespread. High risk areas

identified are the Mediterranean region and areas of lesser risk include northwest Europe (i.e. the UK, France and Scandinavia). Of Importance to this study was the finding of Sánchez *et al.*, (2004) that 'runoff is the most important cause of severe soil erosion' and consequently, measures that reduce runoff are crucial to soil protection.

2.1.3 Impacts of soil erosion

Soil management and specifically soil erosion are moving up the political and legislative agenda. The impact of soil erosion on overall soil quality is emphasised by Dorren *et al.*, (2004) and is reflected in the emphasis placed on soil erosion in the draft Soil Strategy for England (DEFRA, 2008a) and the concern over sediment (McHugh *et al.*, 2002) and sediment bound pollutants (primarily phosphorous). The loss of soil from agricultural fields is in itself of increasing concern to the agricultural industry in terms of the loss of a growing medium (on-site effects), but also to local authorities and environment interest groups when the mobilised soil particulates and nutrients enter the local waterways (off-site effects). The European Union's Water Framework Directive (EU WFD) (Council of the European Parliament, 2000), is an example of the legal obligation European member nations have towards improving the quality of natural waterways (Article 4). Agriculture is known to be a principle source of nitrate, phosphorus and pesticide pollutants (Kay *et al.*, 2009).

2.1.4 Soil compaction

As highlighted in 2.1.2, soil compaction presents a further risk to soil erosion acceleration through the deterioration of soil structure and subsequent effects on soil hydrology (Morgan, 2005). Jones *et al.*, (2004) state that more than a third of European soils are vulnerable to compaction, mostly from agricultural land use. Of importance to this study, Jones *et al.*, (2004) add that soil compaction: (i) increases the risk of soil erosion on sloping land, and (ii) accelerates effective runoff into catchments (i.e. increasing flooding risk). DEFRA, (2008) estimate that the annual cost of flooding in England and Wales due to soil structural degradation is between £29.0 to £128 million (at 2004/05 prices).

2.1.5 Ameliorating soil erosion

Strategies to reduce soil erosion across Europe are highlighted by Bautista *et al.*, (2004) with specific improvement measures for agriculture including:

- Land use planning: location of agricultural land and crop diversification
- Soil management practices: improvement of erosion reducing soil properties (of significance to this study for improved grassland management)

- Preservation of natural landscape elements to control overland flow and soil erosion (absorbing and infiltrating overland flow through, for example increased surface roughness, which is of interest for this study).

2.2 Grassland management

2.2.1 Background to grassland management in UK and Europe

'Grass is the United Kingdom's most important crop' according to Finch *et al.*, (2002, p. 391) and 'should be treated as an important natural resource'. According to DEFRA, (2009) grassland ($\geq$ five years old) covers 6.04×10^6 ha, or 32% of the total agricultural land in the UK (18.7×10^6 ha). The production of 1 t ha^{-1} of grass (dry matter) requires $200\text{-}250 \text{ t ha}^{-1}$ (25 mm ha^{-1}) of water (Frame, 1992). The ability to maintain the right balance of soil moisture and soil aeration is critical to root development and grass yield particularly when grass growing days are limited to $200\text{-}240 \text{ d yr}^{-1}$ for counties like Herefordshire (Down *et al.*, 1981).

2.2.2 Grassland impacts on soil conservation

The formation of compacted pans at ploughing depth leads to the destruction of the upper soil structure of grassland. This in turn leads to poor drainage (Frame, 1992). 'Stock trampling', the poaching affect of grazing livestock modifies the soil structure by 'altering the equilibrium between soil particles, air and water' (Frame, 1992) leading to impeded grass root development, reduced grass growth rate and yield. Further, compaction and disruption of soil structure leads to reduced soil porosity, puddling and increased risk of surface water runoff and soil erosion (Frame, 1992).

Patto *et al.*, (1978) give a very useful and comprehensive assessment of the impact of livestock poaching (plastic deformation of the soil surface by animal hooves) in England and Wales. Though dated, this report highlights important facts about poaching and the extent to which pasture in England and Wales is susceptible to poaching damage. The overriding factor in the susceptibility classes employed by Patto *et al.*, (1978) is rainfall distribution, with isohyets ≥ 1140 mm mean annual rainfall giving the highest susceptibility risk (mainly highland regions). Further, forces exerted by a standing cow can be as much as 0.2 M Pa ($2 \text{ kg force cm}^{-2}$), as compared with $0.1\text{-}0.2 \text{ M Pa}$ beneath tractor tyres depending upon inflation pressures. The importance of the grass sward in reducing the impact of cattle-induced poaching is made very clear by Patto *et al.*, (1978). Firstly, the grass mat itself provides physical protection for the soil surface; second, the presence of roots increases soil shear strength and load bearing capacity; thirdly, the decomposition of plant residues bonds and develops water stable aggregates to further strengthen the soil structure and facilitate infiltration.

Bilotta *et al.*, (2007) provide a lengthy insight into the affects grazing has on permanent pasture soils in the UK. Their review addresses the different impacts grazing animals have on soil structure, most notably cattle. Soil strength declines progressively with increases in stocking density in close association with the presence of free surface water. Decline in soil structure is further influenced by the rate to which surface water infiltrates into the soil. Bilotta *et al.*, (2007) demonstrate that there is a need to improve soil structure in order to maintain the ecosystem function of water storage whilst sustaining existing and predicted stocking densities. It is interesting to note that free surface water, and not necessarily stocking density is believed to be the main control over the development of poaching and impeded surface drainage and that the use of a soil aerator can ameliorate this factor.

Impeded surface drainage and soil compaction from pastoral agriculture impacts directly on water quality and flood risk for catchments in England and Wales (DEFRA, 2005; Environment Agency, 2007). This further inhibits the task of local authorities in the UK to meet water quality targets as set by the EU WFD (Council of the European Parliament, 2000). To find a way of improving compacted grassland through reducing compaction, reducing poaching risk and runoff through improved infiltration is the basis of this study.

2.3 Soil aerators

2.3.1 Previous work

Permanent grasslands on typical brown earths such as those investigated by Davies *et al.*, (1989) exhibited a rapid rise in bulk density at 100-120 mm depth as manifested by a compacted pan which impedes infiltration and promotes surface water logging. Soil aerators therefore need to penetrate around such depths in order to improve aeration, infiltration, root penetration and reduce physiological damage to grass due to anoxic conditions. However, in terms of improving production, Fortune *et al.*, (1999) found only small and inconsistent differences between yields on plots spiked (slotted) with aerators as compared with un-treated plots on grazed and silage grassland in southern Ireland. They attribute the fall in yield to root damage from blades. Fortune *et al.*, (1999) used an Aerway Pasture Aerator which comprised of two horizontal rotors supporting six sets of four blades mounted 90° from each other. The blades were 200 mm long and the working width of the machine was 2.4 m. Compared to the soil aerator under investigation by this study, the Aerway machine's blades are set at a vertical angle of 0°, their horizontal angle appeared not to be altered, there are only four blades per disc as compared to ten on the investigated aerator, plus the Aerway blades are 80 mm longer.

The real benefits of soil aerators come from their ability to increase the surface area of topsoils by improving macroporosity which increases aeration, water and nutrient infiltration, and root penetration (Crawford and Douglas, 1993). Using a soil aerator with 180 mm long, 6 mm wide blades, Crawford and

Douglas (1993) were able to demonstrate that soil aerator performance was significantly correlated to the depth of penetration (mean 136 mm) and the size of the aperture the blades created in the soil surface (120-140 mm in length). This performance was closely related to soil moisture (on both sandy loams and clay loams) and the weight loading on the soil aerator (ballast). Further, Crawford and Douglas, (1993) produced a regression equation which highlighted the significance of penetration depth and slot aperture. They highlight that to control 'rain-fed' runoff would be best achieved with long slot apertures through increased interception. Crawford and Douglas, (1993) did not investigate their soil aerator under controlled soil-bin conditions unlike this study. The soil-bin is an ideal test bed to determine the best configuration for slot formation and minimum force requirements.

In comparison to the aerators previously mentioned, David Ritchie Implements Limited of Forfar, Scotland found that for their soil aerators to be effective at penetrating soil pans across a range of soils the blades must be at least 160 mm in length (Personal communication: Bob Ritchie). This has implications for the soil aerator being investigated in terms of shattering compacted soil and improving infiltration. In addition, like the Aerway aerator, the Ritchie aerator blades are not inclined from the vertical like those of the bladed disc soil aerator investigated in this study which can generate soil shattering in a different manner. The soil aerator being investigated cannot be run at depths exceeding 110 mm due the limitations of machine clearance and damage to machine and crop from excessive forces.

The work of Crawford and Douglas, (1993) provides an insight on how to assess the performance of soil aerators. They calculated the internal surface area of the slots by assuming a triangular shape created by a passing blade within the soil and then, using the blade width, estimate the total slot volume per hectare, in their case $9.64 \text{ m}^3 \text{ ha}^{-1}$ after one pass of the aerator. Such an increase in soil surface area has positive implications for soil, crop and water management. In summary, blade length and depth of soil penetration of soil aerators are the main parameters to be considered. The increase in soil surface volume will be investigated for the Herefordshire trials of the study aerator for its potential influence on runoff.

Contrary to Fortune *et al.*, (1999), Crawford and Douglas (1993) found the increase in soil aeration as a likely benefit to crop development. However, for crop dry matter yield and nitrogen uptake, Douglas *et al.*, (1995) found no significant increase when using an aerator. Potential negative effects of aerators include lifting loose soil to the surface which is not desirable for silage cropping due to the contamination of the grass and loss of soil pore space as a result of the blade action displacing soil (local compaction) which Crawford and Douglas, (1993) and Fortune *et al.*, (1999) did not assess. This will be observed during the soil-bin and field trials of the study aerator.

Vliet *et al.*, (2006) found that perpendicular to slope aeration treatments significantly reduce runoff by 47-81% over a year as compared to their control

on silt loams and sandy loams of British Columbia, Canada. Their study addressed the influence aeration slotting had on the interception of surface applied liquid manures and found there to be a significant reduction in solids and nutrients in runoff. Vliet *et al.*, (2006) used the 3.0 m wide Aerway 100Q soil aerator and 21 x 6 m erosion plots. This work by Vliet *et al.*, (2006) shows that soil aerators can reduce runoff with across slope treatments however, they did not test this theory up-down slope. They used large erosion plots over a long time period which this study will not be able to do, but highlights the possibilities of future investigatory methods and materials. The uniqueness of this study is the influence a soil aerator has on soil disturbance in a soil-bin which previous studies on various aerators have not investigated.

