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Macropore Flow and Soil Hydraulic Properties as Affected by Manure/Biosolids Injector Implements Under Variable Soil Physical Conditions

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MACROPORE FLOW AND SOIL HYDRAULIC PROPERTIES AS AFFECTED BY MANURE/BIOSOLIDS INJECTOR IMPLEMENTS UNDER VARIABLE SOIL PHYSICAL CONDITIONS

by

Karine Turpin

A thesis submitted to the School of Graduate Studies and Research
in partial fulfillment of the requirements
for the degree of M.Sc. in Earth Sciences

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ABSTRACT

The aim of this study was to investigate, at various soil water contents, the tillage effects of two different types of injectors on soil hydraulic properties of a loamy clay soil located in Winchester, Ontario, Canada. The two injectors considered are the AerWay SSD (A) and the Kongskilde Vibro-Flex (K). The soil-properties changes associated with the injectors were assessed at ten different soil water contents for both injectors.

The first part of this research involves the evaluation of field saturated hydraulic conductivity (K_{fs}), matrix flux potential (ϕ_m), bulk density (ρ_b) and volumetric water content (θ) for undisturbed soil (U) and for soil disturbed by injector (D). The field saturated hydraulic conductivities measured on disturbed soil for the Kongskilde (D_K) were in 80% of the cases lower than those measured on undisturbed soil (U_K). In contrast, K_{fs} measured on disturbed soil for the AerWay (D_A) were higher in 90% of the cases. These results indicate that the Kongskilde reduces the infiltration capacity of the soil, which may be the result of reduced effective porosity via the smearing of the soil surface. They also indicate that the AerWay is facilitating infiltration, most likely by fracturing the soil surface.

The second part of this study involves a dye tracer experiment conducted on disturbed soil to evaluate the movement pathways of water through soil. In contrast to the AerWay, no relation could be established between liquid transport variables and the water content at which the Kongskilde was run. Greatest depths of penetration observed for the AerWay treatment occurred at run average water contents above 29.7 % vol. and below 19.7 % vol. Sorptive capacity of the upper layers was maximized when soil water contents were between 21.7 % vol. and 31.3 % vol.

RÉSUMÉ

L'objectif visé par cette étude est d'investiguer les effets découlant du travail du sol par deux différents types d'injecteurs sur les propriétés hydrauliques d'un sol situé à Winchester, Ontario, Canada et ce pour un éventail de teneurs en eau différentes. Les deux injecteurs considérés sont le AerWay SSD (A) et le Kongskilde Vibro-Flex (K). Les changements de propriétés du sol associés avec les injecteurs on été évalués à dix différentes teneurs en eau du sol.

La première partie de l'étude est consacrée à l'évaluation de la conductivité hydraulique du sol à saturation (K_{fs}), du potentiel matriciel (ϕ_m), de la densité apparente (ρ_b) et de la teneur en eau du sol (θ) dans les conditions où le sol est intact (U) et celles où le sol fut perturbé par l'injecteur (D). Les mesures de conductivité hydraulique du sol à saturation prises sur le sol perturbé par le Kongskilde (D_K) étaient plus petites que celles mesurées sur le sol intact (U_K) dans une proportion de 80%. À l'opposé, la conductivité hydraulique du sol perturbé par le AerWay (D_A) était plus élevée que celle du sol intact (U_A) dans 90% des conditions étudiées. Ces résultats suggèrent que le Kongskilde diminue la capacité d'infiltration du sol et ce, probablement suite à la réduction de la porosité effective via le lissage de la surface du sol.

La deuxième partie de l'étude utilise un traceur colorant sur les parcelles de sol perturbé dans le but d'évaluer le mouvement de l'eau dans le sol. Contrairement au AerWay, aucune relation n'a été identifiée entre les variables décrivant le transport de l'eau dans le sol et la teneur en eau du sol au moment des opérations de labour à l'aide du Kongskilde. Pour ce qui est du AerWay, les plus grandes profondeurs de pénétration du colorant furent observées lors d'opérations de labour se déroulant à des teneurs en eau du sol plus grandes que 29.7 % vol.

ou plus petites que 19.7 % vol. La capacité de sorption des couches supérieures du sol fut maximisée lorsque la teneur en eau du sol se situait entre 21.7 % vol. et 31.3 % vol.

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This study was possible because of the support and mentoring of many individuals. I would like to thank David Lapen without whom this study would never have been accomplished. David Lapen provided direction, inspiration, and most importantly worked very hard to make it all possible by finding sources of funding and by providing equipment necessary to conduct the study. I would also like to thank William (Bill) E. Curnoe, director of Kemptville College for the use of their facilities at Winchester and for his collaboration to this project; Mark Edwards for technical support, Zora Prostran, Joanna James, Matt Dorie, Lise Boissonnault, Kyle Murphy, for helping with the field work; David Irving for farming operations; Michel Robin for supervision and my life companion Eric Potvin for his love, patience and encouragement.

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STATEMENT OF ORIGINAL CONTRIBUTION

This thesis was prepared and written by Karine Turpin. Karine Turpin did data analysis and image processing. Karine Turpin and David Lapen's crew from Agriculture and Agri-food Canada gathered all the data essential to this study. A list of the persons and their affiliation information is listed in Appendix 1. David Lapen supervised and provided guarantors for the project. David Irving was responsible for the all the farming operations. Karine Turpin is the primary author on both coauthored manuscripts presented in this thesis. The coauthors provided funding for the project and/or technical support and/or guidance.

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CHAPTER 1
INTRODUCTION AND LITERATURE REVIEW

1.1 Problem

One of today's research priorities, according to the Ontario Soil, Water and Air Research and Services Committee (OSWARSC) is to develop better manure and biosolids application systems in order to reduce the impact of agricultural operations on environmental quality (Reid, 2002). The growing concern for soil/water contamination resulting from application of manure and biosolids to agricultural lands may be attributed to recent events in Ontario, more specifically, the well-known tragedy of Walkerton, where 7 persons died and 2,321 people became sick as a result of drinking water supply contamination by manure applied on an agricultural land located nearby the water supply well (O'Connor, 2002). New guidelines and regulations for nutrient management, addressing the issue of water quality and based on appropriate scientific results are needed to keep on using this valuable resource that are manure and biosolids.

The study of the impact of management techniques on preferential flow of manure and biosolids through soil macropores[1] is one of many aspects that needs to be examined in order to reduce water contamination risks from agricultural activities. Injection of manure/biosolids into soil has recently been associated with higher nutrient leaching compared to more conventional methods such as broadcasting (Fleming and Bradshaw, 1992; Smith and Chambers, 1997). Studies suggest that liquid manure is readily gaining access to tile drains through soil macropores (Dean and Foran, 1992; King et al., 1994). One way to

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[1] Large pores into the soil created by soil cracking, fauna and flora, which dominate vertical infiltration flow rates

reduce preferential flow of liquid through the soil matrix is to eradicate the continuity of these channels. Tillage was proven by many authors to destroy pore connections and reduce the rapid downward infiltration of water (Azzoz and Arshad, 1996; Bandaranayake et al., 1998; Osunbitan et al., 2004; Wahl et al., 2004). Since injector implement is basically a tillage tool with a distributor added, there is good reason to believe that the injector device will affect the preferential flow of manure as well.

Studies conducted on tillage regimes and their effects on soil properties and preferential flow are not sufficient to characterize infiltration of liquid following injection because these effects were not described immediately after cultivation. Those studies place emphasis on the long-term effects of a particular tillage method. Research needs to call attention to the specific location where manure is dropped, that is the slits created at the time of injection, which is where the manure is leaching. Moreover, the timing of the injection has a great influence on the leaching potential of liquid manure/biosolids as the soil water content plays a decisive role in the soil infiltration properties (Azzoz and Arshad, 1996 and Jabro, 1996).

1.2 Study Purpose and Objectives and Thesis Organization

The purpose of this study is to expand our knowledge regarding the injector implement effects on soil hydraulic properties under various soil water content in order to reduce leaching of nutrients and pathogens on agricultural land.

The primary objectives of this thesis are:

i. Identify the optimal soil water content at which the hydraulic conductivity is minimized for two manure/biosolids injection approaches (Kongskilde and AerWay) *ii. Characterize through field observations the soil properties changes associated with the Kongskilde and the AerWay*

iii. Evaluate the lateral and vertical water movement through the disturbed soil matrix for both the Kongskilde and the AerWay.

This thesis is written as two review-ready articles that are linked by a general introduction that gives the rationale for the study, an overview of the methodology, and the link between the two parts; and by a concluding chapter that overarches the two parts. Because of this format there is an unavoidable amount of repetition in the two main chapters.

1.3 Conceptual Framework and Overview of Approach

This study was conducted in two parts. The first part consists in the evaluation of the effects of the injector on soil hydraulic conductivity under various soil water contents, which will provide insight on the bulk behaviour of the soil, and the second part involves the evaluation of the water movement though the disturbed soil matrix at various soil water contents using a dye tracer, to provide information on the specific pathways.

The injectors were operated without injecting any liquid to examine the tillage properties of the implement without the confounding effects of liquid injection. Observations on the soil fracturing and evaluation of the tine effects on soil infiltration properties were accomplished. For the first part of the study, water content (θ), bulk density (ρ_b) and infiltration rates were initially measured on undisturbed (U) soil for comparison purposes. Afterwards, infiltration rates were measured in the furrows created by the Kongskilde and in the pockets formed by the AerWay SSD. θ and ρ_b were also measured on disturbed (D) soils (except ρ_b for AerWay).

For the second part of the study, Acid Blue 9 was poured into a confined area of disturbed soil, that is, inside a pocket for the AerWay and into a 10 cm furrow stretch for the Kongskilde. After settling for two days, a 1m x 1m area centred on the dye was excavated at 5, 10, 15, 20, 30, 40, 50 cm and digital pictures were taken at each depth to evaluate the area and extent of the blue dye.

Through the summer and fall 2004, a total of ten injection simulations were carried out at ten different soil water contents for both the AerWay SSD and the Kongskilde. These simulations were achieved on a tile-drained field located near Winchester, Ontario, Canada (lat. 45°03'N, long. 75°21'W). For each soil water contents studied, undisturbed and disturbed measurements of infiltration rates, bulk densities and water contents were taken and two dye tracer trials was performed for each injector.

CHAPTER 2

EFFECTS OF AERWAY AND KONGSKILDE TILLAGE IMPLEMENTS ON SILT-CLAY LOAM SOIL HYDRAULIC PROPERTIES UNDER VARIOUS SOIL WATER CONTENT CONDITIONS

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2.1 Introduction

Ammonia emissions and odour following land application of manures and biosolids can be greatly reduced by injection or sub-surface deposition of manure and slurries into the soil as an alternative to broadcasting them over the land surface (Chen et al., 2001; Frost, 1994; Hanna et al., 2000; Hansen et al., 2003; Smith et al., 2002; van Vliet et al., 2000a). Some other advantages of injection and sub-surface deposition approaches include reduced nutrient concentration in surface runoff (Daverede et al., 2004; Ross et al., 1978; Pote et al., 2003; van Vliet et al., 2000b) and increased uniformity of the manure spreading patterns (Bittman et al., 2002; Chambers et al., 1998). Nevertheless, manure injection has been associated with higher leaching of chemicals (Fleming and Bradshaw, 1992; Smith and Chambers, 1997). Fleming and Bradshaw (1992) assessed the impact of various management techniques on tile drainage water quality. They found that the cumulative loading of $N\text{-}NH_4$ to the tile drain was greatest in the manure injected treatment followed by manure broadcast, manure broadcast on previously chiselled ploughed land, and no manure (control) treatments.

King et al. (1994) suggest that liquid slurries applied on or directly into an undisturbed soil may result in tile water contamination due to preferential flow via soil macropores. Macropores are large pores that can transmit fluids and entrained contaminants rapidly via advection or gravity processes to groundwater and tile drainage systems; effectively bypassing rooting zones where nutrients are needed for crop production (Bandaranayake et al., 1998; Fleming et al., 1992; Azzoz and Arshad, 1996; Azzoz et al. 1996; Endale, 2002). Heavier textured soils that retain macropore memory and functional structure more efficiently than more friable soils (eg., sands) may be especially prone to macropore problems (Flury et al., 1994).

Tillage activities can destroy intrinsic soil structural elements in the cultivation layer and consequently can reduce pore structure and potential for macropore flow (Edwards et al., 1988; Benjamin, 1993; Azzoz and Arshad, 1996, Azzoz et al., 1996; Bandaranayake et al., 1998; Arshad et al. 1999; Andreini and Steenhuis, 1990; Shipitalo et al. 2000; Endale et al., 2002; Osunbitan et al., 2004; Wahl et al., 2004). Although there have been many studies that have evaluated tillage effects on soil physical properties (McGechan, 2002), there is a general lack of study on the effect of immediate changes in water (liquid slurry surrogate) transmission properties resulting from tine-soil interaction, under many different antecedent soil conditions (Harrigan, T.M. et al., 2004). Such research is important with respect to evaluation of the capacity of various kinds of tines to modify macroporosity in the slurry application zone under a variety of common slurry application conditions a soil might represent over a year. The research reported here attempts to do this for two tillage implements, the Kongskilde Vibro-Flex and the AerWay SSD, used on a clay loam soil for a variety of soil water content conditions.

The Vibro-Flex injector could be regarded as a chisel type injector, while the AerWay SSD (Sub Surface Deposition) is an aerator type injector. Both injectors are described in section 2.2.2. It is believed that the Kongskilde tine will smear off macropores and reduce transmission properties at the base of the furrow. The soil lifting and fracturing induced by the twisted-shape tine of the AerWay is expected to increase surface infiltration, while reducing the potential for deep penetration of liquid by truncation of macropores and creation of large dead end pores (slits).

Ultimately, the purpose of this research is to help inform management practices that will reduce the potential for macropore-based transport of contaminants to shallow groundwater and tile drainage systems, resulting from land application of liquid slurry. The specific objective of this study is to evaluate changes in local (tine-soil interaction area) soil water transmission properties resulting from two contrasting shallow-tillage approaches (Kongskilde Vibro-Flex and the AerWay SSD) used over a variety of soil water content conditions on a clay loam soil in eastern Ontario, Canada.

2.2 Materials and Methods

2.2.1 Field Site

The study site is located at a tile-drained field (Figure 2.1) located near Winchester, Ontario, Canada (lat. 45°03'N, long. 75°21'W). The soil is classified as a North Gower clay loam (Orthic Humic Gleysol). Soil texture at depth between 0 to 0.15 m is approximately 0.21 g g^{-1} sand, 0.38 g g^{-1} clay and 0.41 g g^{-1} silt. The field had been under timothy (*Phleum pratense* L.) and brome grass (*Bromus inermis* Leyss.) for nine years prior to 1996 and was never tilled while under hay production. In 1996, the field was subdivided into crop plots, roughly 300 m long and 13 m wide. From 1996 to 2002, the field was under cash (corn-corn-alfalfa-alfalfa) and livestock (corn-corn-wheat-soybean) cropping management practices. During the 1996-2002 period, all plots were conventionally tilled; spring cultivation with mouldboard ploughing in fall.

In 2003, the field was in wheat production. The field was not cultivated after wheat harvest in August 2003. The soil was not tilled during year 2004 and no crops were planted (year field experiments were conducted). Herbicides were, however, applied to the field in June and September 2004 to reduce weed growth. A meteorological station at the site provided information on precipitation over the study period (see Figure 2.2).

2.2.2 Tillage Implements

This study focussed on changes in soil water transmission properties resulting from Kongskilde-type (K) and AerWay SSD (A) (aerator type tine) tine-soil interaction for different surface soil water content conditions. There was no attempt to compare the two injectors, and as detailed later, the measurements zones and techniques are not comparable. The Kongskilde Vibro-Flex 2011 (Kongskilde, Exeter, ON), presented in Figure 2.3 a and b, is composed of two rows of tines for a total of 11 tines and a working width of 3 m. The AerWay SSD manure applicator (Holland Equipment Limited, Norwich, ON) (Figure 2.3 c and d) has a working width of 3.05 m and is made of 16 shattertines (http://www.aerway.com/Brochures/AgMtl/3.0%20AerWay%20Conservation%20Tillage%20Brochure.pdf). These “shattertines” can create discrete soil pockets spaced 0.19 m from each other. The angle of the tines relative to implement direction can be adjusted to modify the size of the pocket; the greater the angle, the greater the openings and the soil disturbance.