2.3.2 Current designs

There are a number of soil aerators on the market produced by agricultural implement manufacturers as previously mentioned. The David Ritchie Implements Limited aerator (David Ritchie Limited, 2009) has a working width of 2.5-3m and uses boron blades with a horizontal angle adjustment of 10°. They claim that their design 'increases the shattering effect on compacted grassland' (David Ritchie Limited, 2009). Their claims on this machine appear not to be supported by formal research but through farm and sports surface trials. No effects on yield or runoff are noted by Ritchie Implements.

Aerway in the United States is another manufacturer of aerators. The Aerway SSD (Aerway Agriculture, 2009) was trialled by Bittman *et al.*, (2005) for surface banding of liquid manure and produced positive results by effectively trapping the manure and increasing nitrogen uptake by 7.5% and yield by 6.9% (the cost effectiveness of which was not known). This application of an aerator in the context of nutrient management is of particular importance in relation to grassland nutrient management under DEFRA's Catchment Sensitive Farming Delivery Initiative (CSFDI) (DEFRA, 2007) and Nitrate Vulnerable Zones in England (NVZs) (DEFRA, 2002).

The range of claims by the manufacturers of soil aerators are as follows:

- Compaction relieved with the introduction of oxygen,
- aerated soils recover quicker after mowing,
- increased root development,
- grass leys last longer,
- increased microbial action for better utilisation of fertilisers,
- improved N fixation for legumes (clover), and
- surface drainage improved, with slurry and rainwater absorbed more quickly with runoff risk reduced.

This last point is one which is of most interest to the current study. This claim by the manufacturer Aerway for their regular aerator model has not been substantiated by scientific research but taken from the experience of designers and land managers that slotting will, assist infiltration.

3 Methodology

The aim of this thesis is to assess the impact of an innovative soil aerator on soil physical properties and soil surface hydrology through runoff interception.

3.1 Soil aerator designed and built at Showle Court Farm

3.1.1 Description

The soil aerator evaluated in this study comprises of a series of independently ground-driven rotating steel discs, 520 mm in diameter and 20 mm in thickness, upon which are mounted 10 steel cutting blades (Figure 3.1-1). This machine was designed and built by Mr. Roger Clay at Showle Court Farm, an organic dairy farm in northeast Herefordshire. Three variations of the soil aerator exist: 1) a 2.84 m wide tractor mounted unit with two sets of six bladed discs (Figure 3.1-2); 2) a 6 m wide towed unit with two sets of twelve bladed discs (Figure 3.1-3); 3) independently mounted units (Figure 3.1-4). For practicality, the independently mounted variant has been utilised for the investigation into soil physical disturbance at the soil test centre at Cranfield University.



Figure 3.1-1 Soil aerator blade and attachment bolts (rule 150 mm in length)



Figure 3.1-2 Linkage-mounted soil aerator with two sets of six bladed discs



Figure 3.1-3 The 6.8 m wide soil aerator unit with two sets of twelve bladed discs



Figure 3.1-4 Independently mounted soil aerator bladed disc and arm unit

3.2 Soil bin assessment

3.2.1 Background

The first stage of the assessment of the soil aerator was to determine its effect on soil physical properties under controlled conditions at Cranfield University's Soil Dynamics Test Centre at Silsoe, Bedfordshire as described by Godwin *et al.*, (1980), Hann and Giessibi, (1998) and Misiewicz, (2005).

3.2.2 Construction of processor mounting unit

To mount the soil aerator arm and bladed disc to the soil bin processor a frame was constructed that could support the weight of the soil aerator unit (84 kg) shown in Figure 3.1-4. The frame which allowed adjustments to the vertical and horizontal running angles of the disc unit was mounted to the Extended Octagonal-Ring Transducer (EORT) as developed by Godwin, (1975).

3.2.3 Soil bin preparation

The soil bin (Figure 4.1-3) comprises a 1.0 m deep, 1.5 m wide and 20 m long pit which holds a sandy loam soil maintained at a constant moisture content (0.08 mean mass water fraction) and dry bulk density (mean 1.4 g cm^{-3}). A technician (Mr. Roy Newland) operated the processor to 'prep' the soil bin and produce a uniform surface of an evenly compacted soil.

The EORT was connected to a data-logger and computer which had the DasyLab software installed. This system provided real-time measures of vertical and horizontal forces as the aerator engaged the soil. Calibration checks on the data-logger were performed prior to starting treatment runs and on occasions during the experimental period for quality assurance.

3.2.4 Soil bin aerator engagement runs

Following soil bin preparation, the speed of the processor was set to run at approximately 4 km h^{-1} which represents the field operating speed of the implement.

A randomised block program of tests was generated for the three variables to test namely depth, vertical and horizontal angles. This was to remove bias, account for variations in soil moisture and dry bulk density and facilitate robust statistical analysis.

The treatments investigated in this study are given in Table 3.2-1.

Table 3.2-1 Soil aerator test parameters

Depth (mm)	Vertical angle (°)	Horizontal angle (°)
50, 100	0, 2, 18	-5, 0, 5, 10

Following bin preparation, the processor was run for approximately 10.0 m which allowed two revolutions of the bladed disc. On average, four runs were made for each soil-bin preparation. For the test parameters (Table 3.2-1) values of vertical and horizontal (draught) force components over time were provided by the EORT as the soil aerator engaged with the soil of the soil-bin.

3.2.5 Soil engagement analysis

To facilitate statistical analyses, six out of twenty slots were randomly selected for detailed measurements. To discount edge effects as the aerator engaged the test bed measurements were started 1.0 m from the edge of the bed. The measurements at each randomly selected slot include: a photograph, length and width of slot and a cross-sectional drawing of the breakout disturbance perpendicular to the direction of travel. The cross-sectional profile was determined by clearing away the disturbed soil and using a soil profiler (Figure 4.1-6). The cross-sectional breakout area was subsequently calculated using Simpson's rule of parabolas determining the area under a curve. This principle for measuring slot dimensions comes from the work of Crawford and Douglas, (1993).

To determine the degree of soil disturbance created by the soil aerator blades soil breakout was measured and recorded.

3.3 Field assessment by rainfall simulation

3.3.1 Field area

The field trials of the soil aerator were established in a field of permanent pasture called *Showle Bank* (Figure 3.3-1) at Showle Court organic dairy farm, north-east Herefordshire (N 52°05'15.7", W 2°33'73.8"). Mean (1975-2000) maximum annual temperature for the area is 14°C and annual rainfall is 706 mm (Met Office, 2009). To put the test site in context of the region, 43% of total agricultural land in Herefordshire (180,324 ha) is under permanent pasture (Herefordshire Partnership, 2009).



Figure 3.3-1 Showle Bank field

The soils of the test field (Figure 3.3-2) are Typical argillic brown earths of the Bromyard series (Soil Survey of England and Wales, 1983) which are well drained reddish fine silty soils over shales and siltstone (National Soil Resources Institute, 2009). The Bromyard series are water retentive with low bearing strength with negligible poaching risk but susceptible to erosion through arable uses (Ragg *et al.*, 1984).

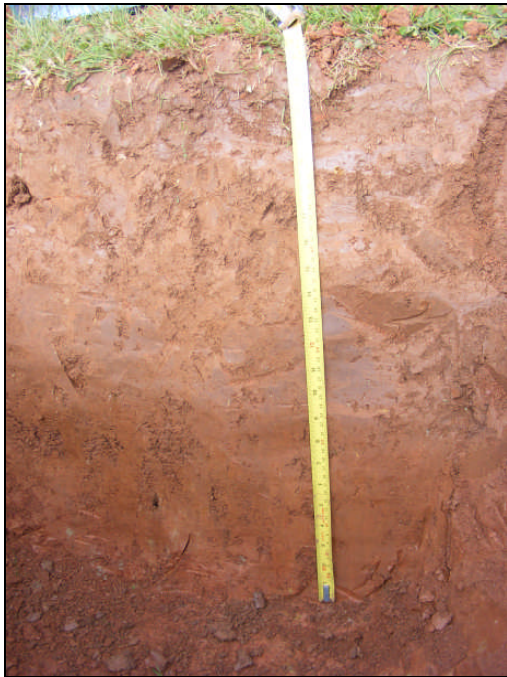


Figure 3.3-2 Soil profile of Bromyard series, Showle Bank field, July 2009

The field, *Showle Bank*, covers an area of approximately 7.0 ha and consists of permanent grass-clover ley with a mean slope of 11° (high erosion risk by water, DEFRA, 2005). It offered good access for vehicles, including tractor units and being regularly grazed, presented a typical improved grassland for the region which has experienced compaction by cattle and prone to surface runoff (personal communication, Mr. J. Clay, Showle Court).

3.3.2 Bromyard soil series at Showle Bank field

Table 3.3-1 describes a soil pit dug at Showle Bank, with Figure 3.3-2 in the methodology section providing a visual reference of the Bromyard soil series which compares well with (National Soil Resources Institute, 2009).

For comparison, mean mass water fraction and dry bulk density for the soil-bin sandy loam was: $\Theta_m=0.08$, $\rho_{\text{DRY}}=1.47 \text{ g cm}^{-3}$.

Table 3.3-1 Soil profile description of Bromyard series at Showle Bank, 31 July 2009 (0-60 cm)

Ap 0-15 cm	Silty clay loam, 5 YR 3/4 (dark reddish brown), stoneless, moderate coarse sub-angular blocky structure, no mottles, fibrous abundant roots, dense with diffuse boundary. $\Theta_m = 0.26$ $\rho_{\text{DRY}} = 1.48 \text{ g cm}^{-3}$
Eb 15-35 cm	Silty clay loam, 5 YR 4/6 (reddish brown), very few (1%) weathered stones, weak coarse sub-angular blocky structure, no mottles, thin fibrous roots, diffuse boundary, worm holes $\Theta_m = 0.18$ $\rho_{\text{DRY}} = 1.60 \text{ g cm}^{-3}$
Bt 35-60	Silty clay loam, 5 YR 4/8 (reddish brown), no stones, weak coarse angular blocky structure, yellow mottles (2%), very thin fibrous roots, diffuse boundary, worm holes $\Theta_m = 0.18$ $\rho_{\text{DRY}} = 1.56 \text{ g cm}^{-3}$

Where Ap, plough horizon; Eb, buried eluviated soil; Bt, subsoil of accumulated silicate clays (Brady and Weil, 2002)

3.3.3 The block design

A continuous slope in the test field was divided into a randomised block design of three blocks, one for each aerator treatment (Table 3.3-2).

Table 3.3-2 Randomised block design for Showle Bank field (blocks measured 5.5 x 5.5 m)

Block 1	Block 2	Block 3
Control (no slots)	Aeration slots parallel to slope (up-down)	Aeration slots perpendicular to slope (across)

Soil samples were collected from each block and sealed in pre-weighed tins and retained for the determination of antecedent soil moisture and dry bulk density.

3.3.4 Treatments runs

The soil aerator was linkage-mounted to a Massey Ferguson 6480 tractor with a wheel base of 3 m (Figure 3.3-3) and was driven across the treatment blocks at a speed of approximately 4 km h^{-1} .



Figure 3.3-3 Soil aerator linkage-mounted to a Massey Ferguson 6480

3.3.5 Erosion plots

To carry out runoff measurements for the different treatments three out of twelve randomly selected erosion plot areas were selected per block. The erosion plot measured 1.5 x 1.0 m and was bounded by stainless steel sheets hammered into the soil surface (Figure 3.3-4).



Figure 3.3-4 Insertion of runoff plot

3.3.6 Rainfall simulator

The rainfall simulator consists of a sprinkler unit which was pitched above the erosion plots using guy-lines and stakes, with water supplied through a pressure metering unit along piping from a petrol pump and reservoir (Figure 3.3-5). The simulator was designed to deliver a predetermined intensity of simulated rainfall through a full cone Lechler nozzle. A gauge unit and regulating valve were monitored to bring the line pressure of water to the required value.



Figure 3.3-5 Complete setup of rainfall simulator (note the pressure gauge and regulating valve below gauge dial, uniform spray from nozzle and wind-break)

For the rainfall simulations, an intensity of 32 mm hr^{-1} for 30 minute duration was adopted. This was determined through laboratory calibration (Hudson, 1995; Heathwaite *et al.*, 1990; Roihan, 1990). This intensity and duration represented a 10 year return period storm event for the study area (Faulkner, 1999). For the simulator to deliver 32 mm hr^{-1} the system pressure was 1.35 Bar. A test of the simulator was made in the field prior to use on the rainfall plots in order to check the system calibration.

3.3.7 Preparation for rainfall simulation and runoff

With the erosion plots in place, a series of measurements were taken. For Blocks 2 and 3 (Table 3.3-2) the lengths, widths and depths of 8 out of 20 randomly selected slots were recorded. The soil moisture in each plot was sampled at three locations before and after each simulation using a Theta moisture probe. The slope angle, shape and aspect within the plot were noted along with vegetation/bare ground cover and prevailing weather conditions.

Subsequently, the simulator was positioned over the centre point of the plot and a wind-break erected on the windward side of the plot to reduce the influence of wind on the simulator spray (Figure 3.3-5). The nozzle was checked for blockages. Rainfall catch-cups were positioned in close proximity to the erosion

plot but away from the spray in order to record any natural rainfall event during the simulation.

Runoff was collected in a measuring jug positioned under the trap outlet. Runoff volume was determined in the field using a volumetric cylinder and the volume recorded. The simulated rainfall intensity was checked during the trials following the method outlined in 3.3.6. The calibration check confirmed that the rainfall simulator was achieving the desired intensity.

3.3.8 Recordings

From the rainfall simulations on the erosion plots, total runoff was recorded at time intervals and observations made on the influence the soil aeration slots on surface water transport.

4 Results

4.1 Results for soil physical disturbance, Soil Dynamics Test Centre, Cranfield University

4.1.1 Influence of running depth, horizontal and vertical angle adjustments on draught forces (kN)

The results indicate that across all vertical and horizontal treatments, increasing running depth from 50 to 100 mm resulted in highly significant increases in draught (Table 4.1-1 and Figure 4.1-1). Further, at 50 mm running depth adjustments to vertical and horizontal angles made no significant difference to draught force (Table 4.1-1 and Figure 4.1-1).

In contrast, at running depths of 100 mm a greater variability in draught force was observed. At a fixed horizontal angle of 0° and -5°, increasing vertical angle from 0° to 18° had no significant effect on draught (Table 4.1-1). In contrast, at fixed horizontal angles of 5° and 10°, significantly greater draught force is required at 0° as compared with both 10° and 18° vertical angles (Table 4.1-1).

At a fixed vertical angle of 0°, the lowest draught force was associated with the -5° horizontal angle treatment with a value of 0.74 kN. Increasing horizontal angle from -5° to 0° and 5° resulted in 54% and 64% increases in draft respectively (Table 4.1-1). No significant increase in draught was observed between the 0° horizontal angle treatments with values of 1.14 kN and 1.20 kN respectively. The highest draught requirement is associated with the 10° horizontal angle treatment with a value of 1.86 kN.

At a fixed vertical angle of both 10° and 18°, no significant difference in draught requirement was observed between the -5°, 0° and 5° horizontal angle treatments. However, increasing horizontal angle to 10° resulted in a significant >20% increase in draught (kN) as compared with the -5°, 0° and 5° horizontal angle treatments.

Table 4.1-1 Mean draught forces (kN) at 50 mm and 100 mm running depths for all vertical and horizontal angles

Depth (mm)	Horizontal angle (°)	Vertical angle (°)		
		0	10	18
50	-5	0.22a ^a	0.12a ^a	0.21a ^a
100		0.74b _a	1.00b _a	0.88b _a
50	0	0.30a ^a	0.32a ^b	0.29a ^a
100		1.14b _b	1.22b _a	0.89b _a
50	5	0.15a ^a	0.34a ^b	0.24a ^a
100		1.20b _b	1.03b _a	1.02b _a
50	10	0.26a ^a	0.24a ^b	0.28a ^a
100		1.86b _c	1.51b _b	1.24b _b

For a given vertical angle (0°, 10° or 18°) within each horizontal angle (-5°, 0°, 5° or 10°) values of draught forces (kN) for 50 or 100 mm depth followed by a different letter are significantly different ($p < 0.05$) following ANOVA Factorial. For 50 mm running depth at a given vertical angle (0°, 10° or 18°) values of draught forces (kN) at each horizontal angle (-5°, 0°, 5° or 10°) followed by the same superscript letter are not significantly different ($p > 0.05$) following ANOVA Factorial. For 100 mm running depth at a given vertical angle (0°, 10° or 18°) values of draught forces (kN) at each horizontal angle (-5°, 0°, 5° or 10°) followed by the same subscript letter are not significantly different ($p > 0.05$) following ANOVA Factorial.

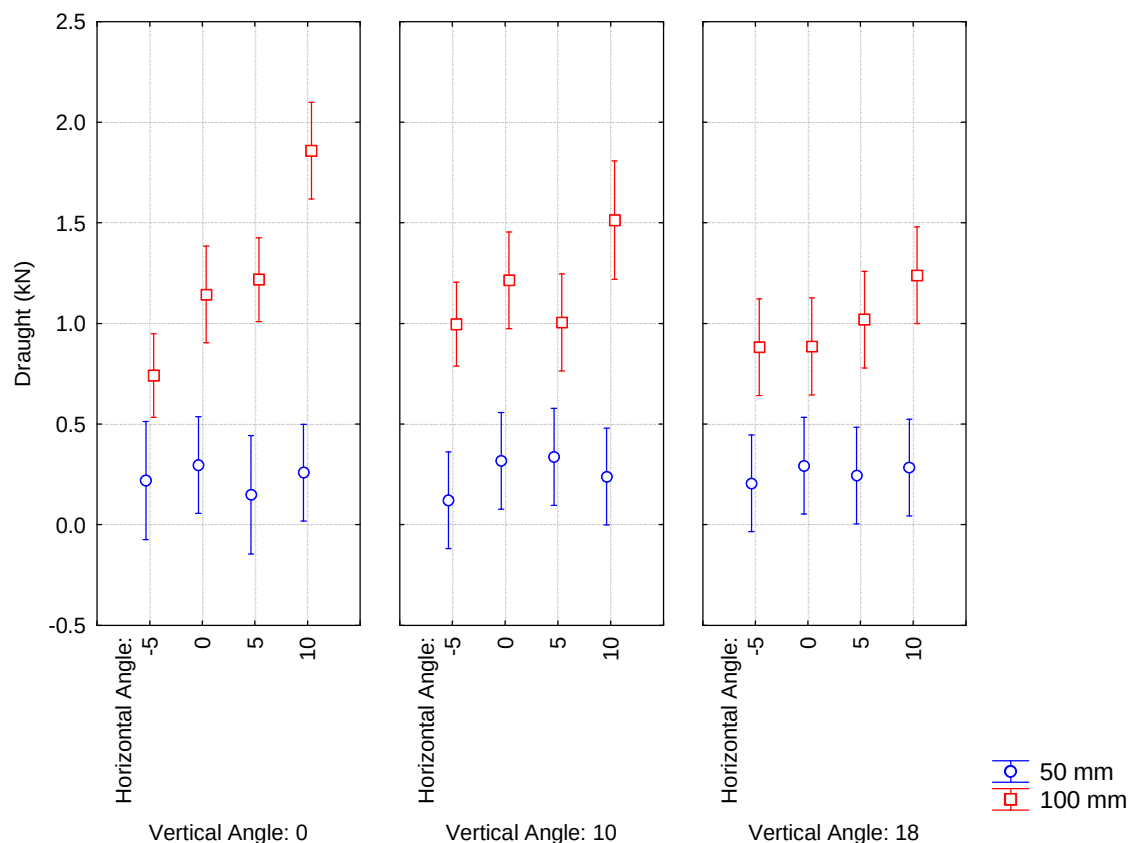


Figure 4.1-1 Draught forces at 50 mm and 100 mm running depth with varying vertical angle and horizontal angles ($p=0.192$) with 95% confidence level

4.1.2 Influence of running depth, vertical and horizontal angles on vertical forces representing ballast requirement

The results indicate that, as expected, across all vertical and horizontal angles, increasing running depth to 100 mm requires up to 280% greater vertical force as compared with 50 mm depth (Table 4.1-2).