For this study, the nominal tillage depth for both units was set to 0.13 m; tests off the site in similar soil types were conducted prior to the experimental runs to adjust depth control mechanisms and ballast (for Aerway). Ballast was required for Aerway for the drier soil to ensure adequate depth penetration by the shattertines. Moreover, common to many manure/biosolids application practices, the offset angle of the AerWay tine relative to pull direction was 10 degree; which is the maximum angle setting (maximum soil disturbance). Both injector units were operated without injecting any liquid to facilitate subsequent soil physical measurements along tine-soil interface locales.

Through the summer and fall 2004, tillage effects on soil hydraulic conductivity was studied for ten different soil water content conditions at various times and locations in the field (Figures 2.1 and 2.2). The tillage runs will be referred to subsequently in this paper as “run”. A tillage run includes a Kongskilde and an AerWay implementation except for runs 6 and 10 (only AerWay) and runs 7 and 8 (only Kongskilde) (Figure 2.1). Each tillage run was performed on a field-area of approximate implement width by 15 meters length.

2.2.3 Soil and Water Flow Variables

A total of 48 soil samples (0-0.15 m depth) were collected at the sampling sites shown on Figure 2.1 in order to evaluate soil texture and soil plasticity over the field. Soil texture was determined via the hydrometer method described in Gee and Or, 2002. The upper plastic limit was determined using the Casagrande method while the Atterberg method was used for the lower plastic limit (McBride, 1993). Volumetric soil water content (θ) for 0.15 m depth was measured prior to the implement runs at respective run locations using a three-pronged TDR probe and a TRASE model 6050 TDR instrument (Soilmoisture Equipment Corporation, Santa Barbara, CA). Bulk density (ρ_b) was also determined at these sites using a core of 7.6 cm length and 4.8 cm diameter.

Soil water content and ρ_b measurements were made prior to each run to determine effectively "undisturbed" or "untilled" (U) soil physical conditions of the infiltration soil layer. These measurements were made in areas near the tillage runs for the Kongskilde treatments and close to the perforated pipes[2] for the AerWay treatments (see Figure 2.1). Undisturbed θ and ρ_b were taken at depths corresponding to the soil layer on which infiltration measurements were made, namely 0.13 to 0.28 m (0.15 m probe) and 0.13 to 0.21 m (0.08 m core length) respectively for the Kongskilde treatment and at 0 to 0.15 m and 0 to 0.08 m depth for the AerWay treatment. In addition, θ and ρ_b was measured in the Kongskilde furrows and θ was taken at 0 to 0.15 m, beside the AerWay pockets, to assess effectively "disturbed" (D) soil physical conditions. ρ_b could not be measured for "disturbed" AerWay pockets.

Soil infiltration rates related to the Kongskilde measurements were made using single-ring pressure infiltrometers (Reynolds, 1993). This non-well infiltration approach was deemed appropriate to characterize macroporosity resulting from tine-soil interactions for the furrow-based Kongskilde where the primary flow direction is vertical. Pressure infiltration

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[2] Used for infiltration rate measurements while assessing undisturbed field-saturated hydraulic conductivity for the AerWay treatments.

measurements were made in the bottom of the furrows created by the Kongskilde tine ("disturbed" (D_K) areas) and at nearby undisturbed locations at 0.13 m depth (nominal tillage depth) (U_K). For the D_K measurements soil that fell back into the furrow following implement run was removed and the infiltration ring (length w/o rim = 0.05 m; inside diameter = 0.1025 m) was subsequently inserted at the base of the furrow (see Figure 2.4). Calculation of field-saturated hydraulic conductivities (K_{fs}), matrix flux potential (ϕ_m), and therefore the macroscopic capillary length parameter (α) was achieved using the multiple-head approach (Reynolds, 1993). Pressure heads of 0.10 and 0.40 m were used for this study. Macroscopic capillary length, α, parameter is calculated by dividing K_{fs} by ϕ_m and represents the ratio of gravity to capillarity forces during infiltration (Reynolds, 1993).
Undisturbed AerWay (U_A) and AerWay soil pocket (D_A) flow rates were measured using a Guelph permeameter following the constant head well permeameter method described in Reynolds, (1993). U_A flow rates, for each run, were measured at pressure heads of 5 cm and 12 cm in 13 cm deep perforated ABS pipes that were inserted into the ground in May 2004 (see Figures 2.1 and 2.5). The use of pipe was deemed a good way to prevent the collapse of the well at the time of measurements and was considered a less disruptive method compared to excavating new holes for each measurement period. Most importantly, the method was developed to eliminate spatial variability problems that could potentially reduce interpretability in temporal trends as linked with water content changes. D_A flow rates were measured in the AerWay pockets at a pressure head of 5 cm (bottom of pocket) and also at a pressure head corresponding to the water level in the pocket when the water level approximates the soil surface (referred to subsequently as "maximum head"); generally

around 10 cm. It was felt that the measure of infiltration rates through the AerWay pocket would be representative of the whole tilled soil since over 70 % of the applied manure would flow directly into the slits immediately after application considering a usual manure application rate of 67,000 l/ha (appox. pocket volume of 0.45 l and about 105,000 slits/ha).

For D_A measurements, post-tillage soil fragments in the pockets were first carefully removed. A nylon mesh (approximate mesh size was 0.002 m) was carefully placed in the pocket to mould the pocket walls and was used to facilitate the removal of the glass beads. Glass beads (0.002 m diameter), used to measure pocket volumes and stabilize the pocket walls, were placed in the mesh-lined pocket for subsequent measurements. A volume of 10 mL of glass beads was first placed at the pocket bottom, on which, the permeameter bottom was placed (Figure 2.6 a). After lowering the Guelph permeameter into the hole, glass beads were added to a height of 5 cm (corresponding to the first pressure head) and the volume was noted (Figure 2.6 b). Afterwards, the pocket was filled with glass beads all the way to the soil surface and the volume was again recorded (Figure 2.6 c). The radius of the well was approximated by $a = \sqrt{\frac{V}{h\pi}}$, where a is the radius of the well (pocket), V is the volume of the pocket and h is the pressure head (D. Reynolds, personal communication). Calculation of field-saturated hydraulic conductivities (K_{fs}), for the 5 cm and maximum head measures, is described by (Reynolds, 1993).

For U_K, D_K, U_A and D_A it was aimed to have 16 measurements per measurement run. In some cases, weather/resource constraints or space limitations precluded this amount of measurements to be made. θ and ρ_b measurements were made near (≈0.5 m) each respective measurement site, where applicable.

In cases of rain event, large tarps covering the entire run site were used in order to keep the soil water content conditions the same over the length of the measurement period or prevent a pre-selected site having desirable soil water content condition to be altered.

2.3 Results

2.3.1 Kongskilde Results

Descriptive statistics of measured soil physical properties for each run are presented in Table 2.1. For eighty percent of the observations, the run's mean log K_{fs} values were higher for the undisturbed (U_K) than for the disturbed (D_K) sampling locations (Figure 2.7). The soil water content data show a range of 13.9 % and 11.8 % between run 11 (driest) and run 2 (wettest) for "undisturbed" and "disturbed" soil conditions respectively. Figure 2.8 illustrates that for 67 % of the runs, the average (α) was higher for U_K infiltration measurements compared to D_K (alpha values produced from run 8 may have been problematic, and were therefore not shown on figure 2.8).

One-way analyses of variance (ANOVA) were performed in order to determine if log K_{fs} and θ were significantly different between runs, as it was hypothesized that tine-soil interactions will have different effects on soil hydraulic conductivity depending on soil water content conditions. The statistical model used was the following:

$$X_{ij} = \mu + \alpha_i + \varepsilon_{j(i)}, i = 1,2..., k; j = 1,2..., n_i, \qquad \text{eq. 1}$$

where μ is the global average, α is the deviation caused by grouping, ϵ is the deviation caused by random error. The ANOVAs revealed that log K_{fs} and θ were significantly different between runs for all treatments ($p < 0.01$), as the variance between runs was significantly higher than the variance within runs (Tables 2.2 and 2.3). The Bonferroni pair-wise post-hoc test was used to identify the runs that produced results that were different than the others at a 95% confidence level. For U_K, run 2 had a significantly higher θ than all other runs except run 4, while runs 9 and 11 had a significantly lower θ than the others (Figure 2.9 a and Table 2.4). Run 11 was the driest. D_K produced similar outcomes with runs 1 and 2 mean θ values being significantly higher than the other runs (except run 8) and run 11 being significantly lower than other runs (Figure 2.9 b and Table 2.4).

A table of Bonferroni post-hoc comparisons revealing significant mean differences in log K_{fs} between runs is presented in Table 2.5. The table shows that for U_K, mean log K_{fs} from run 11 was significantly different from most runs and as shown in figure 2.9 a, was the highest mean log K_{fs} observed of all runs. For D_K, run 1 had the lowest mean log K_{fs} and was statistically similar to runs 2, 7 and 8. Run 11 also had the highest mean log K_{fs} observed but was significantly different only from runs 1, 2, 7 and 8.

The pressure infiltrometer method determines the hydraulic conductivity at saturation and therefore, should not depend on soil water content. However, the soil macroporosity changes along with soil water content, for instance desiccation cracks form at low water content. Moreover, the soil-tine interaction changes with soil water content (i.e. fracturing, smearing, clogging). In order to assess the effect on soil hydraulic properties of soil water content as related to macroporosity and soil-tine interaction changes, regression analysis of log K_{fs} vs. θ was carried for undisturbed (control) and disturbed (tilled soil) Kongskilde. Figure 2.10 presents a graph of linear regressions and 95 % confidence limits illustrating the relationships between log K_{fs} and θ for each treatment (also see Table 2.6). Both regressions were statistically significant ($p < 0.01$). Tests on the slopes and intercepts revealed that slopes of U_K and D_K are both statistically different from 0 and are statistically different from each other ($p < 0.01$). It further revealed that intercepts of U_K and D_K are not statistically different from zero ($p > 0.05$) but are marginally different ($p = 0.02$) from each other. Important information that can be extracted from the regression results are: 1) regression slopes are negative for both U_K and D_K, 2) regression line for D_K is below that of U_K (lower K_{fs} for D_K) for higher water contents and, 3) the two regression lines converge with drop in soil water content to meet at $\theta = 25.6$ % vol., 4) and finally, the 95 % confidence intervals of U_K and D_K overlap below 25.6 % vol.

"Steady-state" flow rates were not always achieved during pressure infiltrometer measurements. Evaluation of conditions in and around the infiltrometer ring after measurement, often supported soil structural mechanisms for such conditions. Figure 2.11 illustrates the percent of time "steady-state" flow rates were achieved (% SS) for a run vs. its average water content (measured at 0.13 m depth). There is a positive relationship ($p < 0.01$) between the run average θ and the percent of time "steady-state" was achieved for a specific run. The D_K regression line is located above that for the U_K.

2.3.2 AerWay Results

Descriptive statistics for the undisturbed (U_A) and disturbed (D_A) soil physical parameters are provided in Tables 2.7 and 2.8 respectively. In contrast to the Kongskilde results, hydraulic conductivities were higher for disturbed soil compared to undisturbed soil. Actually, run average log K_{fs} were higher for D_A compared to U_A for 80% of the runs when the pressure head was set to 5 cm and in 90% of the runs when the pressure head was set to the "maximum head" (Figure 2.12). Moreover, run average log K_{fs} were always higher for maximum head relative to 5 cm head measures (Figure 2.13).

One-way analyses of variance were performed to uncover significant differences in log K_{fs} and θ between runs, as it was hypothesized that tine-soil interactions will have different effects on soil hydraulic conductivity depending on soil water content conditions. The statistical model used was the same as for Kongskilde (eq. 1). The ANOVAs revealed that log K_{fs} and θ were significantly different between runs for all treatments ($p < 0.01$) (Tables 2.9 and 2.10).

The Bonferroni pair-wise post-hoc test was used to identify the runs that produced results that were different than the others at a 95% confidence level (Tables 2.11 and 2.12). Results for the undisturbed AerWay treatment, presented in Table 2.11 combined with figure 2.13, show that runs 2 and 6 had significantly higher mean θ than the other runs (run 6 has the highest mean θ) and that run 11 was the driest. Similar outcomes were obtained for the disturbed AerWay treatment with runs 2, 6 and 12 mean θ values being significantly higher than those from the other runs (exception: no difference between run 4 and 12) and run 11 being significantly drier than the other runs.

Bonferroni pair-wise post-hoc tests realised on mean log K_{fs} values (Table 2.12) and Figure 2.13 indicate that U_A (5 cm head) mean log K_{fs} values from runs 1, 2 and 6 are significantly different (lower) than those of runs 5, 9 and 10 (higher). Also that U_A (maximum head) mean log K_{fs} value from run 6 is significantly different (lower) than those of runs 4, 5, 9, and 10. D_A (5 cm head) mean log K_{fs} values from runs 6 and 9 were found to be significantly lower than for most runs. As for D_A (maximum head), run 6 mean log K_{fs} value was significantly lower than those from all other runs and run 11 had a significantly higher mean log K_{fs} than runs 2, 6, 9, 10, 12.

Graphs of regression lines and 95 % confidence limits, showing the relationships between log K_{fs} vs. θ for each AerWay treatment, is presented in Figure 2.14 (also see Table 2.6). As mentioned earlier, this is key information in order to assess the effect of macroporosity and soil-tine interaction changes, associated with changes in water content, on soil hydraulic properties. All regressions were statistically significant ($p < 0.01$). Tests on the slopes and intercepts revealed that slopes and intercepts of U_A and D_A for both pressure heads are statistically different from 0 ($p < 0.01$). It further revealed that slopes of U_A ($h = 5$ cm) and D_A ($h = 5$ cm) are marginally different ($p = 0.04$) from each other, while slopes of U_A ($h =$ Max) and D_A ($h =$ Max) are not statistically different ($p > 0.05$). There is no difference between the intercepts of U_A and D_A for both pressure heads ($p > 0.05$). Important information that can be extracted from Figure 2.14 is: 1) slopes are negative for all AerWay treatments, 2) maximum head resulted in higher K_{fs}, relative to 5 cm head, 3) regression lines of D_A are located above those of U_A for their respective pressure head, 4) like the U_K and D_K results, regression lines of U_A and D_A converge with a decrease in water content, 5) and finally, the 95 % confidence intervals of U_A and D_A overlap below $\approx$24 % vol. water content for 5 cm pressure head and over the entire range of water content for the maximum pressure head.

A graph of the percent of time where “steady state” flow rates were achieved as a function of the run average water content is presented in Figure 2.15. There is a positive relationship between the run average θ and the percent of time "steady-state" was achieved for a specific run (significant at 0.05 level). The slopes of the regression lines are steeper for D_A than for U_A.

2.4 Discussion

Variability in bulk densities measured over the field was small (Table 2.1, 2.7 and Figure 2.1). The average upper plastic limit determined from 48 samples (Figure 2.1) was 47.3 % (SEM = 0.47) and the average lower plastic limit was 30.3 % (SEM = 0.31). Soil texture, also determined from 48 soil samples (Figure 2.1), is classified as a clay loam with average % clay of 38.2 (SEM = 0.56), % silt of 40.4 (SEM = 0.54) and % sand of 21.4 (SEM = 0.37). Given the homogeneity of the field bulk density, soil plasticity limits and soil texture, and the similar cropping operation since 1987, it is believed that the variability within a run is representative of the variability of the field.

2.4.1 Kongskilde Discussion

The data suggest that the Kongskilde injector was responsible for a reduction in the field-saturated hydraulic conductivity as undisturbed soils had higher average log K_{fs} than disturbed soils for 80 % of the runs (Figure 2.7). Flow limitation induced by smearing of soil macropores by the injector tine may be responsible for the observed difference in K_{fs} between U_K and D_K. As a matter of fact, this process was identified in the field. By visual observations of the soil surfaces used for undisturbed measurements and the base of the Kongskilde furrow, it was obvious that the Kongskilde tine polished the soil and smeared the macropores. Undisturbed soil contained a large amount of wormholes and other macropores, which were not visible at the bottom of the furrows. Furthermore, α was lower for D_K

compared to U_K in 67 % of the runs indicating a less structured soil containing fewer macropores (Figure 2.8).

The Bonferroni comparison table (Tables 2.4 and 2.5) combined with Figure 2.9 demonstrate that extreme values of water content are related to extreme values of K_{fs}. Actually, run 11, which was the driest, is also the run that produced the highest K_{fs} for both U_K and D_K. Moreover, run 1 for treatment D_K was significantly wetter than most runs and was associated with the lowest average log K_{fs} observed. Run 1 actually corresponds to the first injection run in the spring (Figure 2.2) and therefore did not contain notable historically developed desiccation cracks.