Further, in similarity with draught force (Section 1.1.1), at running depths of 50 mm, no significant difference in vertical force is noted irrespective of vertical or horizontal angles (Figure 4.1-2). Similar trends are observed for running depths of 100 mm at fixed horizontal angles of -5° , 5° and 10° , and at vertical angles of 0° , 10° and to 18° (Table 4.1-2, Figure 4.1-2).

At a fixed horizontal angle of 0° no significant difference in vertical force was observed between the 0° and 10° vertical angle treatments. However vertical force reduced by 1.3 times when vertical angle was increased to 18° (Figure 4.1-2, Table 4.1-2).

With regards to the influence of horizontal angle adjustments, at a fixed vertical angle of 0° , vertical force requirement was in the order $-5^\circ < 0^\circ = 5^\circ = 10^\circ$ horizontal, with values of 1.97 and 2.55 kN for the -5° and 10° horizontal angle treatments respectively (Table 4.1-2 and Figure 4.1-2).

Further, at a fixed vertical angle of 10° , adjusting horizontal angle from -5° to 10° had no significant impact on ballast requirement with values of 2.07, 2.54, 2.19 and 2.72 kN, respectively (Figure 4.1-2). With regards to breakout area, for 10° vertical (Figure 4.1-5), there is a significant fall in area by approximately 65% at 0° horizontal compared to -5° , 5° and 10° . This is reflected as poor efficiency as shown in Figure 4.1-7.

For a vertical angle of 18° , the vertical forces between -5° , 0° and 5° do not show a significant difference. However, vertical force at 10° horizontal is approximately 150% greater than the vertical force at -5° (Table 4.1-2).

Table 4.1-2 Mean vertical forces (kN) for running depths of 50 mm and 100 mm at varying vertical and horizontal angles

Depth (mm)	Horizontal angle (°)	Vertical angle (°)		
		0	10	18
50	-5	0.72a ^a	0.49a ^a	0.63a ^a
100		1.79b _a	2.07b _a	1.68b _a
50	0	0.91a ^a	1.07a ^b	1.16a ^a
100		2.52b _b	2.54b _a	1.95b _a
50	5	0.58a ^a	1.11a ^b	0.75a ^a
100		2.46b _b	2.19b _a	2.23b _b
50	10	0.86a ^a	0.69a ^b	0.96a ^a
100		2.55b _b	2.72b _a	2.52b _b

For a given vertical angle (0°, 10° or 18°) within each horizontal angle (-5°, 0°, 5° or 10°) values of vertical forces (kN) for 50 or 100 mm depth followed by a different letter are significantly different ($p < 0.05$) following ANOVA Factorial. For 50 mm running depth (a) and a given vertical angle (0°, 10° or 18°) values of vertical forces (kN) at each horizontal angle (-5°, 0°, 5° or 10°) followed by the same superscript letter (a) are not significantly different ($p > 0.05$) following ANOVA Factorial. For 100 mm running depth (b) and a given vertical angle (0°, 10° or 18°) values of vertical forces (kN) at each horizontal angle (-5°, 0°, 5° or 10°) followed by the same subscript letter (b) are not significantly different ($p > 0.05$) following ANOVA Factorial.

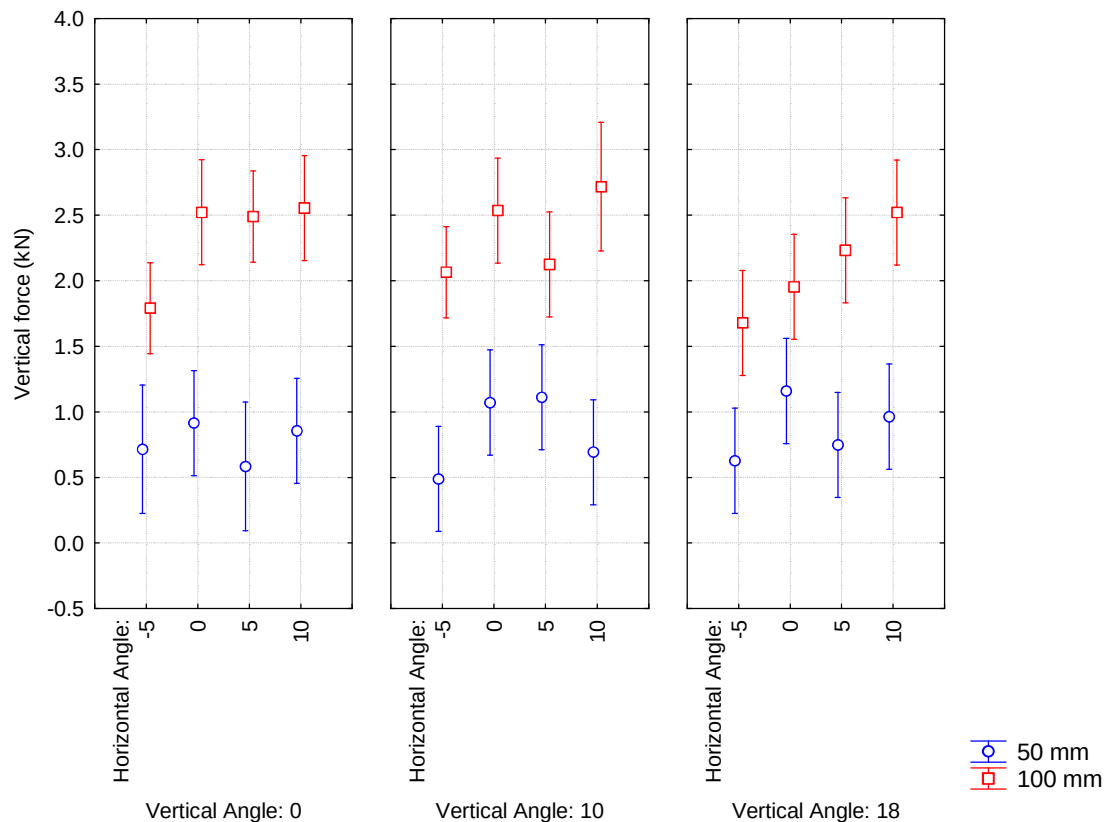


Figure 4.1-2 Vertical forces for the soil aerator for ANOVA combinations of depth, vertical angle and horizontal angle ($p=0.169$) with 95% confidence level

4.1.3 Cross-sectional breakout area as influenced by running depth, vertical angle and horizontal angle

The cross-sectional breakout by the soil aerator refers to the soil failure induced by the blades as they engage the soil and generate a cutting, lifting and compacting action (Figure 4.1-3 and Figure 4.1-4). As the blades are of a chisel design and enter the soil at an angle from the vertical, they impart a crescent failure or breakout towards the soil surface (Godwin and Spoor, 1977).

The depth of the aerator blades has a significant effect on the mean cross-sectional breakout area of slots. Irrespective of vertical and horizontal angles, Figure 4.1-5 shows breakout area at 100 mm depth to be approximately 280% greater than for the 50 mm depth treatments.

At 50 mm running depth, there is a degree of variability in breakout area (Table 4.1-3, Figure 4.1-5). At a fixed vertical angle of 0° there is no significant difference in breakout area across all horizontal angles for 50 mm running depth. At 10° vertical, there is no significant difference in breakout area between 0° and 5° horizontal angles or for between -5° and 10° horizontal angle treatments, but there is a significant difference between these two sets (Figure 4.1-5). Similarly, at a fixed vertical angle of 18°, breakout area at -5° horizontal angle is significantly higher than at 0° and 5° horizontal angle, but not significantly different to the breakout area at 10° horizontal (Table 4.1-3 and Figure 4.1-5).

Table 4.1-3 Mean cross-section breakout area (cm²) at 50 mm and 100 mm depths

Depth (mm)	Horizontal angle (°)	Vertical angle (°)		
		0	10	18
50	-5	23.80a ^a	35.69a ^b	35.05a ^b
100		75.86b _a	77.31b _a	91.94b _a
50	0	17.41a ^a	15.92a ^a	13.46a ^a
100		47.84b _a	50.59b _a	78.06b _a
50	5	24.07a ^a	24.00a ^a	22.12a ^a
100		70.18b _a	76.90b _a	102.52b _a
50	10	33.56a ^a	38.24a ^b	31.07a ^a
100		93.02b _a	85.80b _b	98.85b _a

For a given vertical angle (0°, 10° or 18°) within each horizontal angle (-5°, 0°, 5° or 10°) values of cross-section breakout area (cm²) for 50 or 100 mm depth followed by a different letter are significantly different (p<0.05) following ANOVA Factorial. For 50 mm running depth (a) and a given vertical angle (0°, 10° or 18°) values of cross-section breakout area (cm²) at each horizontal angle (-5°, 0°, 5° or 10°) followed by the same superscript letter (a) are not significantly different (p>0.05) following ANOVA Factorial. For 100 mm running depth (b) and a given vertical angle (0°, 10° or 18°) values of cross-section breakout area (cm²) at each horizontal angle (-5°, 0°, 5° or 10°) followed by the same subscript letter (b) are not significantly different (p>0.05) following ANOVA Factorial.

At 100 mm running depth there is a greater variability in breakout area compared to 50 mm depth. For a fixed horizontal angle of -5° , breakout area at 0° and 10° vertical angles are not significantly different whereas at 18° vertical angle however there shows to be a significant 120% increase in breakout area compared to 10° vertical angle (Table 4.1-3 and Figure 4.1-5).

For fixed horizontal angles of 0° and 5° , the breakout areas at 0° and 10° vertical angles are not significantly different. However, at an 18° vertical angle, breakout area is 150% greater than at 10° vertical angle (Figure 4.1-5). With regards to a horizontal angle of 10° , there is no significant difference in breakout areas between 0° , 10° and 18° vertical angles.

For a fixed vertical angle of 0° , mean breakout area at 0° horizontal angle is approximately 150% greater as compared to the -5° and 5° horizontal angle treatments. At -5° and 5° horizontal angles there is no significant difference in breakout area. At 10° horizontal angle there is a significant rise in mean breakout area (120%) as compared to the -5° horizontal angle treatment (Table 4.1-3 and Figure 4.1-5).

For a fixed vertical angle of 10° , breakout area trends are similar to those at 0° vertical angle (Figure 4.1-5) with the exception that at 10° horizontal angle breakout area is not significantly different as compared with the 5° or -5° horizontal angle settings.

At a fixed vertical angle of 18° , overall breakout is up to 150% greater for each horizontal angle as compared to both 0° and 10° vertical angles. As shown in Figure 4.1-5, breakout area at 18° vertical angle displays similar trends to those at 10° vertical angles with exception that at 10° horizontal angle mean breakout area drops by approximately 3% as compared to 5° horizontal angle which is against the trend observed for 0° and 10° vertical angles.



Figure 4.1-3 A completed soil-bin 'run' at 100 mm depth and 10° vertical at 10° horizontal (left), -5° horizontal (middle), and 5° horizontal (right).



Figure 4.1-4 Soil breakout through soil aerator blade engagement at 100 mm depth, 18° vertical and 0° horizontal (note lifting and displacement of soil surface, tape at 100 mm)

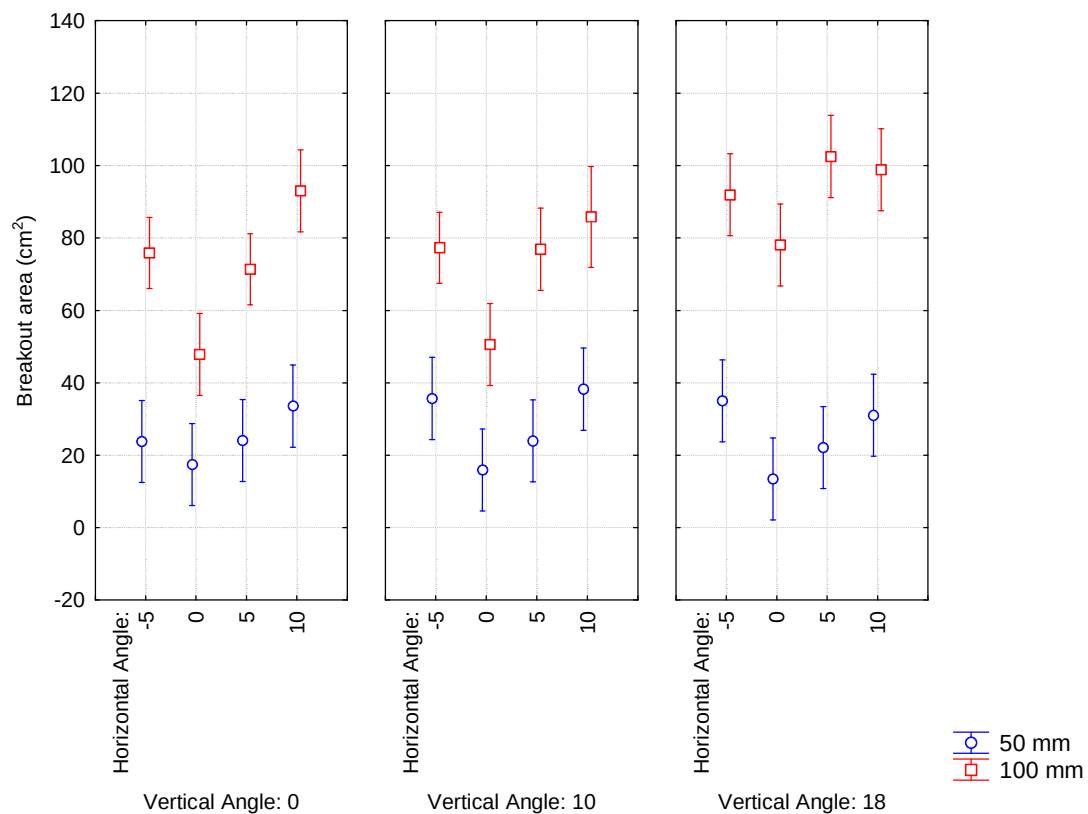


Figure 4.1-5 Mean cross-sectional breakout area at 50 mm and 100 mm running depths for all horizontal and vertical angles of blades ($p=0.420$) with 95% confidence level

A further finding when investigating the breakout characteristics of the slots at 100 mm depth was their connectivity resulting from overlapping crescent failures. Figure 4.1-6 shows the connectivity encountered at 100 mm depth with the blades engaging the soil at 18° vertical angle, 10° horizontal angle. The ‘col’ between breakouts was 20-50 mm below the surface.

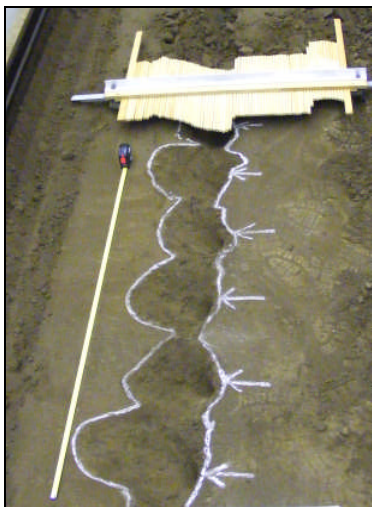


Figure 4.1-6 Breakout connectivity between slots for 100 mm depth at 18° vertical and 10° horizontal. Arrows denote blade points. Tape measure at 1.0 m. Direction of travel is from bottom to top of image (blades inclined towards right of image)

4.1.4 Specific draught

Specific draught is an inverse measure of tillage tool draught force efficiency as described by McKyes, (1985). The specific draught (kPa) is calculated by dividing the horizontal draught force (N) by the cross-sectional area (cm²) of the disturbed soil.

Figure 4.1-7 shows the relation between the blade parameters (horizontal and vertical angles) and specific draught. There is less clear distinction between 50 mm and 100 mm depths as compared to normal draught (Figure 4.1-1).

However, of note is the inefficiency of the 50 mm running depth to breakout soil at the 0° horizontal angle, as compared with -5°, 5° and 10° horizontal angle treatments showing no significant difference between them. When comparing against breakout area at 50 mm running depth in Figure 4.1-5, the inefficiency highlighted above corresponds with a fall in breakout area at 0° horizontal angle.

At a running depth of 100 mm there is generally more consistent efficiency (Figure 4.1-7) which corresponds to overall breakout area (Figure 4.1-5). For fixed horizontal angles of -5° and 5°, there is no significant difference in specific draught across all vertical angles which is also reflected in breakout area (Figure 4.1-5)

However, at a fixed horizontal angle of 0°, specific draught at 0° and 10° vertical angles show no significant difference (Figure 4.1-7), whereas at 18° vertical angle specific draught is approximately 50% less than at 0° and 10° vertical angles. For a fixed horizontal angle of 10°, specific draught at 10° and 18° vertical angles show no significant difference, however at 0° vertical angle, specific draught increases by approximately 200% as compared to specific draught at 10° and 18° vertical angle. This is due to a sharp rise in draught as shown in Figure 4.1-1.

For a fixed vertical angle of 0°, specific draught at -5° horizontal angle is significantly lower as compared to 0°, 5° and 10° horizontal angles. There is clearly no significance in specific draught between the 0° and 10° horizontal angles. However, specific draught at 5° horizontal angle is at least 28% lower than the 0° and 10° horizontal angle settings (Figure 4.1-7). In comparison, a fixed vertical angle of 10° produced no significant difference in specific draught between -5°, 5° and 10° horizontal angles. Specific draught at 0° horizontal angle is significantly higher to specific draught at -5°, 5° and 10° horizontal angles by approximately 180% (Figure 4.1-7).

For a fixed vertical angle of 18° there is no significant difference in specific draught across all horizontal angles, but appreciably, at this vertical angle, specific draught is consistently lower as compared to the 0° and 10° vertical angle settings.

From the results, running the soil aerator at 18° vertical, 100 mm depth irrespective of horizontal angle, specific draught is at a minimum and infers that these setting are the most efficient configuration.

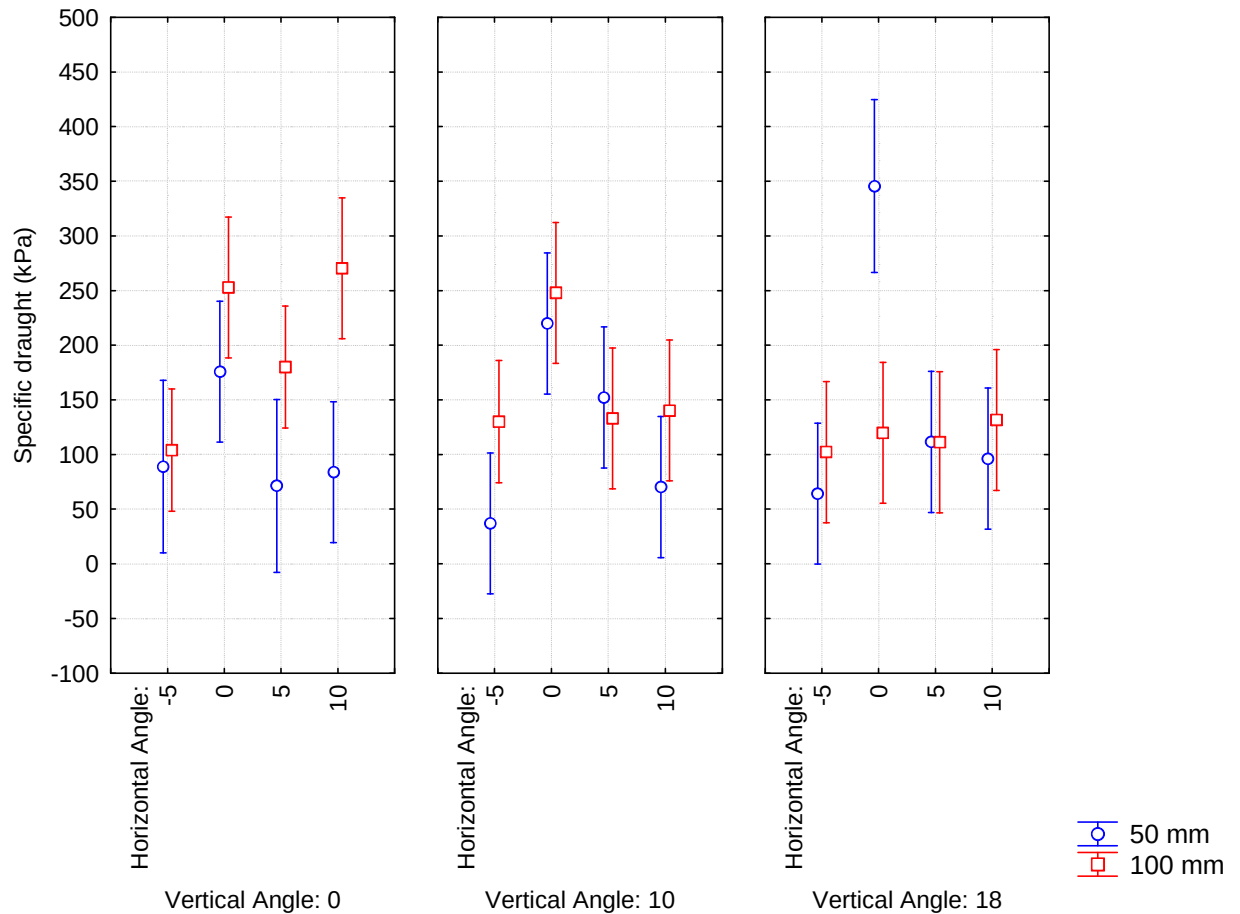


Figure 4.1-7 Mean specific draught for 50 mm and 100 mm running depths, varying horizontal and vertical angles ($p=0.014$) with 95% confidence level

4.2 Field test results: soil aerator treatments on a sloping grassland and erosion plot runoff

4.2.1 Overall comparison between block treatments from erosion plot runoff measurements

When comparing between the control (T1), up-down slope slotting (T2) and across slope slotting (T3) treatments (Table 4.2-1), the ANOVA results at 95% confidence level show no significant difference ($p=0.073$) in runoff between the 5 to 30 minute sampling intervals (Figure 4.2-1). The total runoff values at the 5 minute intervals between all treatments show no significant difference. At 10 and 15 minute intervals, runoff for T2 is significantly lower to runoff for T1 and T3 (Figure 4.2-2). For the time intervals between 20 to 30 minutes, there is no significant difference in total runoff for all treatments.