The negative relationship between log K_{fs} and θ was present before working the soil with the implements. The negative relationship between log K_{fs} and θ for control treatments must result from macropores present in the soil. As the soil is drying and shrinking, more macropores form, increasing the K_{fs} (Jabro, 1996). The opposite is also valid as the swelling of soil, during the wetting process, diminishes the amount of macropores available for preferential flow of fluids.

The positive relationship between the percent steady state achieved for each run and the run average θ (Figure 2.11 and 2.15) support this hypothesis. Effectively, reaching the steady-state flow rates while doing infiltration measurements greatly depends on the presence of cracks or other structures that cause water to bypass the soil matrix. In reality, steady state would eventually be reached if the quantity of water in the reservoir were unlimited. "This is primarily because this type of flow (essentially pipe and fracture flow) progresses to steady state very slowly. If the permeameter/infiltrometer reservoir were large enough, flow would eventually become steady because the macropores and cracks would eventually fill up with water and/or there would be sufficient lateral infiltration through the macropore walls to produce a 3-D infiltration pattern, which progresses to steady state rapidly"(email from Dr. W.D. Reynolds). Therefore, the low percent of steady-state flow rates attained for runs with low average water content is likely the result of soil cracking occurring in dry weather. Figure 2.11 also suggest that the number of macropores occurring in undisturbed treatment is greater than for disturbed treatment with a generally lower % SS reached for each run, reinforcing the statement of the first paragraph of section 2.4.1.

In Figure 2.10, the regression lines of log K_{fs} vs. θ for undisturbed treatment is above that of disturbed treatment for θ over 25.6 % vol., suggesting that soil smearing caused by the tine at high water content reduces soil hydraulic conductivity. The slope for D_K is a little steeper compared to U_K. In fact, the difference between U_K and D_K rises as the water content increases suggesting that the soil smearing and pruning of macropores by the injector tine may have been more important at high soil water content. There is not much difference between U_K and D_K at water content below 25.6 % vol., as reflected by the overlapping of the 95% confidence interval from both regressions.

2.4.2 AerWay Discussion

A different K_{fs}-θ trend is observed with the AerWay as the run average log K_{fs} are generally lower for undisturbed treatments compared to disturbed (see Figure 2.12); the opposite was observed for Kongskilde. Visual observations of the soil fractures explain very well this phenomenon. The multiple cracks surrounding the pockets facilitate the movement of water through the soil surface (Figure 2.16). Field saturated hydraulic conductivity calculated from the flow rates obtained for a maximum pressure head relative to those obtained for a 5 cm head were always higher (Figure 2.13). This is because the bottom of the pocket is generally smeared and contains fewer fissures compared to the higher portion of the pocket. When the water is allowed to reach the surface, a large number of cracks become available for flow, increasing the hydraulic conductivity.

As previously discussed for Kongskilde, success in achieving steady state flow rates is reduced by soil macroporosity. The speculations above are strengthened by the information contained in Figure 2.15. In fact, U_A treatment generally had a higher % SS compared to D_A, suggesting that fewer cracks were present in the U_A treatment. Furthermore, regression lines of % SS versus average θ for 5 cm head treatments are located above those of maximum head treatments implying more fractures closer to the surface of the well or pocket. The smaller slope value for U_A compared to D_A indicates that soil-fracturing caused by the injector augments as water content decline.

Some information discussed in the first two paragraphs of section 2.4.2 can be observed on Figure 2.14, these are: the higher hydraulic conductivities for D_A compared to U_A and the higher hydraulic conductivities when measured using the maximum head relative to a 5 cm head. The regression analysis also shows a decrease in mean log K_{fs} as the water content increases, which may suggest that something, perhaps soil swelling reduces the hydraulic conductivity at high water content (Also see paragraph 3 and 4 of the Kongskilde discussion). In addition, The Bonferroni comparison tables (Tables 2.11 and 2.12), in combination with Figure 2.13 demonstrate that high values of θ are related to low values of log K_{fs}. For example, run 6 had the highest observed water content and also the lowest log

K_{fs} of all runs. After rain events occurring from day 196 to the day of implement run number 6 (219), swelling process healed all the fractures previously present in the field (Figure 2.2). This may explain the sudden drop in hydraulic conductivity for run 6 shown on Figure 2.12 and 2.13. It may also explain the similar observation for run 7 (Kongskilde) a few days after run 6 (Figure 2.2 and 2.7).

The regression lines of U_A and D_A at maximum pressure head are almost parallel on figure 2.14 and the slope test confirmed that both slopes are the same, suggesting that the water content at time of injection did not affect the soil-tine interaction enough to change the soil hydraulic conductivity. This is quite surprising since the soil smearing at high water content was expected to reduce the hydraulic conductivity below that observed for control treatment. The increase difference between the regression lines of D_A and U_A at 5 cm head while θ increases was even less anticipated as most of the smearing was expected to occur at the bottom of the pocket.

2.5 Conclusions

The study provided some indications on how the injectors affect soil hydraulic conductivity and how soil water content conditions can influence the soil-tine interaction. General findings are as follows:

a There were significant negative relationships between Kfs and θ for all tine disturbed and undisturbed soil conditions. Such relationships, for this silty-clay loam soil, likely result from soil shrink-swell processes and the significant fractures/cracks that can occur during lower soil water content conditions (increase in large macropores at lower water contents).

b Due to the action of the Kongskilde Vibro-Flex of smearing and pruning macropores, K_{fs} was on average higher for undisturbed relative to tine influenced conditions for most water content conditions. This was underscored by alpha for disturbed treatment being generally lower than for the undisturbed treatment.

c There were generally greater differences in soil hydraulic conductivities between undisturbed and disturbed Kongskilde treatments at higher water contents suggesting that macropore-reducing efficiency of the tine were greater at higher water contents where the tine could effectively smear over the larger intrinsic macropores.

d The AerWay tine-disturbed soils had generally higher soil hydraulic conductivities than undisturbed soils for soil water content conditions studied as a result of the soil fractures produced by torquing action of the AerWay tine.

e Higher hydraulic conductivities were observed for measurements at maximum pressure head compared to measurements at pressure head of 5 cm suggesting that fracture and macropores are more abundant from 0-7 cm depth compared to 7-12 cm depth (AerWay).

Even though the lowest soil hydraulic conductivities were observed at high water content for both the Kongskilde and the AerWay, it is not recommended to run the injectors on wet soil (above the lower plastic limit, in this case above 30.3%) as it results in major compaction and create a lot of clogging on the implements (see Figure 2.17).

Based on the results from this study, it is not recommended to inject manure/biosolids with the injector implement on dry soil since it would result in fast flow through soil macropores and potentially contaminate tile water and groundwater. However, the results from this study alone are not sufficient to elucidate the transport pathways of liquid through the soil. The fractures created by the AerWay tine may facilitate the infiltration of liquid through the soil but the tine may as well be disrupting pre-existing macropores and reduce their continuity to a point where potential risks of contaminating groundwater are reduced.

CHAPTER 3

BRILLIANT BLUE DYE TRACER TO EVALUATE WATER TRANSPORT BEHAVIOR RESULTING FROM TILLAGE TINE-SOIL INTERACTION AT DIFFERENT SOIL WATER CONTENTS

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3.1 Introduction

The environmental effects on groundwater and tile water quality of manure and biosolids spreading on agricultural land have gained interest in the past few years following events such as the Walkerton tragedy (O'Connor, 2002). Characterization of contaminant flow pathways for different application management practices is necessary to protect water quality from agricultural pollutants.

Liquid manure/biosolids injection to agricultural lands has recently been associated with higher chemical leaching compared to more conventional methods such as broadcasting (Fleming and Bradshaw, 1992; Smith and Chambers, 1997). Studies suggest that liquid manure is readily gaining access to tile drains through soil macropores (Dean and Foran, 1992; King et al., 1994). Breaking the continuity of these channels can reduce preferential flow of liquid through the soil profile. For example, tillage was proven by many authors to destroy pore connections and reduce the rapid downward infiltration of water (Azzoz and Arshad, 1996; Bandaranayake et al., 1998; Osunbitan et al., 2004; Wahl et al., 2004). It is believed that soil disruption caused by the tillage action of the injector implement may reduce pore continuity and consequently reduce water contamination risks following manure spreading.

Dye tracers have been used in order to visualize preferential flow of liquid through soil macropores. The anionic Brilliant blue FCF (C.I. 42090), also known as C.I. food blue 2, FD&C blue 1 and acid blue 9, is frequently used to investigate water flow through soils (Andreini and Steenhuis, 1990; Peterson et al., 2001; Reichenberger et al., 2002; Weiler and Flühler, 2003). Despite the fact that Brilliant blue FCF sorbs to soil materials, Germán-Heins and Flury (2000) believe that in terms of toxicity, mobility and visibility, brilliant blue is the best dye tracer to study hydrological processes in the vadose zone.

This study was realized as a supplement to Chapter 2. Both studies took place at the same time and location. For this chapter, the dye tracer Brilliant blue FCF was used to visualize transport pathways of dyed water through soil disturbed by two different tillage implements; the Kongskilde Vibro-Flex and the AerWay SSD. The Vibro-Flex injector could be regarded as a chisel type injector, while the AerWay SSD (Sub Surface Deposition) is an aerator type injector. Both injectors are described in section 3.2.2. Coloured water infiltration (liquid manure surrogate) is expected to depend greatly on soil water conditions. Macropore flow will presumably occur at low water content via desiccation cracks as well as under wet conditions, when larger pores are operational. It is believed that the Kongskilde tine will smear off macropores and reduce transmission properties at the base of the furrow. The soil lifting and fracturing induced by the twisted-shape tine of the AerWay is expected to increase surface infiltration, while reducing the potential for deep penetration of liquid by truncation of macropores and creation of large dead end pores (slits).

The objective of this study is to evaluate, at various soil water contents, the lateral and the vertical water transport pathways after tillage action induced by Kongskilde and the AerWay. These tillage implements are common implements used on manure injection systems for shallow application practices. The overall purpose of this investigation was to determine if there were certain soil physical conditions that fostered greater water sorptivity and reduced macropore flow. Such information is critical for informing proper slurry land application practices.

3.2 Materials and Methods

3.2.1 Field Site

The study site is located at a tile-drained field (Figure 3.1) located near Winchester, Ontario, Canada (lat. 45°03'N, long. 75°21'W). The soil is classified as a North Gower clay loam (Orthic Humic Gleysol). Soil texture at depth between 0 to 0.15 m is approximately 0.21 g g^{-1} sand, 0.38 g g^{-1} clay and 0.41 g g^{-1} silt. The field had been under timothy (*Phleum pratense* L.) and brome grass (*Bromus inermis* Leyss.) for nine years prior to 1996 and was never tilled while under hay production. In 1996, the field was subdivided into crop plots, roughly 300 m long and 13 m wide. From 1996 to 2002, the field was under cash (corn-corn-wheat-soybean) and livestock (corn-corn-alfalfa-alfalfa) cropping management practices.

During the 1996-2002 period, all plots were conventionally tilled; spring cultivation with mouldboard ploughing in fall.

In 2003, the field was in wheat production. The field was not cultivated after wheat harvest in August 2003. The soil was not tilled during year 2004 and no crops were planted (year field experiments were conducted). Herbicides were, however, applied to the field in June and September 2004 to reduce weed growth. A meteorological station at the site provided information on precipitation over the study period (Figure 3.2).

3.2.2 General Approach

This study focussed on water transport pathways resulting from Kongskilde (K) (chisel type S tine) and AerWay SSD (A) (aerator type tine) tine-soil interaction for different surface soil water content conditions. The Kongskilde Vibro-Flex 2011 (Kongskilde, Exeter, ON), presented in figure 3.3 a and b, was used in this study. The unit was composed of two rows of tines for a total of 11 tines and a working width of 3 m. The AerWay SSD manure applicator (Holland Equipment Limited, Norwich, ON) (Figure 3.3 c and d) used has a working width of 3.05 m and is made of 16 shattertines (http://www.aerway.com/Brochures/AgMtl/3.0%20AerWay%20Conservation%20Tillage%20Brochure.pdf). These "shattertines" can create discrete soil pockets spaced 0.19 m from each other. Depth of penetration of the tines can accommodate tillage depths of 0.1 to 0.2 m. The angle of the tines relative to implement direction can be adjusted to modify the size of the pocket; the greater the angle, the greater the openings and the soil disturbance.

For this study, the nominal tillage depth for both units was set to 0.13 m; tests off the site in similar soil types were conducted prior to the experimental runs to adjust depth control mechanisms and ballast (for AerWay). Ballast was required for AerWay for the drier soil to ensure adequate depth penetration by the shattertines. Moreover, common to many manure/biosolids application practices, the offset angle of the AerWay tine relative to pull direction was 10 degrees; which is the maximum angle setting (maximum soil disturbance). Both injector units were operated without injecting any liquid to facilitate subsequent soil physical measurements along tine-soil interface locales.

Through the summer and fall 2004, tillage effects on soil transport pathway of liquid through the soil was evaluated for 6 and 10 different soil water contents at various times and locations in the field were selected as experimental sites for the Kongskilde and the AerWay implementations correspondingly (Figures 3.1 and 3.2). The tillage runs will be referred to subsequently in this paper as "run". The "run" refers to the time when the tillage implementations were carried out, 1 being the earliest and 12 being the latest (Figure 3.2). For some runs, transport pathway was evaluated for both implements (runs 5, 9, 11 and 12), while for some other runs, only the Kongskilde (run 7 and 8) or the AerWay (runs 1, 2, 3, 4, 6 and 10) were considered (Figure 3.1). Each tillage run was performed on a field-area of approximate implement width by 15 meters length.

Two reps were conducted per injector, per run. For each trial, 500 mL of Brilliant blue FCF (5 g/mL) was poured into a confined area of soil disturbed by implement tines, i.e., inside a soil pocket for the AerWay and in a 0.1 m furrow stretch for the Kongskilde. The volume of liquid poured into the Kongskilde furrow corresponds to approximately 1.2 times the maximum rate of injection to land with very low runoff potential (150 m^3/ha; Nutrient Management Act). As for the AerWay, the volume of liquid used essentially filled up the

AerWay slits (0.10 to 0.12 m of liquid depending on the slot shape). Assuming that all the manure applied flows into the soil openings, a minimum application rate of roughly 50 m^3/ha would be required for the applied manure to fill up the pockets. Before adding the liquid, loose soil in the furrow was cleared away. Then, two metal sheets (0.30 × 0.30 × 0.003 m) spaced 0.1 m apart were inserted to a depth of 0.05 m (relative to the bottom of the furrow) to prevent the liquid from flowing along the channel. Short-circuit flow along the side of the walls were minimized by tamping the contact area with a pencil. Figure 3.4 shows the retaining walls used to confine the dye.

Preparation of the soil pocket for the AerWay simply consisted in removing the loose soil and applying dyed liquid in the pocket (Figure 3.5). The stained soil was covered for a two day settling period. Afterward, 1 × 1 m area centered on the dye application zone was excavated to depths of 5, 10, 15, 20, 30, 40 and 50 cm. At each depth, loose soil was removed in a low-disturbance fashion via vacuum. A digital camera mounted over the pit was used to take pictures at each respective depth increment.

Precipitation, water content (θ) and bulk density (ρ_b) data were measured in the context of the study presented in Chapter 2.

3.2.3 Digital Image Analysis

Digital pictures were analysed using Analysis DOCU (Soft Imaging System, Lakewook, CO, USA). Pictures were calibrated using an object of known length in the picture. Pixels illustrating stained soil were selected by setting thresholds for red, green and blue (RGB) values. About thirteen thresholds were necessary in order to select all the area stained by dye. The thresholds changed slightly from picture to picture because of variation in soil colour and light intensity. Selected pixels were coloured in green (RGB = 0, 255, 0) and a phase analysis[3] was performed in order to determine the area (cm^2) covered by dye (Figure 3.6). Figure 3.7 demonstrates this entire procedure. Dye spreading, which corresponds to the product of the N-S and E-W distances of dye spreading was also measured (see Figure 3.6). Variables used to characterize flow pathways are depth of penetration (D), area covered by dye (A) and spreading (S). The depth of penetration indicates how far the dye infiltrates and therefore, risk of groundwater contamination. The area variable is an indication of how much dye sorbed to the soil at various depth while the spreading indicates the extent of lateral movement of liquid through the soil. The ratio of spreading to area is also a good indication of macropore flow and fingering as the ratio augments with the increase dye partitioning patterns.

CART, a robust regression tree analysis approach discussed in much more detail in Breiman et al. 1984, was used as an exploratory way to search for significant trends and relationships between water content conditions and dye characterizing variables (depth, area and spreading). CART is a non-parametric, binary recursive partitioning approach. "Binary" because CART is partitioning independent data into two more homogenous groups (low variance) on the basis of an independent variable split criterion and "recursive" because the binary split process is repeated on the subgroups until further splits are either impossible or limited by the user defined parameters.

CART always starts by building, using all available data, a maximal tree, i.e. when further splitting is impossible. Afterwards, CART prunes away branches of the maximal

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[3] "Phase Analysis is the quantitative analysis of the area(s) of various color-value range(s) of the object" (User's Guide analysis)

tree, which clearly overfits the data, to form smaller trees. Those simpler trees are all candidate for the final "optimal" tree. In this study, 10-fold cross-validation was used to determine goodness of fit of the sub-trees produced. The purpose of the cross-validation is to determine which tree size provides the best performance with respect to an independent dataset. For this procedure, CART divides the data into 10 parts; nine parts are used to build the maximal tree and the remaining part is used to determine the error rate on the sub-trees. This process is repeated until each subset of data is used once to test the model. The errors obtained from each test subsets are combined to form the error rates for sub-trees. The errors rates are then applied to the models first built using all available data. The sub-tree having the smaller error rate is selected as the optimal tree.

For this study, the default settings were used for the regression tree analysis and only the first three splits were considered, given the small amount of data.

3.3 Results and Discussion

3.3.1 Kongskilde

Depth of penetration of the blue dye for each run is shown on Figure 3.8. Except for replicate number 2 of run 8, dye reached a depth of a least 60 cm in all cases. Figure 3.9 presents the area covered by dye and the spreading of the dye for each run and each depth excavated. Water contents below 30 cm depth were around 30 % vol. ± 2 % over the season except in the spring (runs 1 and 2) when the water content was 35 % vol. and during the dry conditions experience in run 11 when the water content was 28 % vol.

No particular trend or relationship between run average water content and dye movement variables were established suggesting that the soil-tine interaction may not be a factor affecting transport pathway of liquid applied directly at the base of the furrow.

3.3.2 AerWay

Figure 3.10 shows the depth of penetration of the blue dye for both reps of each run. The dye did not reach 50 cm for run 3, 5, 9 and 10 (middle range values of soil water conditions). Figure 3.11 demonstrates that depth of dye penetration can be summarized by a quadratic function of run average water content ($D = 0.5511\theta^2 - 26.429\theta + 359.3$; $R^2 = 0.6624$) with the centre located at –24.0 % vol. Run 1 was considered as an outlier and was not used to build the second order regression as well as for the CART analysis (Figure 3.11). The reason for excluding Run 1 is that even though soil water content at the surface was 25.4 % vol., this run was the first one in the spring (May 12th, 2004) and the soil at depth was conditionally near saturation. Potential for high water content at greater soil depth to augment transport was certainly responsible for the high depths of penetration observed for the first run but should not be the case for the other runs as there was more uniform sub soil water contents over the rest of the field season. Table 3.1 summarises the results obtained for the CART analysis and indicates splits for the variable "depth" at 19.7 % and at 29.7 %.

Figure 3.12 presents the data for each depth of the area covered by dye and of the extent of dye spreading vs. run mean water content. Relevant information that can be extracted from Figure 3.12 combined to Table 3.1 is as follow: at 5 and 10 cm depth, the area covered by dye (A) is larger for middle range values of run average water content more precisely between 21.7 % vol. and 31.3 % vol. The situation reverses at 30, 40 and 50 cm depth with higher values of A at water content lower than 19.7 % vol. and at water content higher than 29.7 % vol. Relevant splits occurred for spreading (S) at depth of 30 and 40 cm indicating higher spreading for low water content and high water content.

For middle range run average water contents, most of the dye stayed closer to the surface (large values of A for the 5 and 10 cm depths) and small quantities if any reached 30, 40 and 50 cm depth. The high depths of penetration observed at high water contents are believably caused by the increased capacity of soil to transport water due to larger effective pore sizes, whereas for those observed at low water content, soil cracking is most likely to engender preferential flow resulting in high depths of penetration.

For both the Kongskilde and the AerWay, the ratio of spreading over area generally increases with depth; the major rise occurring while going from 20 to 30 cm (Figure 3.9 and 3.12). The increase in the ratio of spreading over area (S/A) with increasing depth indicates that preferential flow through macropores is the most important transport process responsible for dye penetration at depth. In fact, past 20 cm depth, fingering is visible and dye often surrounds earthworm burrows or cracks (Figure 3.13). Small S/A ratio at low depth suggests that convection and diffusion are important processes contributing to the dispersion of dye closer to surface.

3.4 Conclusions

The study was useful for determining soil structure, and soil-tine interaction mechanisms resulting in the transport of liquid in a soil profile above tile drains. The general approach of this work could be used to help define appropriate slurry application times; or at least a lower limit on application. As it stands currently in Ontario, Canada, there are subjective upper soil water content limit guidelines to slurry application, but none at lower water contents (M. Payne, OMAF, personal communication) where soil structure based macroporosity may augment liquid transport to tile drains and shallow groundwater.

For both the Kongskilde and the AerWay, preferential flow was visible through fingering, mostly at depth of 30, 40 and 50 cm.

No particular trends could be identified for Kongskilde with respect to water content conditions vs. depth of penetration and area covered by dye/spreading at each excavated depth. Dye reached a depth of a least 60 cm in every trial but one. These results suggest that soil-tine interaction at deeper depths where water contents are not as extreme do not maximize sorptive capacity of upper layers as readily.

On the other hand, trends between dye movement and run average water content were identified. Greatest depths of penetration occurred at run average water contents above 29.7 % vol. and below 19.7 % vol. High depths of penetration were also observed for the first run in the spring when the soil at depth was conditionally near saturation; spring water conditions is actually when manure is generally injected. Sorptive capacity of the upper layers was maximized when soil water contents were between 21.7 % vol. and 31.3 % vol. (large A at depths of 5 and 10 cm). These results suggest that higher risks of groundwater contamination while injecting liquid using the AerWay take place when soil water content is either high (>29.7 % vol.) or low (<19.7 % vol.). Preferential flow happening in dry conditions and the increased pore space available for flow at high water contents are believed to be the explanation for those observations.

CHAPTER 4

GENERAL SUMMARY AND CONCLUSIONS

The objectives of this thesis are to (1) identify the optimal soil water content that minimizes soil hydraulic conductivity for two manure/biosolids injection approaches (Kongskilde and AerWay), (2) characterize through field observations, the soil properties changes associated with the Kongskilde and the AerWay and finally (3) to evaluate the movement of water through the disturbed soil matrix for both the Kongskilde and the AerWay. This thesis is divided into two review-ready articles (chapter 2 and 3), chapter 2 addressing the first and second objectives mentioned above, while chapter 3 is addressing the third one. The objective of this chapter is to summarize the information contained in the two previous chapters and to give general recommendations based on the study findings.

Preferential flow was identified as being the major process controlling soil hydraulic conductivity. The negative relationship between K_{fs} and θ, as well as the positive relationship between % SS and θ (chapter 2) was likely the result of soil swelling and shrinking, which heal or create fractures in the soil and through which water can bypass the soil matrix. Evidence of preferential flow was found in chapter 3 for both the Kongskilde and the AerWay. Preferential flow of water was visible through fingering, mostly at depth of 30, 40 and 50 cm.

Undisturbed soils resulted in higher hydraulic conductivities than soils disturbed by the Kongskilde tine for θ > 25.6 % vol. (chapter 2). This was believed to be the result of smearing of soil and pruning of macropores by the injector tine (supported by visual observation). The smearing and pruning of macropores by the injector tine may have been more important in wet conditions as suggested by the increased difference between undisturbed and disturbed Kongskilde treatments as the water content rises.

Even though the Kongskilde tine was shown to smear off macropore in wet soil conditions (chapter 2), soil water content at the time of tillage did not seem to have any effect on the water movement variables described in chapter 3 (depth of penetration, area and spreading). Dye reached a depth of a least 60 cm in every trials but one, suggesting high risks of groundwater contamination no matter the initial soil water content at which the liquid is injected. It is believe that the soil smearing may reduce the infiltration time of the liquid and therefore the soil hydraulic conductivity. However, since the Kongskilde tine is ineffective at breaking down the macropore continuity below the application zone, the infiltrating liquid follows those macropores irrespectively of the infiltration rate.

On the other hand soils disturbed by the AerWay tine resulted in higher hydraulic conductivities than undisturbed soils (chapter 2). Soil fractures produced by the AerWay tine were believed to be the cause; supported by % SS data. Higher hydraulic conductivities were observed for measurements at maximum pressure head compared to measurements at pressure head of 5 cm suggesting that fracture and macropores are more abundant from 0-7 cm depth compared to 7-12 cm depth.

The AerWay twisted-shape tine was shown to increase infiltration capacity of the soil (chapter 2) through its lifting and fracturing action. Maximization of the sorptive capacity of the upper soil layers was maximized at water contents between 21.7 % vol. and 31.3 % vol. The potential for contaminants to reach the water table or the tile drainage system is increased when the soil water content is either high (>29.7 %) or low (<19.7 %). The high depths of penetration observed at high water contents are believably caused by the increased capacity of soil to transport water due to larger effective pore sizes, whereas for those observed at low water content, soil cracking is most likely to engender preferential flow resulting in high depths of penetration.

Even though the lowest soil hydraulic conductivities were observed at high water content for both the Kongskilde and the AerWay (chapter 2), it is not recommended to run the injectors on wet soil (above the lower plastic limit, in this case above 30.3%) as it results in major compaction and soil clogging on the implements. Furthermore, highest depth of dye penetration occurred at high water content for the AerWay in chapter 3, increasing risks of groundwater contamination.

Based on the results from this study, it is neither recommended to inject manure/biosolids on dry soil since the soil hydraulic conductivity (Kongskilde and AerWay) and the depth of penetration of water (only AerWay) at low soil water content are both high, augmenting the risks of fast flow through soil macropores and potential for tile water and groundwater contamination (chapter 2 and 3).

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FIGURES

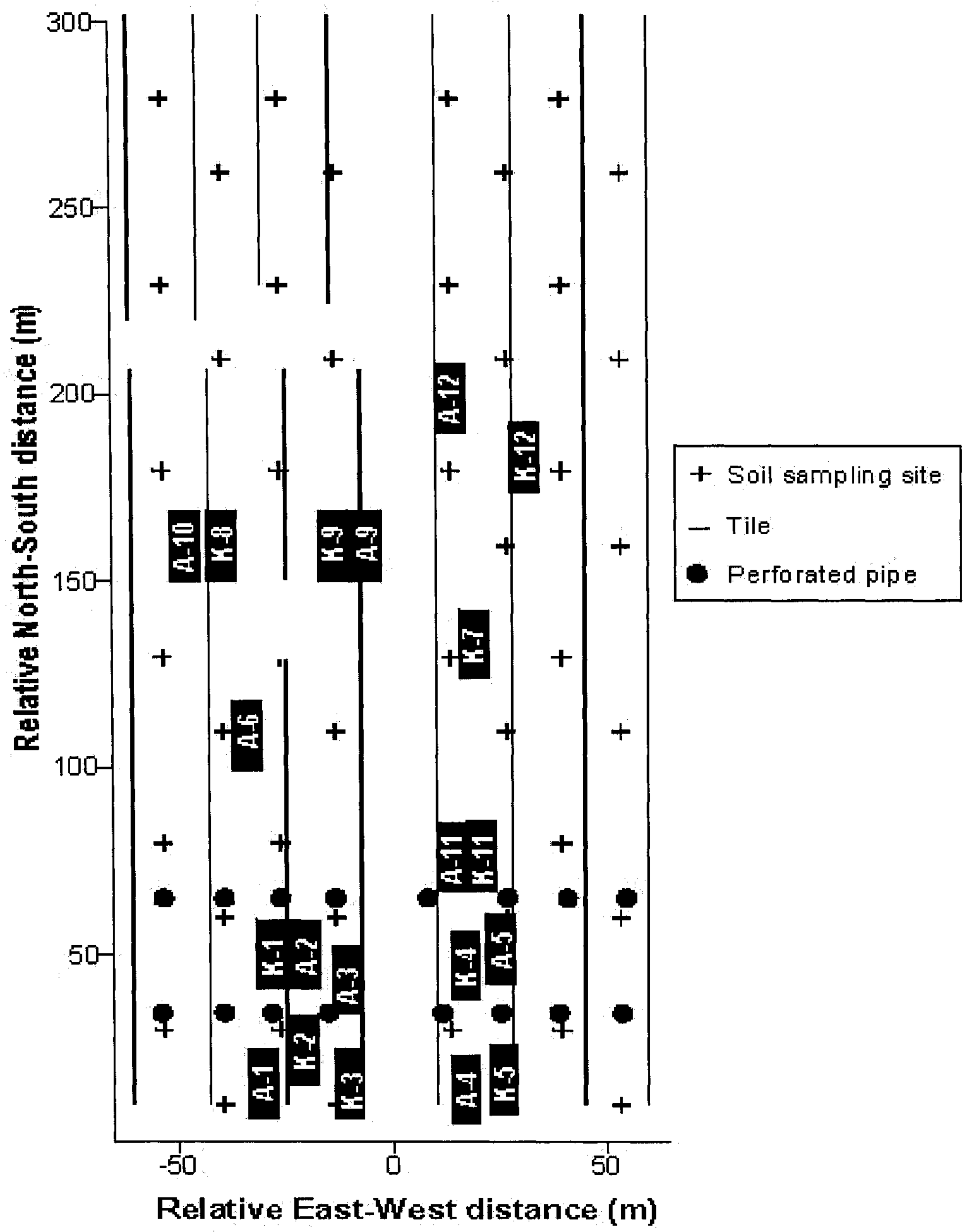


Figure 2.1 Map of the field showing the soil sampling sites, the tile and perforated pipe locations and the areas where the implement runs took place (black rectangles). The implement runs labelled: A = AerWay, K = Kongskilde, # = the run number.

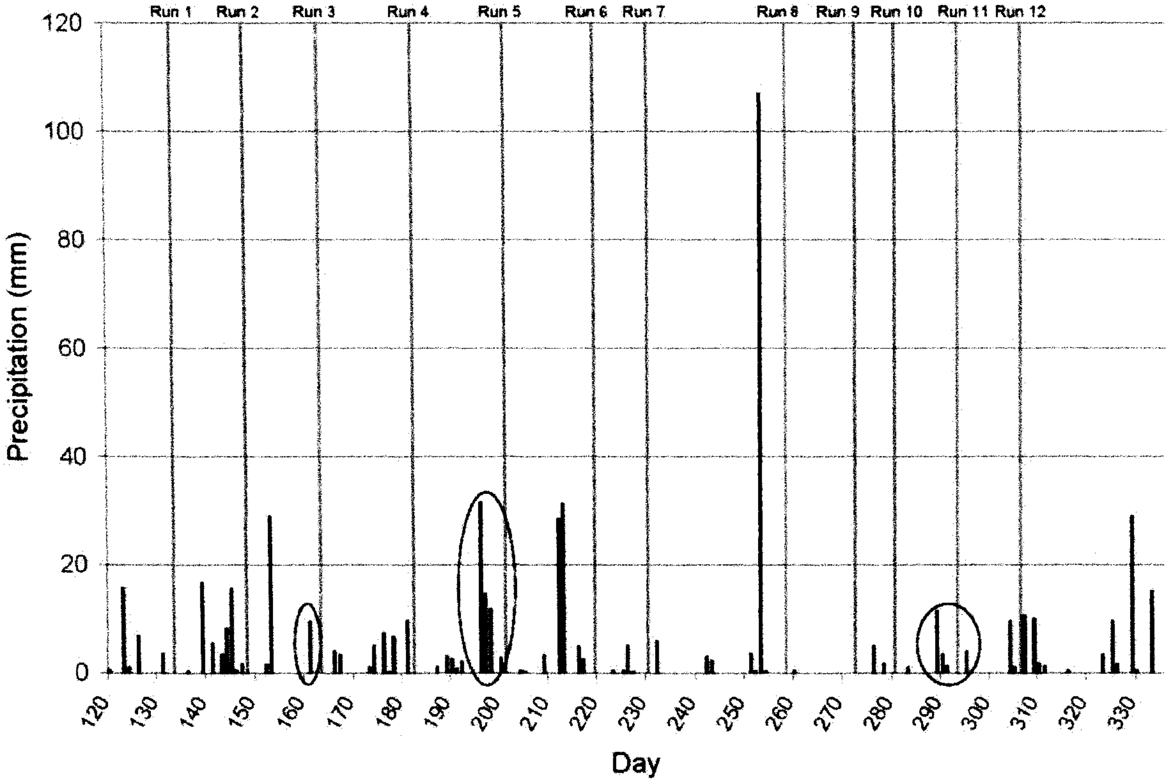


Figure 2.2 Precipitation in Winchester (from April 29th, 2004 to November 30th, 2004) and days when injection runs were carried out. Run 3 was covered during the precipitation event on day 161, run 5 was covered for the precipitation events on days 196, 197 and 198, and run 11 was covered during the precipitation events on days 289, 290 and 295 (circled).