Table 4.2-1 Mean total runoff values (ml) at 5 minute intervals from erosion plots on treatments T1, T2 and T3

Treatment No.	Mean runoff (ml): 5 minute intervals					
	5	10	15	20	25	30
T1	2a	338a	442a	455a	452a	450a
T2	3a	36b	123b	235a	249a	230a
T3	9a	340a	525a	607a	563a	523a

For a given time interval (5, 10, 15, 20, 25 or 30 min) mean runoff values (ml) followed by a different letter are significantly different ($p < 0.05$) following ANOVA Factorial.

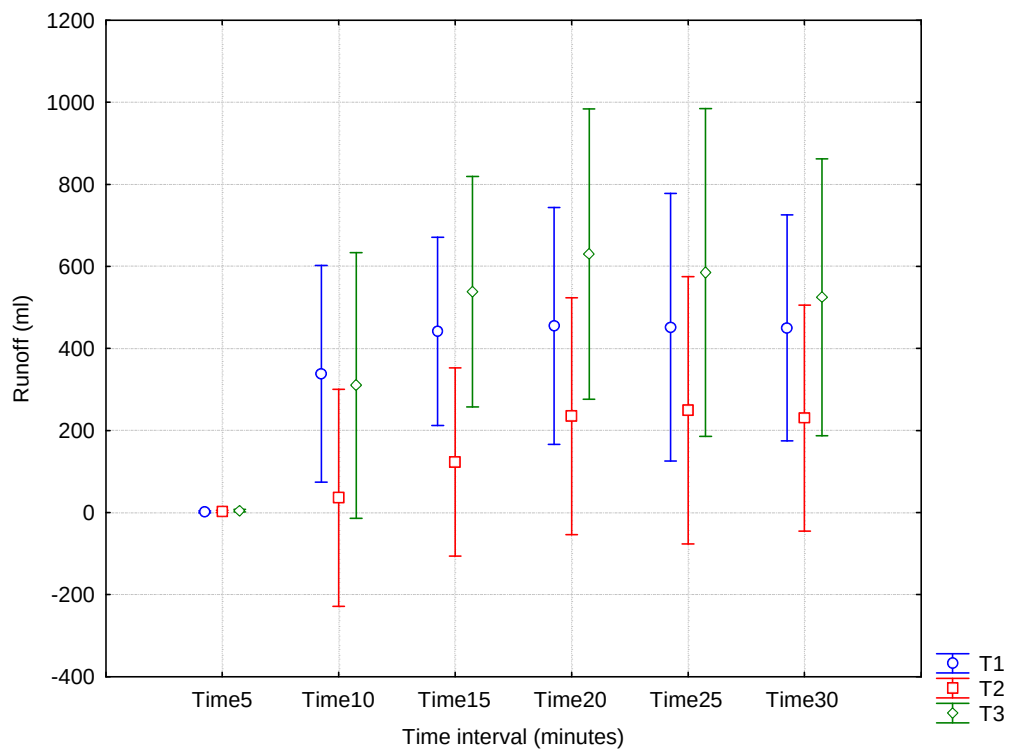


Figure 4.2-1 Mean runoff from erosion plots for T1, T2 and T3 for 30 minutes taken at 5 minute intervals ($p=0.074$) with 95% confidence level

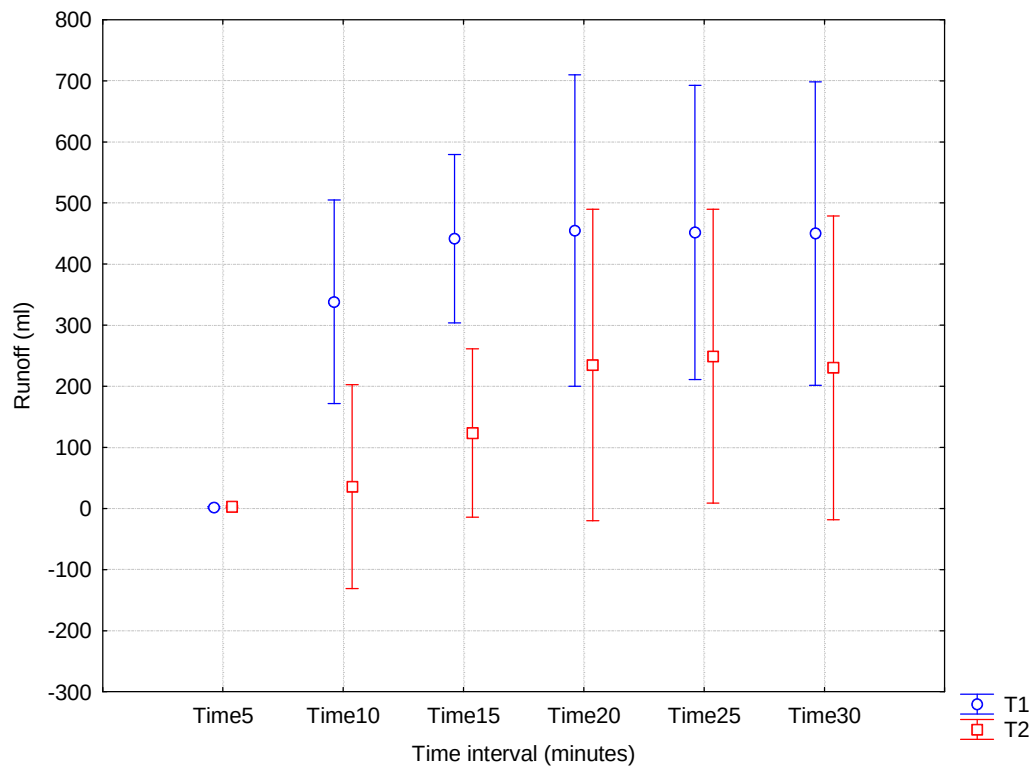


Figure 4.2-2 Mean runoff for T1 and T2 ($p=0.035$) with 95% confidence level

4.2.2 Slotting treatment effects on cumulative runoff from rainfall simulations

As shown in Table 4.2-2, cumulative runoff is significantly influenced by the different treatments. Considering total cumulative runoff results, T1, produced a mean cumulative runoff of 2138 ml (14,253 litre ha⁻¹ or 1.4 mm ha⁻¹). Further cumulative total runoff for T1 is approximately 2 times greater than for T2 at 1096 ml (7307 litre ha⁻¹ or 0.7 mm ha⁻¹). The T1 value is also approximately 250% greater than T3 at 883 ml (5887 litre ha⁻¹ or 0.6 mm ha⁻¹). At the 5 minute interval, cumulative runoff between treatments shows no significant difference.

At the 10, 15 and 20 minute intervals, cumulative runoff for treatments T1 and T2 show no significant difference. However, for T3 there is a significant reduction in cumulative runoff by approximately 88%, 79% and 67% for 10, 15 and 20 minute intervals respectively compared to T1.

At the 25 and 30 minute time intervals, there is no significant difference in cumulative runoff between treatments T2 and T3. However, cumulative runoff for treatments T2 and T3 is significantly reduced by at least 50% compared to runoff for treatment T1.

Table 4.2-2 Mean cumulative runoff for erosion plot treatments T1, T2 and T3

Treatment	Mean cumulative runoff (ml): 5 minute intervals					
	5	10	15	20	25	30
T1	2a	340a	782a	1237a	1688a	2138a
T2	3a	190a	413a	642a	870b	1096b
T3	9a	8b	168b	403b	653b	883b

For a given time interval (5, 10, 15, 20, 25 or 30 min) cumulative runoff values (ml) followed by a different letter are significantly different ($p < 0.05$) following ANOVA Factorial.

Introducing a covariate of mean slot volumes (Section 4.2.3) for treatments T2 and T3 to the ANOVA analysis of cumulative runoff, Figure 4.2-4 highlights the influence slot volume has on runoff from slotted plots. Figure 4.2-4 shows a significant difference in cumulative runoff between T2 and T3 at the 10 minute time interval, however for the 5, 15, 20, 25 and 30 minutes intervals no significant difference between in cumulative runoff was observed for the T2 and T3 treatments.

Comparing Figure 4.2-3 and Figure 4.2-4 highlights the significant difference in mean cumulative runoff for T1 as compared to the adjusted cumulative runoff for T2 and T3 making note of the change in scale on the x-axis.