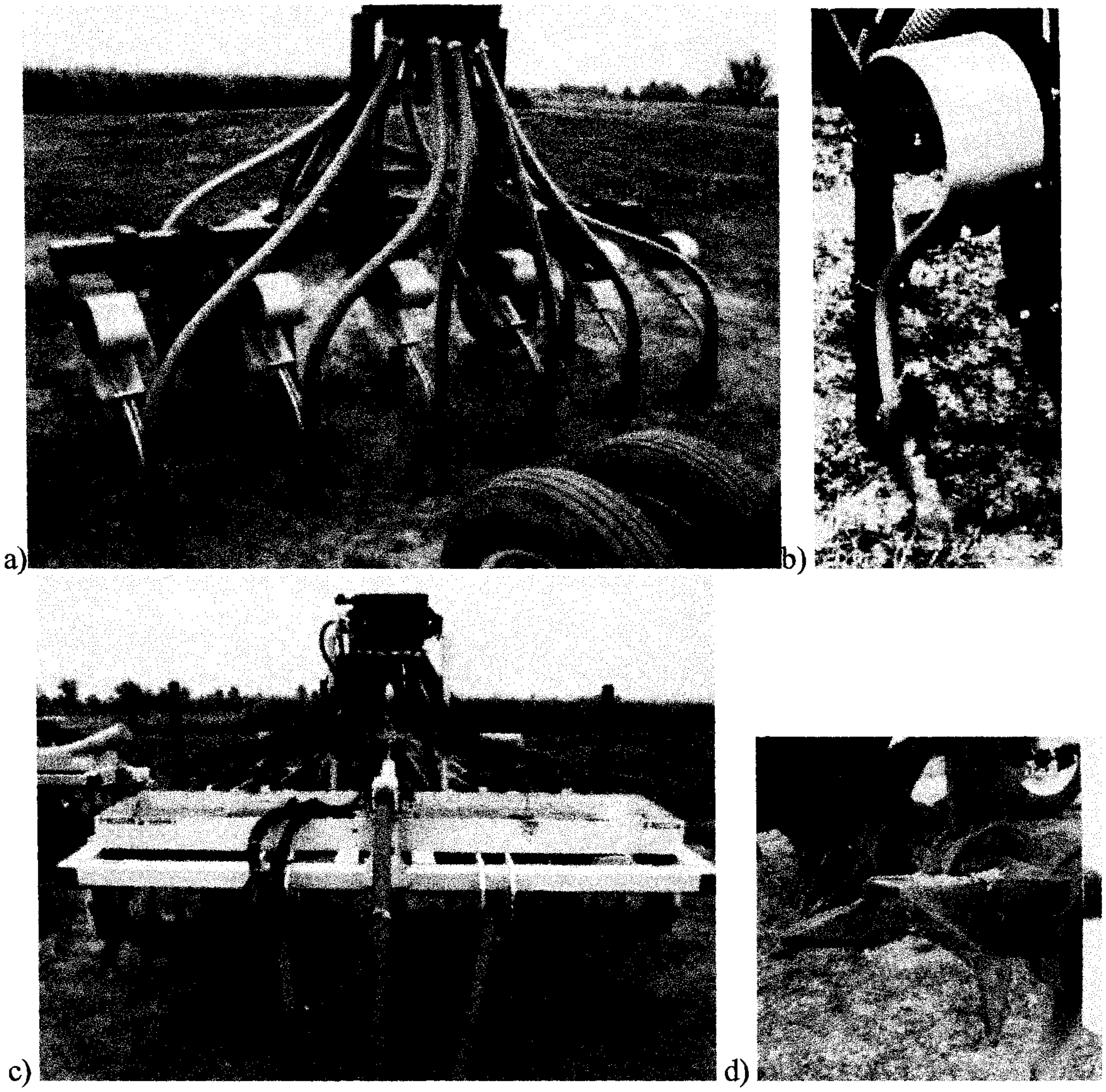


Figure 2.3 Two types of injectors used for the study: a) Kongskilde Vibro-Flex unit b) Vibro-Flex tine c) AerWay SSD unit and d) AerWay shattertines.

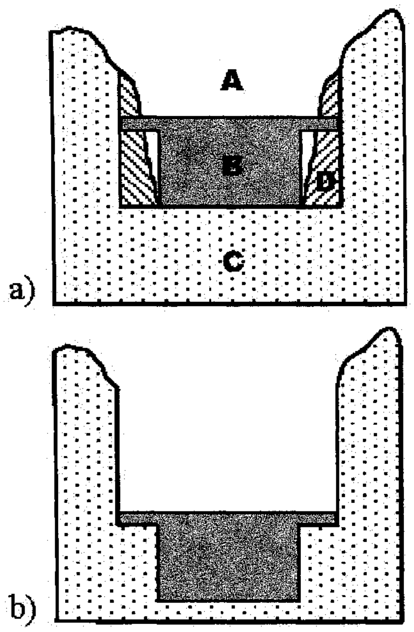


Figure 2.4 Ring insertion for D_K (cross sectional view): a) before insertion of the ring A = furrow, B = ring, C = soil, D = soil removed on the side of the furrow in order to insert the ring properly and b) after insertion of the ring.

Figure 2.5 Perforated pipe used for flow rates measurements using the Guelph permeameter. Pipes are inserted to a depth of 0.13 m. Perforation diameter is about 0.008 m and pipes are covered with screen of mesh 0.0015 m.

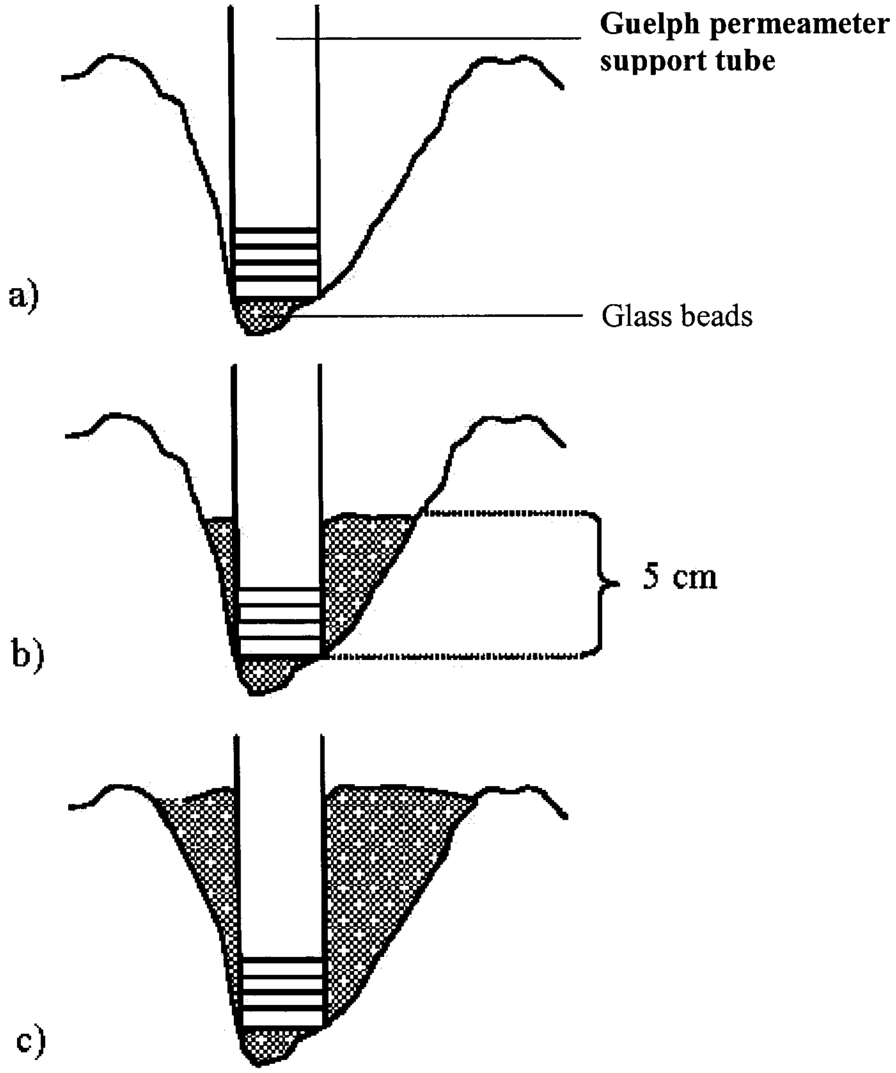


Figure 2.6 Measure of the pocket volume (cross sectional view): a) 5 ml of glass beads at the base of the pocket, b) 5 cm of glass beads added, c) glass beads added to the soil surface.

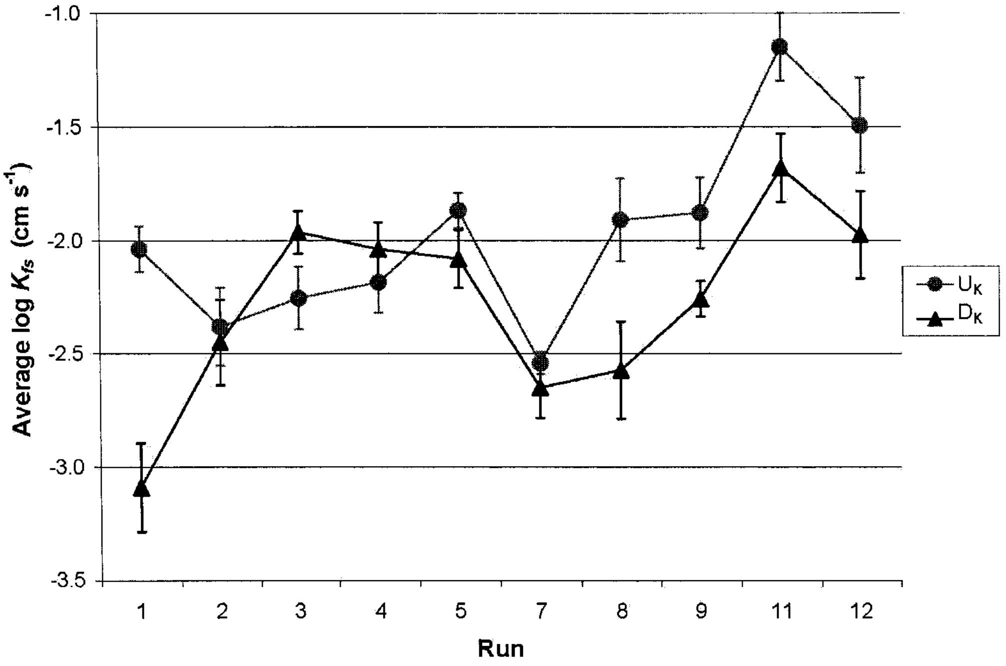


Figure 2.7 Average log K_{fs} for each Kongskilde run for U_K and D_K treatments (error bars represent +/- 1 standard error of the mean).

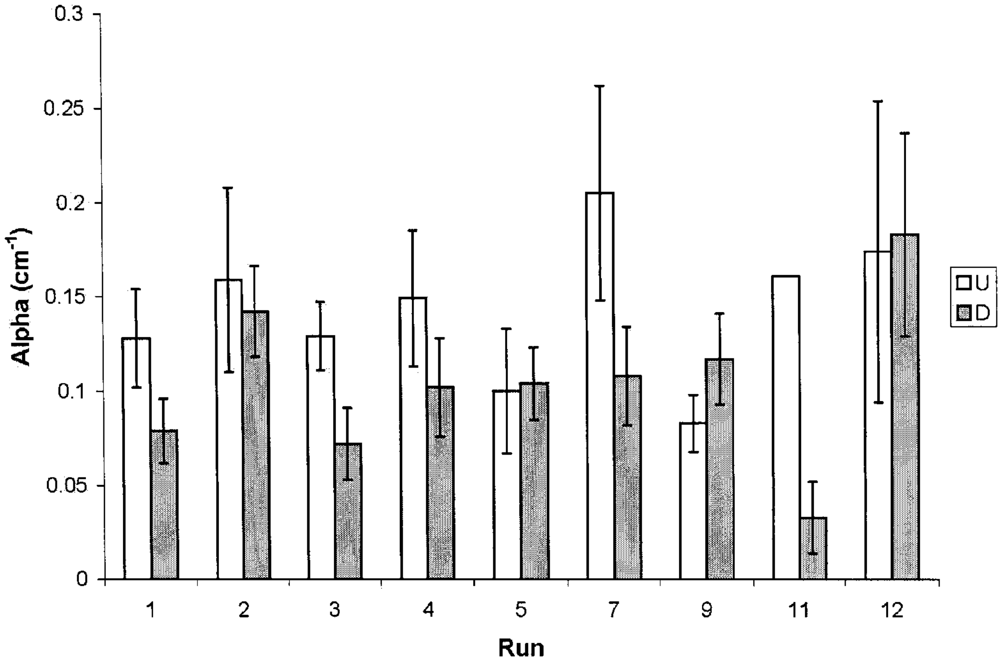


Figure 2.8 Average capillary length parameter for each Kongskilde run for U_K and D_K (error bars represent +/- 1 standard error of the mean).

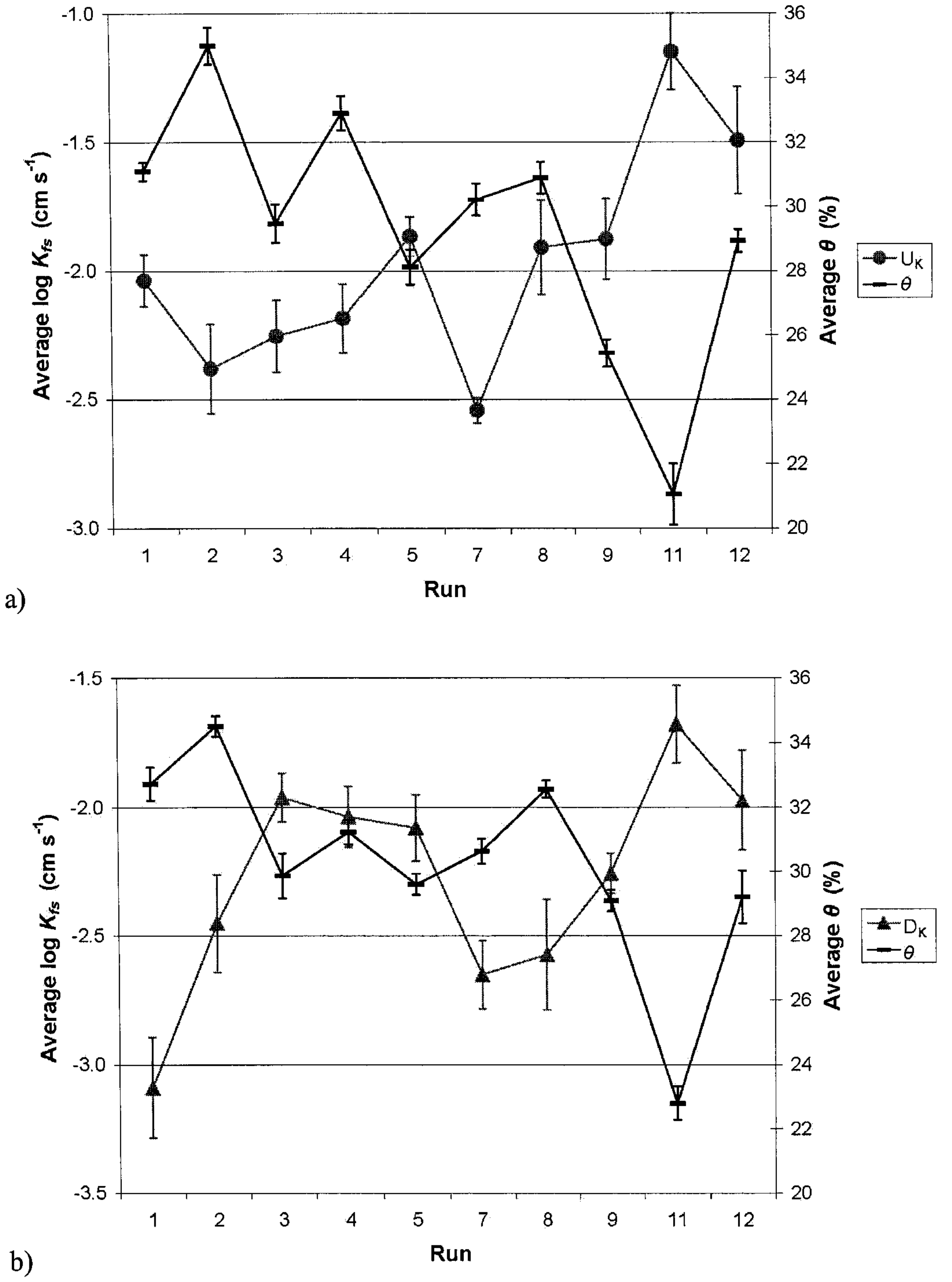


Figure 2.9 Average log K_{fs} and average water content for each Kongskilde run for U_K (a) and D_K (b) (error bars represent +/- 1 standard error of the mean).

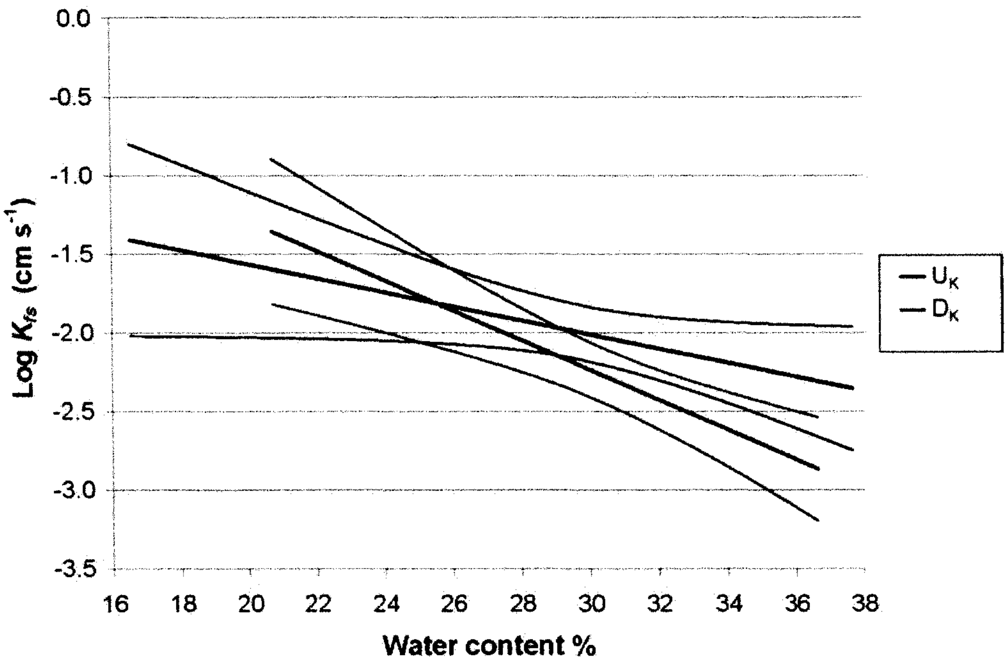


Figure 2.10 Regression lines of log K_{fs} vs. θ and the 95 % confidence limits of the regressions for undisturbed and disturbed Kongskilde.

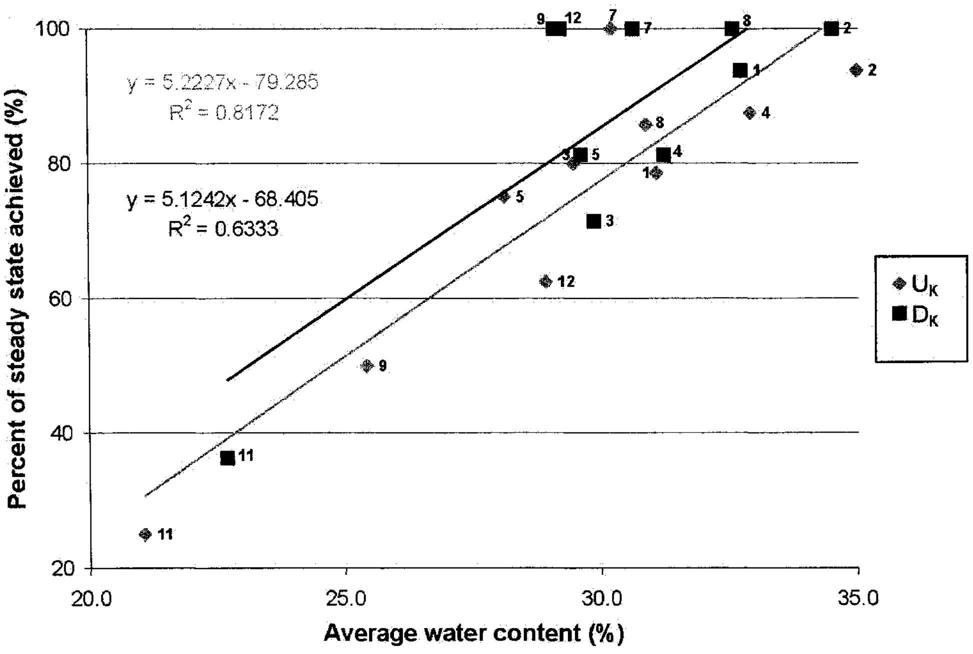


Figure 2.11 Percent of time steady state was achieved for a run while measuring flow rates vs. run average water content measured at 0.13 m depth (tillage depth). Point labels represent runs.

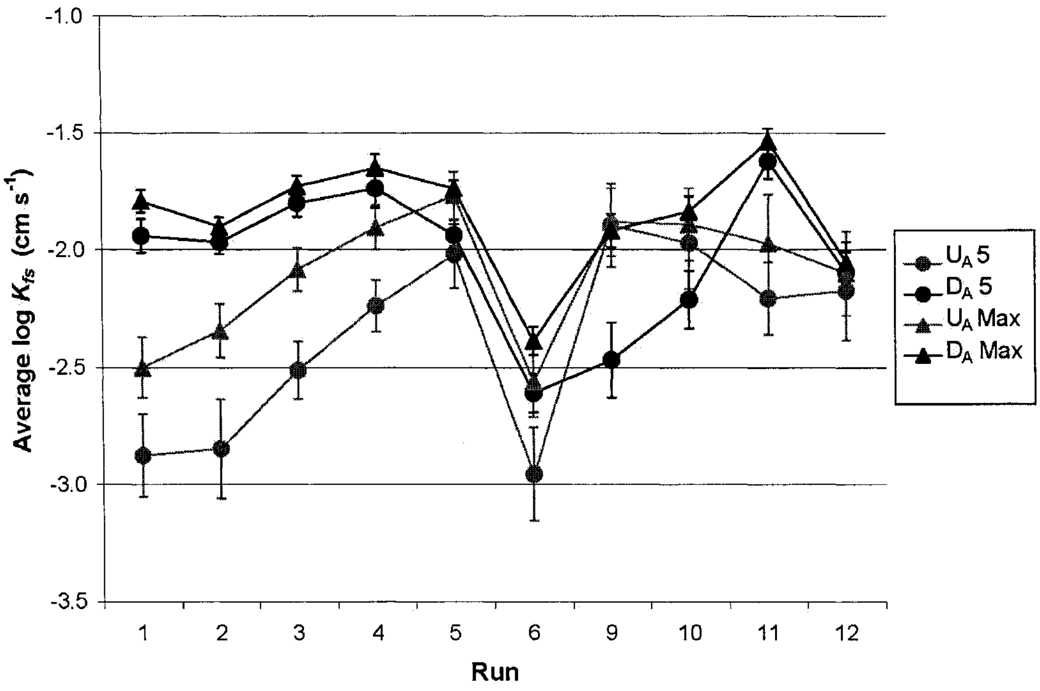


Figure 2.12 Average log K_{fs} at each run for U_A and D_A treatments (error bars represent mean standard error).

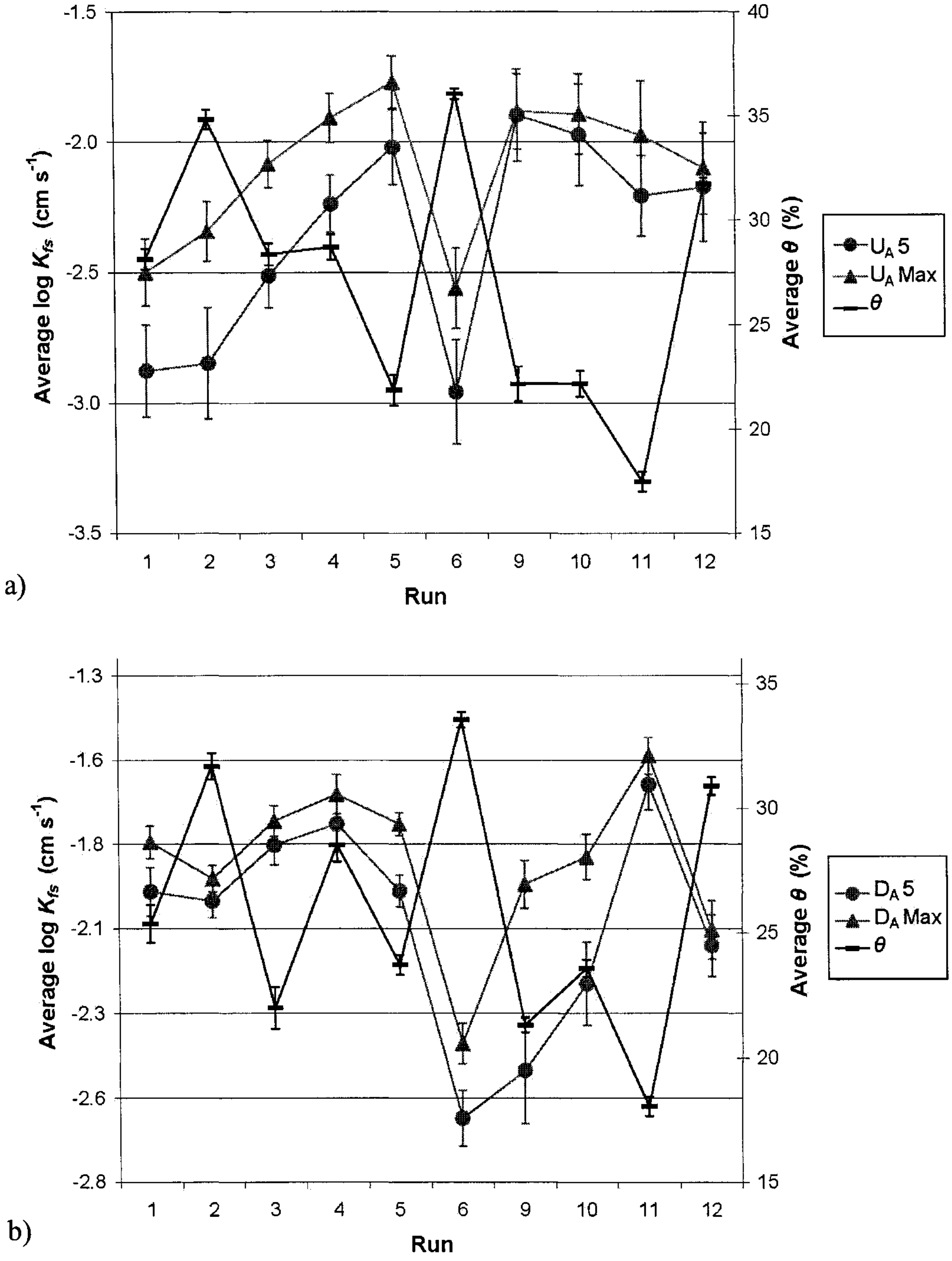


Figure 2.13 Average log K_{fs} and average water content at each run for U_A (a) and D_A (b) (error bars represent mean standard error).

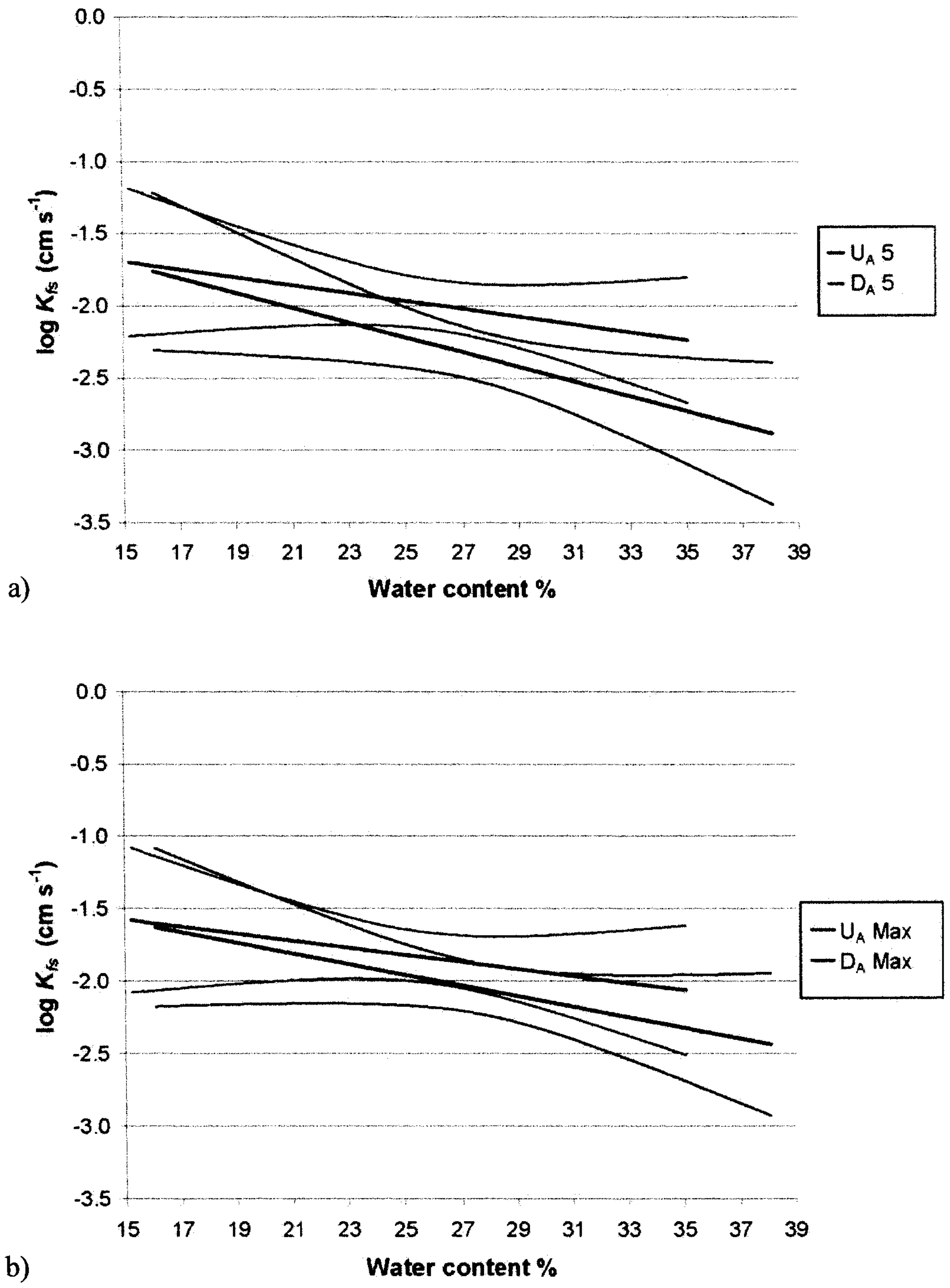


Figure 2.14 Regression lines of log K_{fs} vs. θ and the 95 % confidence limits of the regressions for undisturbed and disturbed AerWay treatments. a) Using hydraulic conductivity data from 5 cm head analysis, b) using hydraulic conductivity data from maximum head analysis.