The rainfall simulator delivered 32 mm hr⁻¹ of water for 30 minutes, equating to 4 litres of water every 5 minutes for each 1.5 m² erosion plot (24 litres cumulative after 30 minutes). Considering that only a proportion of this applied water ran-off the erosion plots (Table 4.2-2), the remainder, at least 53% would

have infiltrated the soil. It is not clear what exact influence the slotting treatments had on infiltration rates, but for T1, only 47% of the water infiltrated as compared to 73% and 78% for T2 and T3 respectively. Using the calculated intercepted applied rainfall, the infiltration for T1 is approximately 30 mm hr^{-1} ($30 \text{ litres hr}^{-1} \text{ m}^{-2}$). Extrapolated to field scale, for every five minutes of a 32 mm hr^{-1} rainfall, infiltration rates for T2 treatment would be $150 \text{ litres ha}^{-1}$, $151 \text{ litres ha}^{-1}$ for T3, with $142 \text{ litres ha}^{-1}$ for T1. The non-significant difference in slot volume between T2 and T3 (Table 4.2-3) would not influence the above infiltration rates. However, the $3.3 \text{ to } 4.4 \text{ m}^3 \text{ ha}^{-1}$ ($3300 \text{ to } 4400 \text{ litres ha}^{-1}$) holding capacity for slotted treatments would significantly increase infiltration as compared to the untreated grassland.

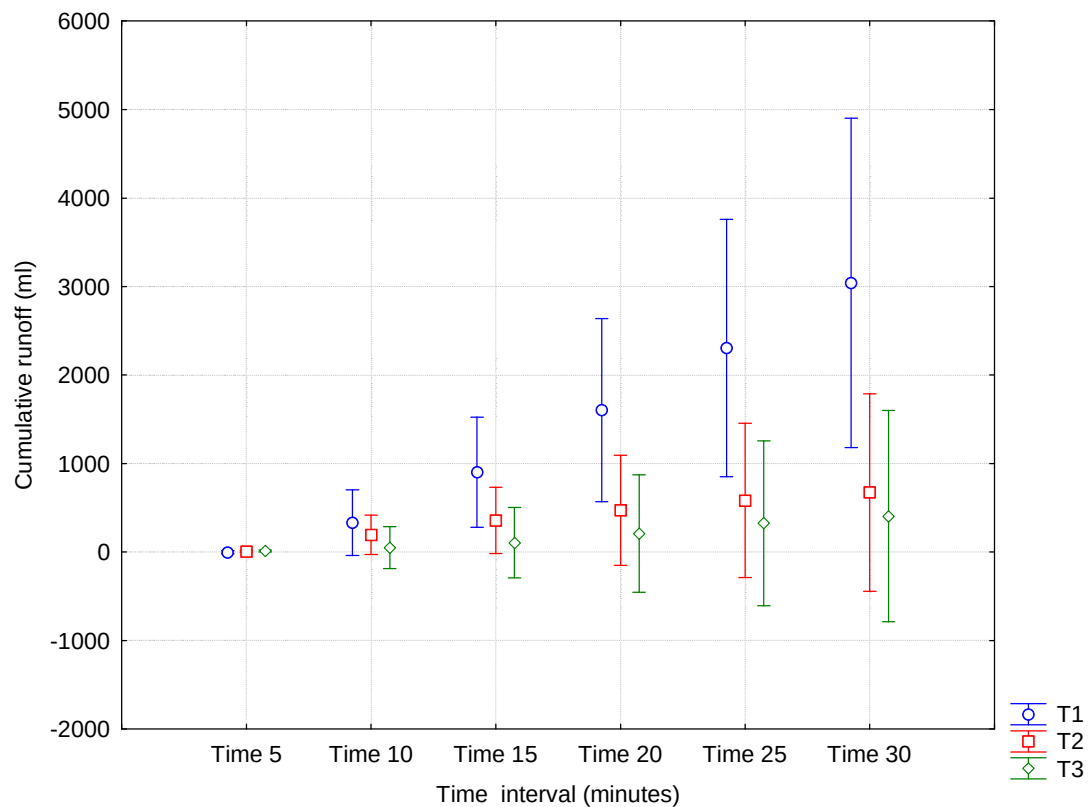


Figure 4.2-3 Mean cumulative runoff (ml) for treatments T1, T2, T3 ($p=0.002$)

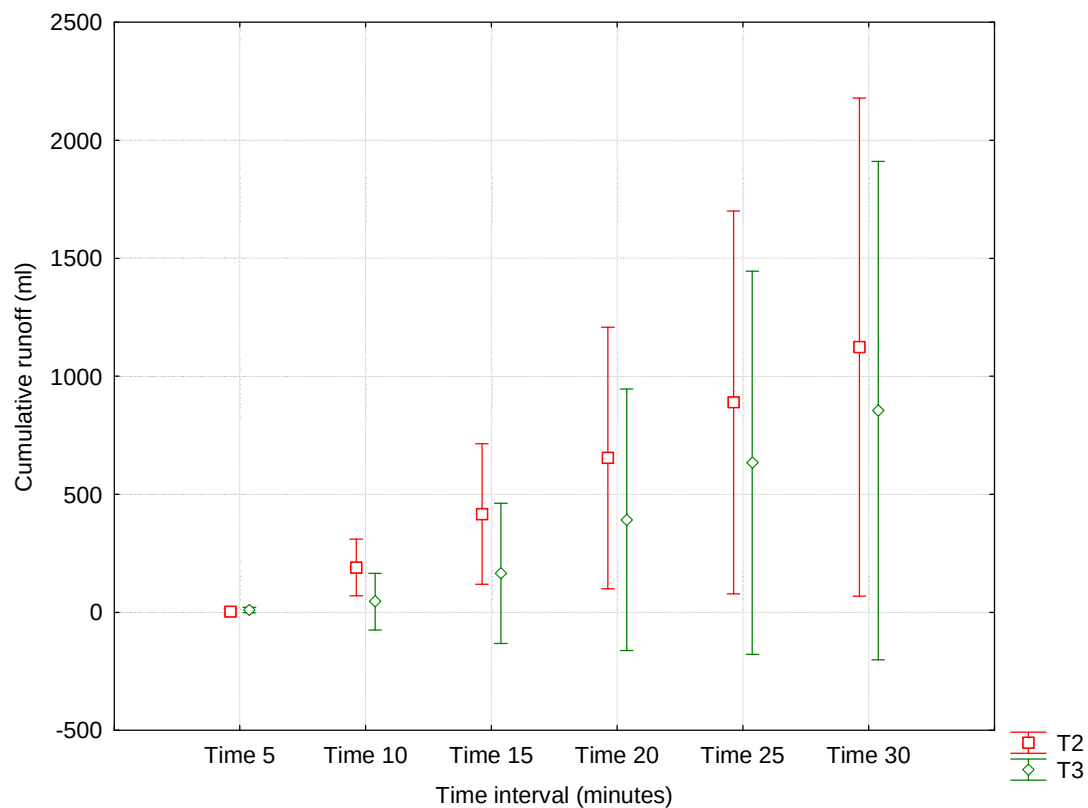


Figure 4.2-4 Mean cumulative runoff (ml) for treatments T2 and T3 with mean slot volume of 42.82 cm³ as covariate (p=0.882) at 95% confidence level

4.2.3 Comparison between field soil aerator slots and soil-bin slots

As mentioned in the literature review (Section 2.3.1), Crawford and Douglas, (1993) calculated the approximate slotting volume over a hectare of land for a single run of the soil aerator they studied. Table 4.2-3 shows the calculated slot volumes (pyramid volume) and slot volume per square metre (m³ m⁻²) for the soil-bin treatments (mean 20 slots m⁻²). Table 4.2-3 also shows slot volumes for field treatments (T1, T2 and T3), as well as the extrapolated slot volume per hectare (m³ ha⁻¹) for soil-bin and field slots. In order to compare between the soil-bin treatments and field treatments, only dimensions of soil-bin slots created at 100 mm running depth, 18° vertical angle and 0° horizontal angle were used (as close to the field aerator configuration as possible, (i.e. maximum running depth ~100 mm, 23° vertical, 0° horizontal)).

Due to the high variability about the mean values, the difference in volume per hectare between T2 and T3 was not significant (p=0.095) as shown in Figure 4.2-5. However, between soil-bin treatments at 50 mm and 100 mm running depth there is a highly significant difference in slot volume.

Table 4.2-3 Slot volumes for erosion plots and extrapolated volume per hectare for a single aerator pass

Treatment	Slot area (m ²)	Mean slot vol. (cm ³)	Mean (m ³ ha ⁻¹)
Soil-bin 50	20a	20a	3.93a
Soil-bin 100	20a	108b	21.51b
T1	0a	0a	0a
T2	16b	42b	3.29b
T3	13b	44b	4.50b

For a given treatment values of slot area (m²), mean slot volume (m³) and mean volume per hectare (m³ ha⁻¹) followed by a different letter are significantly different (p<0.05) following ANOVA Factorial.

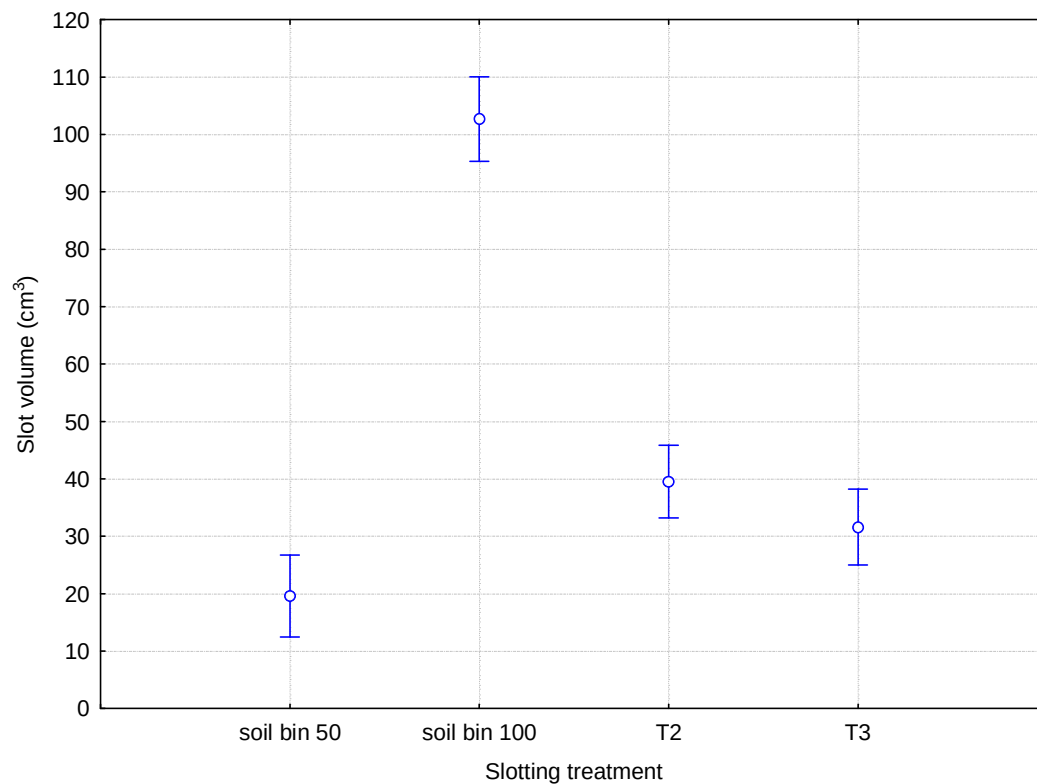


Figure 4.2-5 Mean slot volume (cm³) comparison between soil-bin treatments at 50 and 100 mm running depths against aeration treatments T2 and T3

5 Discussion

Soil physical disturbance as a result of slotting in a soil-bin

As expected, draught force on the soil aerator blades increased with increase in depth from 50 mm to 100 mm (generally, draft increases by the square of depth increase). The full machine would therefore require greater horse-power to tow, but seen by the results for specific draft, there is greater efficiency in soil disturbance at 100 mm. This draft component will vary depending upon the soil being aerated as highlighted by the work of Godwin and Spoor, (1977).