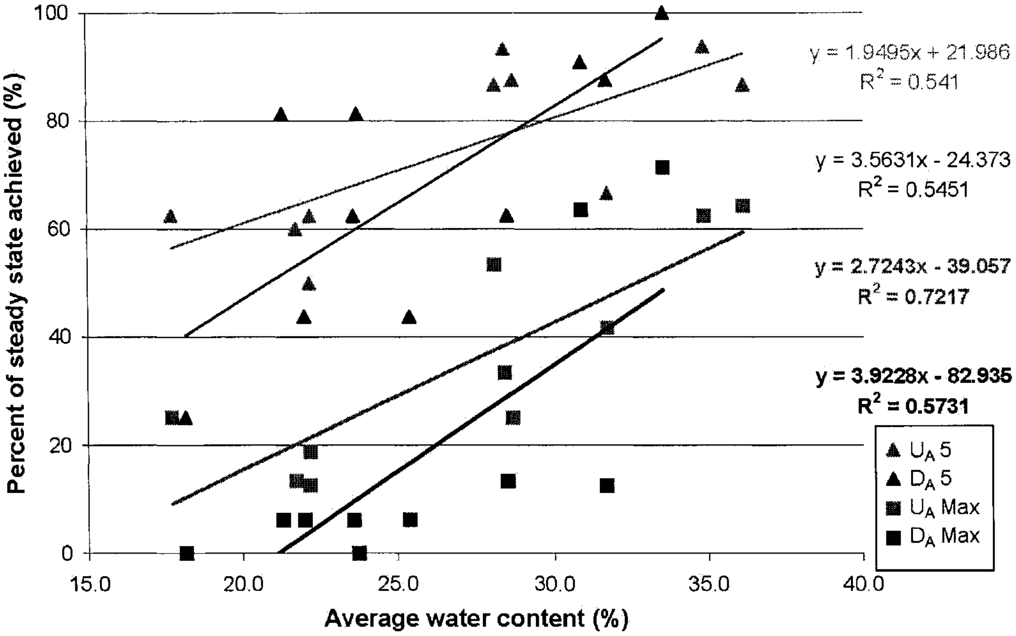


Figure 2.15 Percent of time steady state was achieved for a run while measuring flow rates vs. run average water content measured at surface.

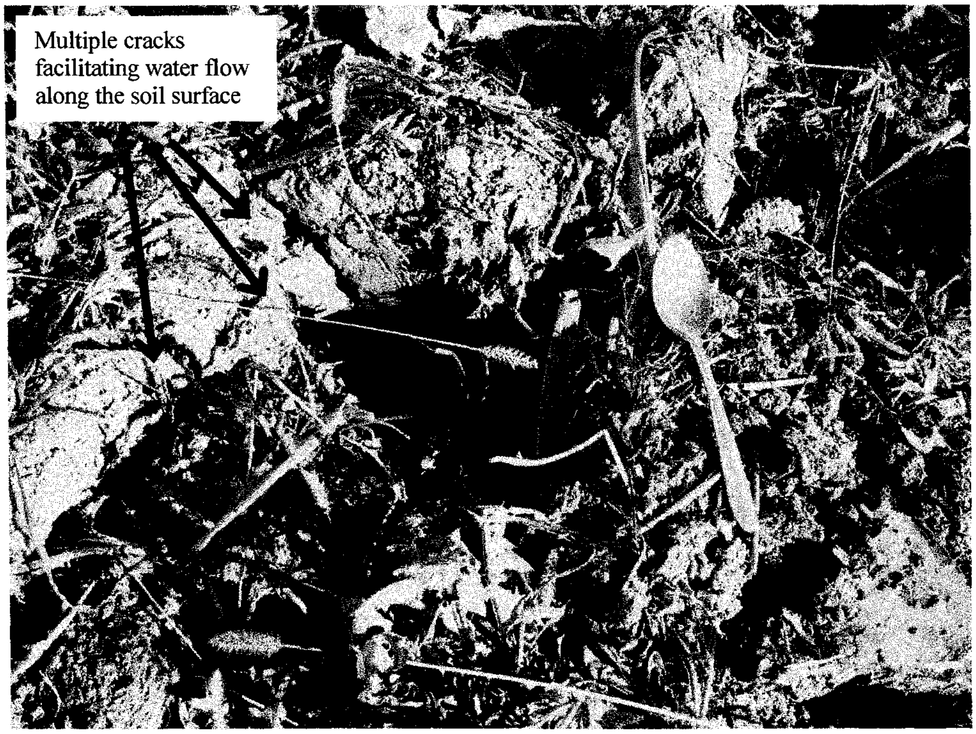
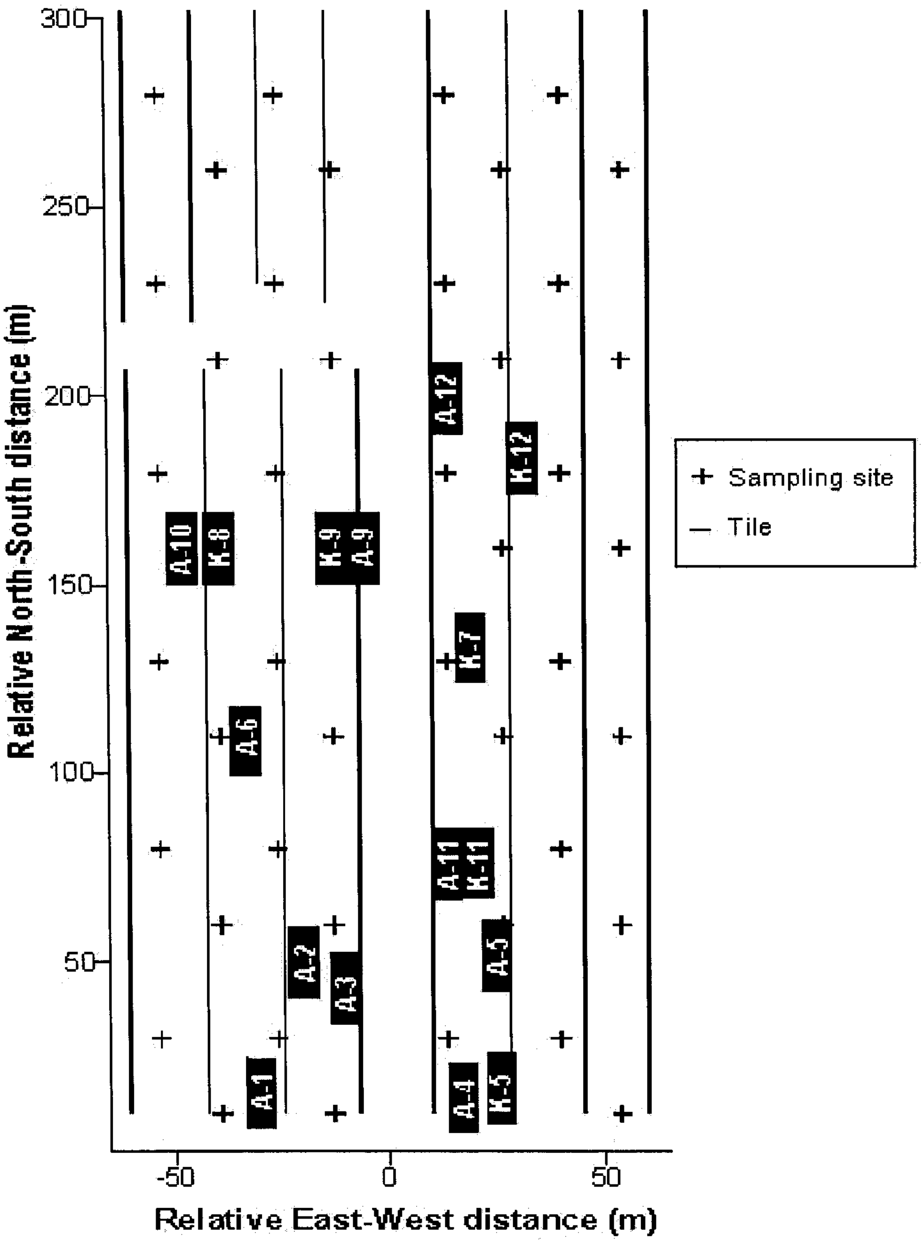


Figure 2.16 Disturbed soil from the Aerway tillage tool.

Figure 2.17 Clogging of the AerWay tine when running the implement on very wet soil.



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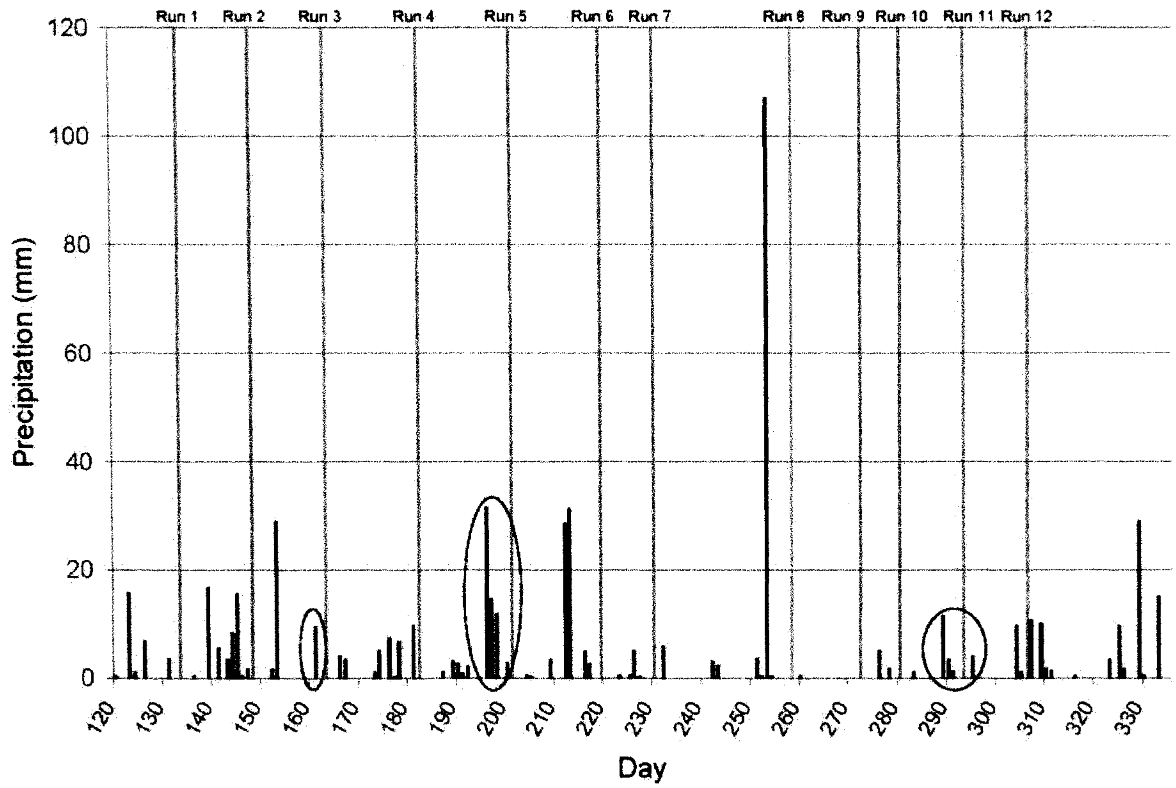

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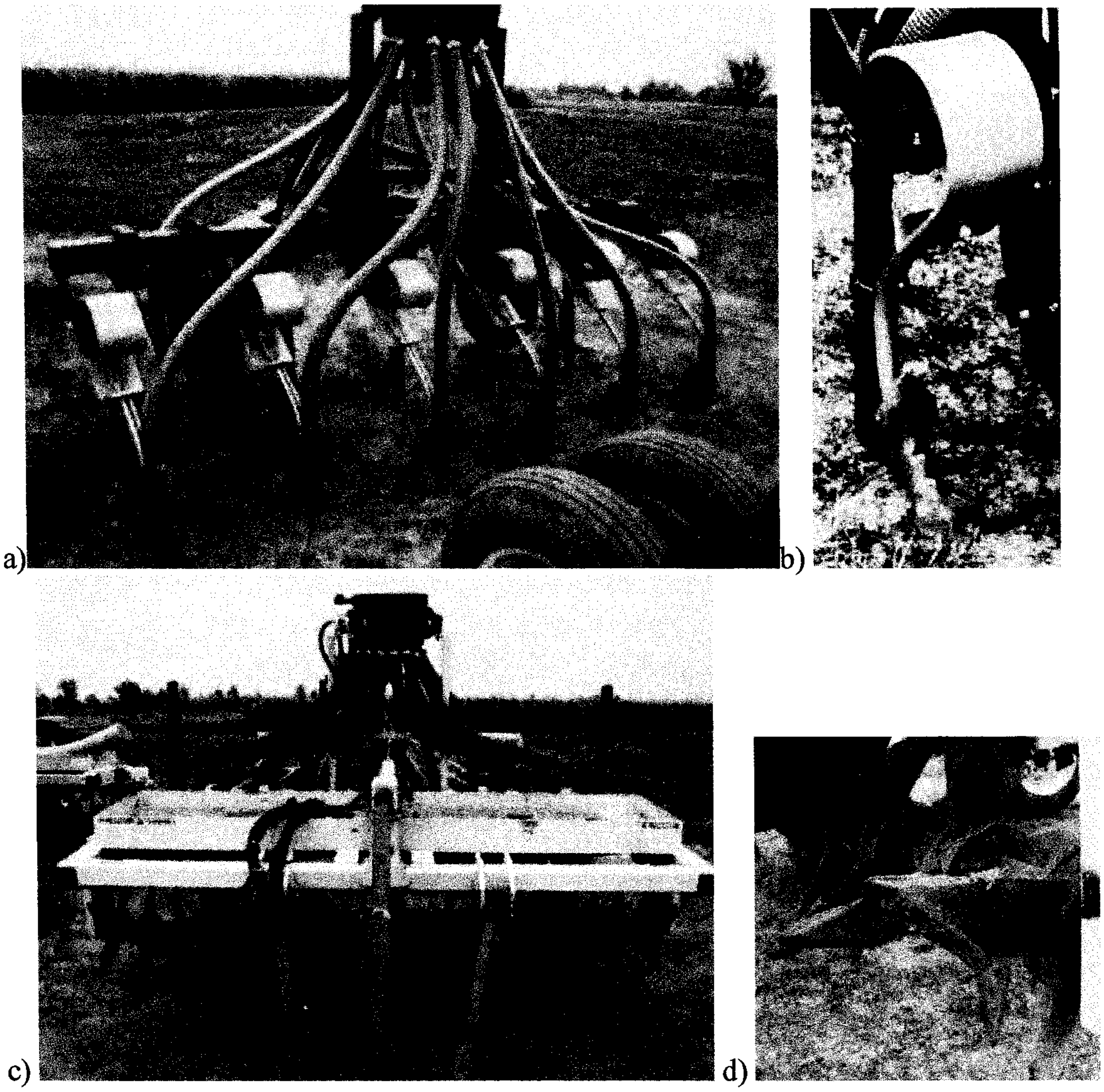

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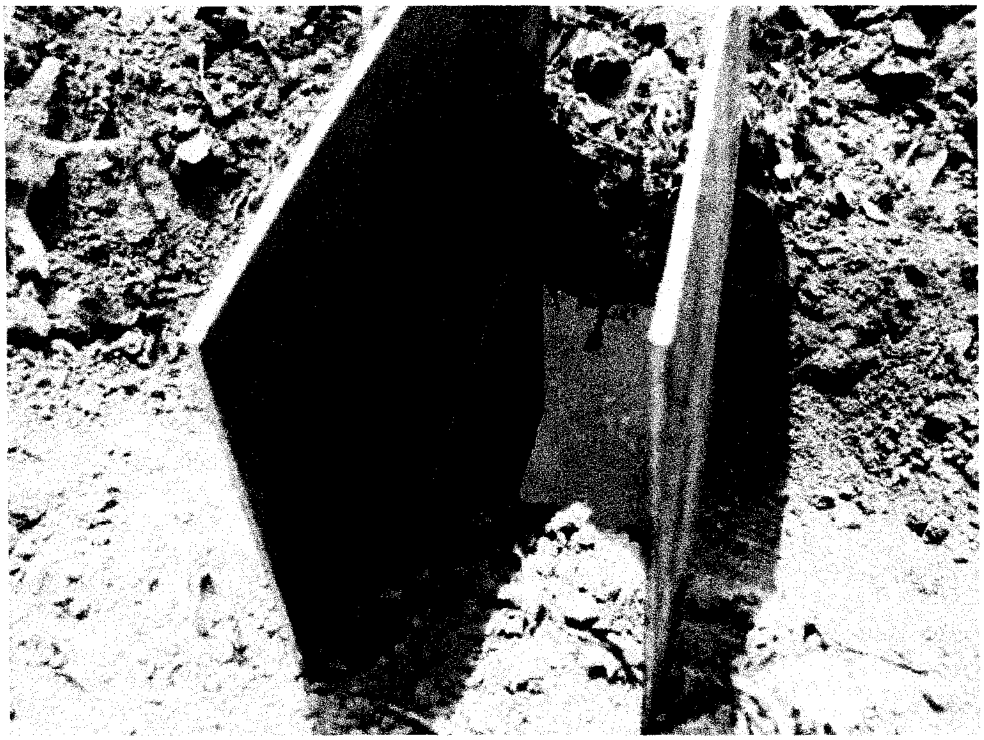

Figure 3.4 Damming system used to confine dye to a 10 cm furrow stretch (Kongskilde).