The results indicate that draught force is mainly independent of vertical angle of the blades, irrespective of depth and horizontal angle. However at 100 mm running depth, the lowest mean draught forces were observed at -5° , 0° and 5° horizontal across all vertical angles which was expected due to a lower blade aspect ratio (length/width) engaging the soil (Godwin and Spoor, 1977). At 18° vertical angle the change in horizontal angle has no significant effect on specific draught. It can then be inferred that the machine, for best efficiency, should have blades engaging the soil at -5° , 0° or 5° horizontal angles, 18° vertical angle at or around 100 mm depth. If longer blades at 120-150 mm (Davies *et al.*, 1989) or 160 mm (personal communication, Bob Ritchie) are used then such vertical and horizontal angles of blade orientation would need to be reassessed. This would be due to the higher degree of soil engagement from higher aspect ratios and therefore higher draught and vertical forces required.

To pull a single aerator disc at such a configuration requires approximately 0.75 kN in a sandy loam soil. Therefore, the full-scale the aerator with two sets of six bladed discs would require approximately 4.5 kN, or 459 kg force. This requirement would vary due to increased bearing friction, the combined weight of the unit and change in the normal force component on slopes (greater draught required working upslope).

As expected, the vertical force component of the soil aerator increased (approximately 250%) when running at 100 mm as compared to 50 mm depth. Simply, the aerator blades had to penetrate and displace more soil with the associated friction force felt between blades and soil (Godwin and Spoor, 1977). Though the aerator was held at set heights with the hydraulic linkage of the soil-bin processor, in a field application, the aerator may require additional ballast that the inherent weight of the machine (approximately 2000 kg) to maintain soil engagement depending on soil strength and towing capabilities of the tractor unit.

Running depths at 50 mm with varying vertical and horizontal angles did not significantly affect the vertical force component as expected due to the low degree of soil disturbance observed during the soil-bin trials. However, at 100 mm depth, varying the horizontal angle had significant effects on vertical force, with vertical angle not being a significant parameter. The lowest mean

vertical force (1.79 kN) was observed at -5° horizontal angle for all vertical angles (0° , 10° and 18°), with only -5° horizontal angle at 0° vertical angle significantly the lowest vertical force (1.68 kN and 1.95 kN respectively). This implies an ideal blade orientation for the soil aerator to maintain lowest vertical forces. If using this blade orientation for the field aerator (two sets of six bladed discs), a total vertical force of 21.5 kN or 2193 kg force (ballast) would be required to maintain the blades in the soil. Blade settings of 0° , 5° or 10° horizontal angles would require approximately 3000 kg force. This orientation also corresponds to the findings for specific draught and the most efficient running of the aerator relative to soil breakout.

Having the aerator blades run at 18° vertical angle at 100 mm depth resulted in maximum efficiency for all vertical angles investigated as the increased rake angle of the blades (effectively a tine design) impart a longer crescent failure breakout (Godwin and Spoor, 1977). Horizontal angle at 18° vertical angle does appear to influence breakout with 5° and 10° horizontal angles showing a tendency to generate a higher mean breakout, as compared to the mean breakout at -5° horizontal angle. Above 0° horizontal angle, breakout increases due to an increased aspect ratio, blades imparting a greater twisting action during soil engagement (angle of attack) and greater lateral displacement.

For practical use, such soil disturbance on pasture and fodder crop management is not ideal due to root damage and soil contamination of grass (Crawford and Douglas, 1993; personal communication, Bob Walker). However, for soils with higher clay content (e.g. Herefordshire Bromyard series), such displacement is more elastic rather than plastic deformation, which further depends on moisture content.

Effects of slotting on runoff

The significant difference in total runoff in the first 15 minutes between the control treatment (T1) and the slotting treatments T2 and T3 demonstrates the influence aeration slots have at intercepting runoff associated with rainfall of 10 year return periods for 30 minute duration and subsequently, at reducing overland flow.

This is of significance for this report when considering rainfall at or below 15 minute duration and intensities of below 32mm hr^{-1} . The results indicate that for such rainfall the T2 and T3 slotting treatments would significantly improve infiltration and reduce runoff. The cumulative runoff results further highlight the ability of slotting parallel (T2) and perpendicular (T3) to slope to impede runoff as compared to untreated grassland (T1). Therefore rainfall on compacted grassland can be effectively trapped by aeration slots and reduce runoff and flood risk.

The connectivity in the slots at 100 mm depth observed during the soil-bin trials brings our attention back to Crawford and Douglas, (1993). They suggest that

such connectivity in using aerators improves soil structure and infiltration by connecting macropores. This is therefore an additional benefit of the soil aerator investigated in this study. Referring to the difference in cumulative runoff between slotting treatments T2 and T3, this connectivity has implications for water mobility down the slope. Continuity between the slots for T2 would effectively create porous drainage channels up-down slope whereas across slope slots (T3) they are effectively connected dams holding back water. Such connections were not observed in the field due to the soil wetness allowing elastic deformation and masking any cracking, but it is believed slots on drier soils would likely have greater connectivity. This implies the timeliness of using the soil aerator and the desired treatment required for a particular slope, soil texture and vegetation cover. This would be a basis for further investigation as well as the interaction between neighbouring slot runs (Figure 4.1-3).

These findings have implications for the use of this soil aerator. Using such machinery up-down slope is easier for an operator and for reduced wear on tractors as compared to running across slope (personal communication, Jim Clay). This is a result of considerable weight on the rear of a tractor and the associated control problems.

Regarding poaching risk (Patto *et al.*, 1978; Bilotta *et al.*, 2007) by reducing runoff and improving infiltration rates, the aerator has potential benefits in improving grassland for grazing and protecting the topsoil against poaching by removing free standing water. This also improves the timeliness of putting cattle out to pasture in the spring by up to two weeks as reported by Balsom, (2009) for a large Gloucestershire dairy farm using a soil aerator to improve grazing access and incorporating sodium amendments. These extra two weeks of grazing will have major implications in terms of cost reductions in dairy farming. Animal health is reportedly better when fed on grass with the result being improved milk yield. Maintenance costs per head of cattle are also reduced with less consumption of feed concentrate, less bedding and reduced slurry storage. Feed savings over two weeks could equate to as much as £970 for a UK mean herd of 114 heads (DEFRA, 2008b) consuming 2 kg soyameal head⁻¹ day⁻¹ at £303 tonne⁻¹ (summer 2009 prices). With regards reducing slurry storage, the control of lagoons is of great concern to dairy farmers. The quicker they can be emptied, the better. Having an extra two weeks in the spring for applying slurry to pasture would be of great interest to farmers in terms of fixing nutrients, reducing storage needs and associated odours and fulfilling stringent NVZ regulations.

Summary and further work

Though a short study, the assessment of the soil aerator has highlighted the effects on draught and vertical force, and soil disturbance through the ability to vary depth, vertical and horizontal angles. From the field trials at Showle Court Farm, the application of such a soil aerator on a grassed slope has reduce runoff by 75%, increase infiltration by 20% and increase storage capacity of the soil surface which compares well with the results of Vliet *et al.*, (2006).

Further work would be to investigate runoff management under slotting treatments in more detail (i.e. over a longer period and on different soil textural classes) and under controlled laboratory environments. Soil moisture recharge, infiltration rates, porosity, nutrient cycling, and microbial populations are soil parameters which can be further investigated. For grassland production, grass yield and grass quality under aeration treatments can also be investigated as remarked upon by Davies *et al.*, (1989), Fortune *et al.*, (1999) and Crawford and Douglas, 1993).

This soil aerator can also be trialled against other aerators on the market as well as using different shapes and sizes of blades (aspect ratio) to determine the best slot creation for particular soils, slope, vegetation and farm management.

6 Conclusions

The assessment of the soil aerator, designed and built by Mr. Roger Clay at Showle Court Farm, Herefordshire, yielded an interesting insight into the effects slotting has on soil structure and soil surface hydrology.

1. Increasing the running depth from 50 mm to 100 mm increased vertical and draught forces by over 250%.
2. The draught force required to pull a full-scale machine with two sets of six blades would require 22.32 kN (approximately 2 tonnes), easily pulled by a 140 hp agricultural tractor.
3. The maximum vertical force requirement was 2.72 kN for a single bladed disc. This equates to approximately 3 tonnes ballast requirement for a two set of six bladed discs machine. This ballast requirement is approaching its inherent weight and therefore little additional ballast would be required to maintain soil engagement.
4. Vertical angle had no significant affect on draught forces.
5. A vertical angle of 18° required the lowest vertical force irrespective of horizontal angle.
6. Applying an increasing vertical angle and horizontal angle increases soil crescent failure.
7. The greatest draught efficiency (lowest specific draught) is at 18° vertical angle irrespective of horizontal angle.
8. Slotting treatments reduced runoff from compacted grassland by 75%.
9. Greater control over soil aerator machines expected parallel to slope.
10. Infiltration rates increased by approximately 20% on slotted grassland compared to unslotted grassland.

From the results of this study, the soil aerator deigned and built at Showle Court Farm is potentially a simple, fast and low-cost method of reducing runoff from compacted grassland. This can bring cost-benefits to pastoral farming in terms of better field access in spring. Environmental benefits would include reduced soil erosion and diffuse pollution to natural water courses.

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