Figure 3.5 AerWay pocket cleared from the loose material that falls back inside after injection.

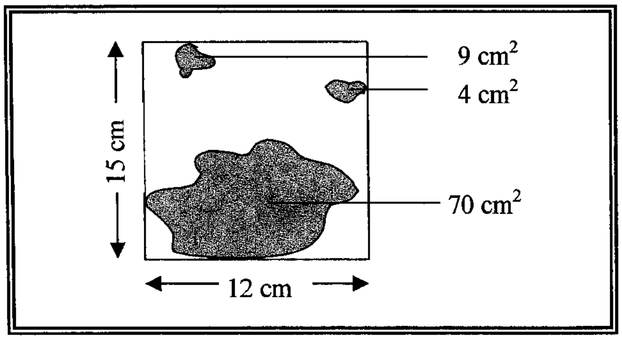

Figure 3.6 Area (A) and spreading (S). In this case, A = 83 cm^2 and S = 12*15 = 180 cm^2.

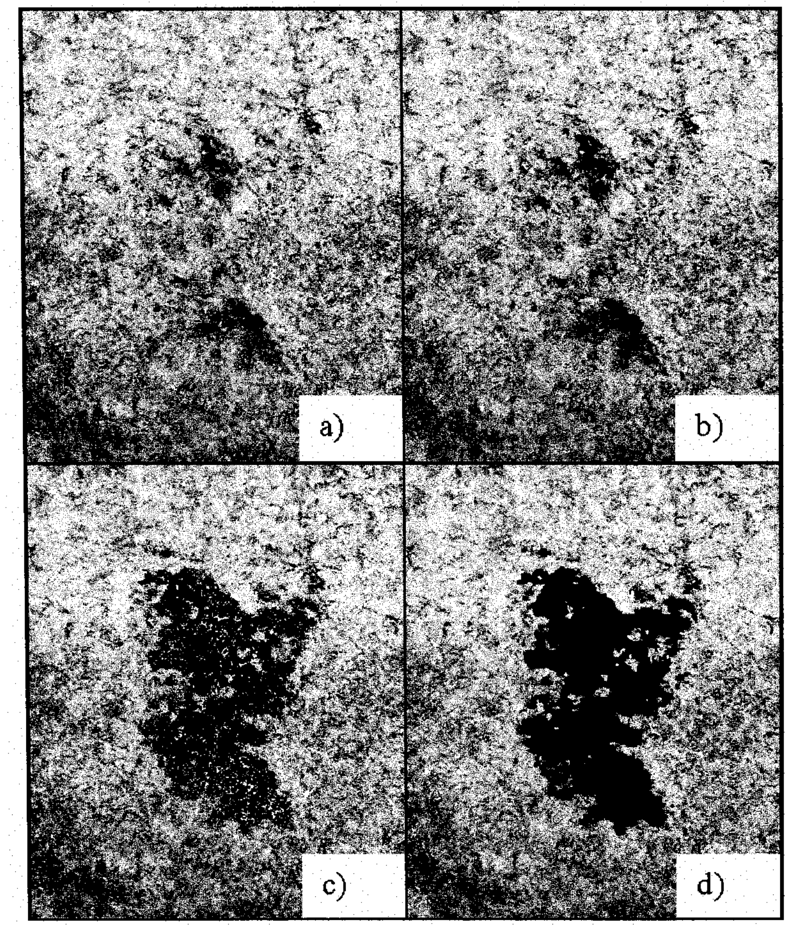

Figure 3.7 Demonstration of picture analysis. a) Soil stained by dye; b) two thresholds were defined and pixels for which RGB values falls into these categories were coloured in blue and pink respectively; c) 13 different thresholds (represented by 13 different colours) were required to select all the different intensities of blue dye; d) the selected pixels are coloured in green and a phase analysis is executed to calculate the area selected.

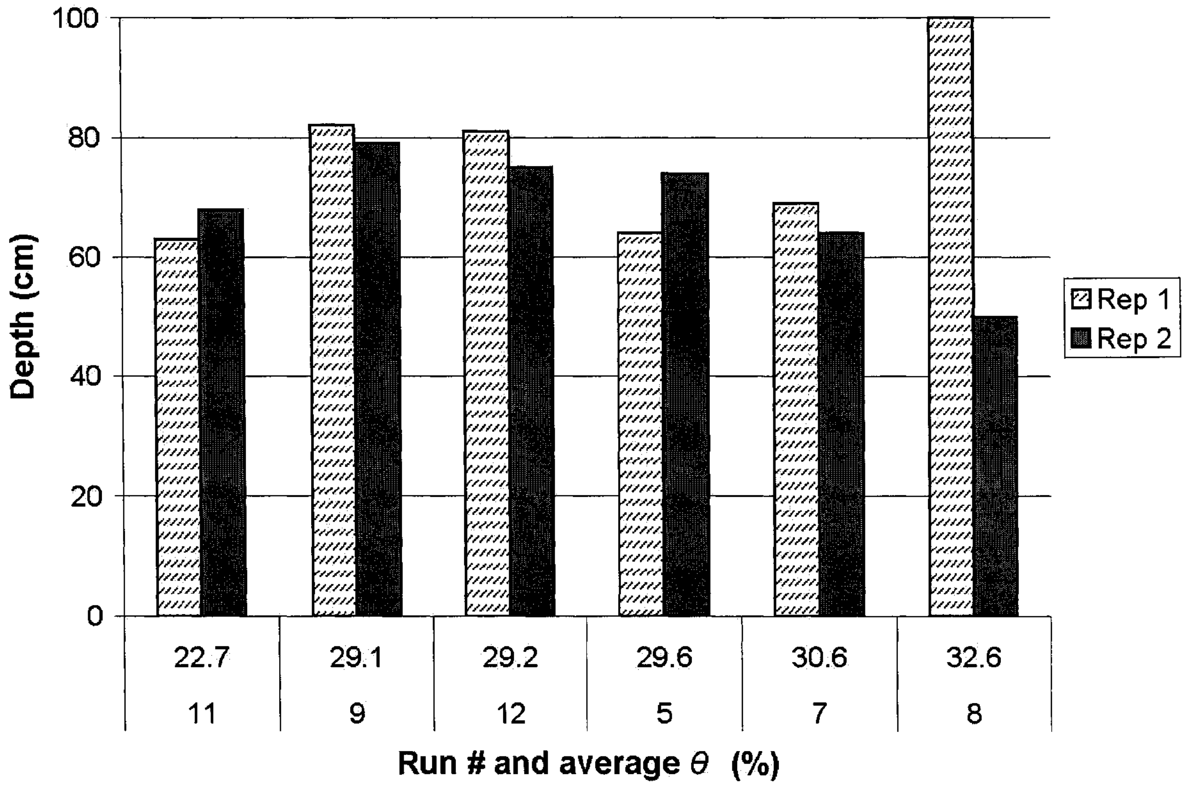

Figure 3.8 Depth of dye penetration at various soil water contents (measured at 0.13 m depth) for the Kongskilde treatment.

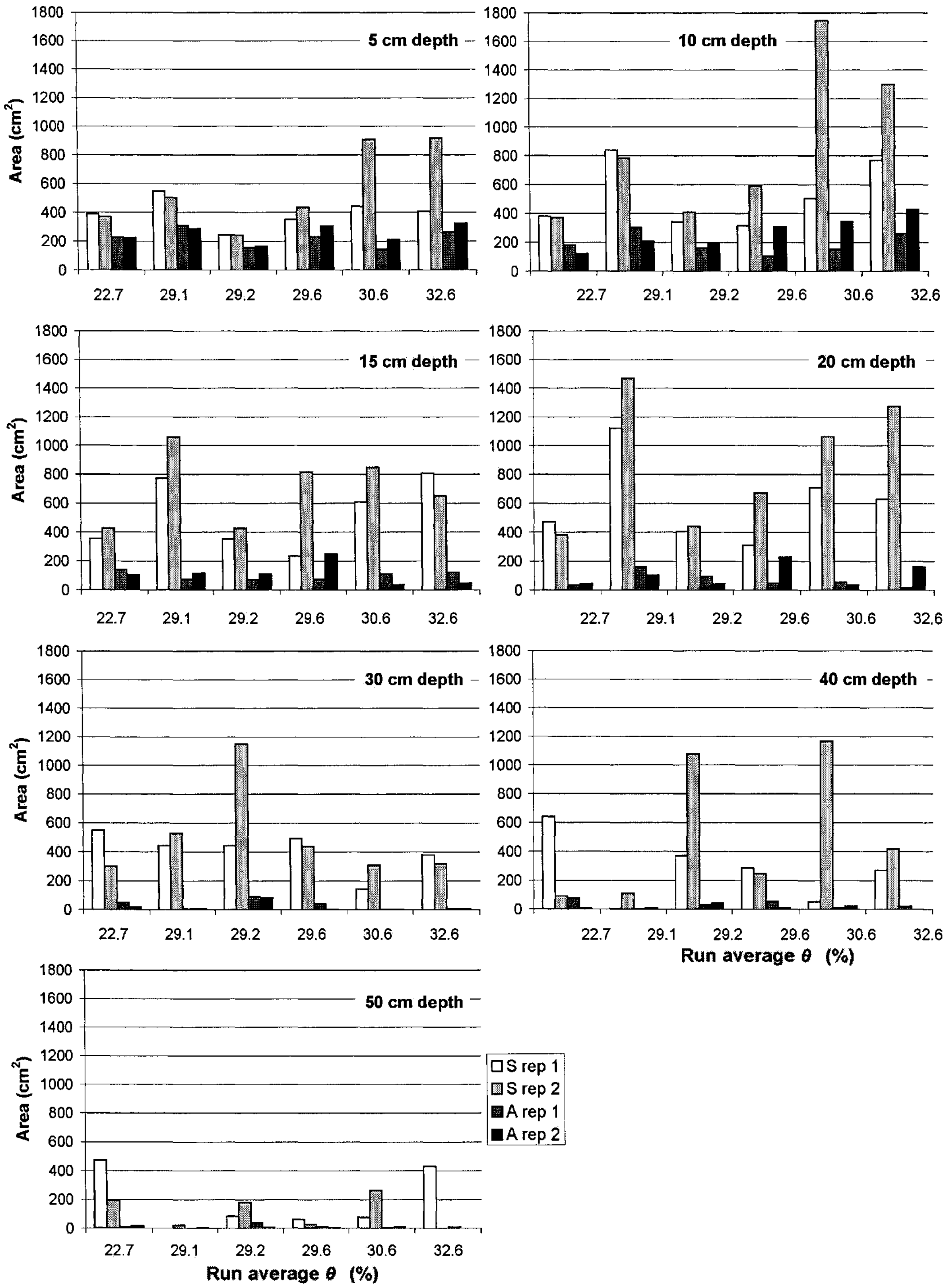

Figure 3.9 Extent of dye spreading and area covered by dye at depth of 5, 10, 15, 20, 30, 40 and 50 cm for the Kongskilde treatment.

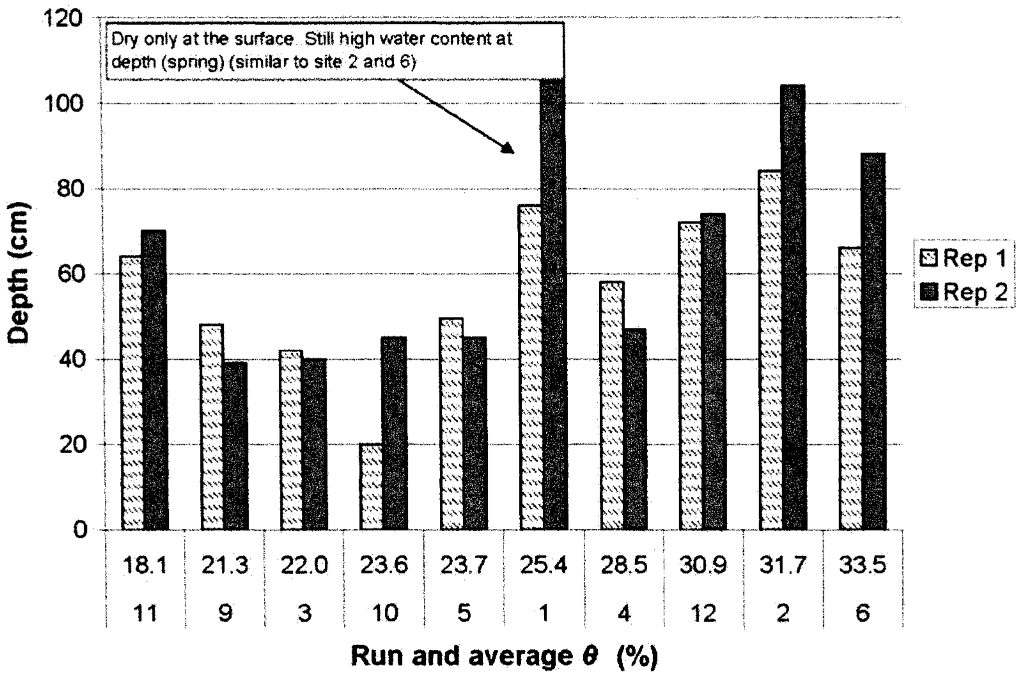

Figure 3.10 Depth of dye penetration at various soil water contents (measured at soil surface) for the AerWay treatment.

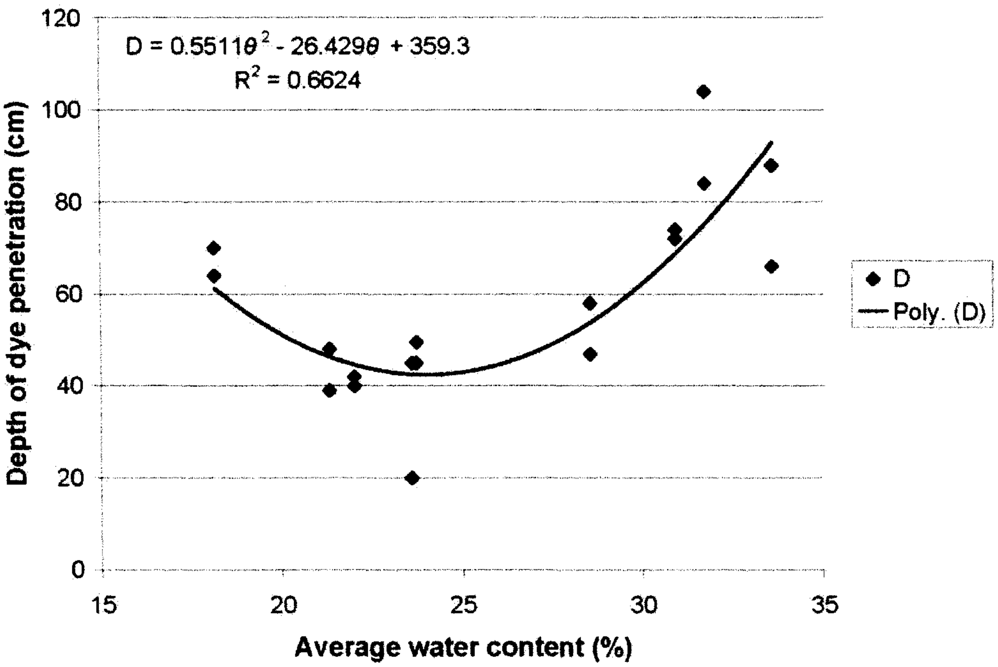

Figure 3.11 Summarization of depth of dye penetration by a quadratic function of run average water content (AerWay).

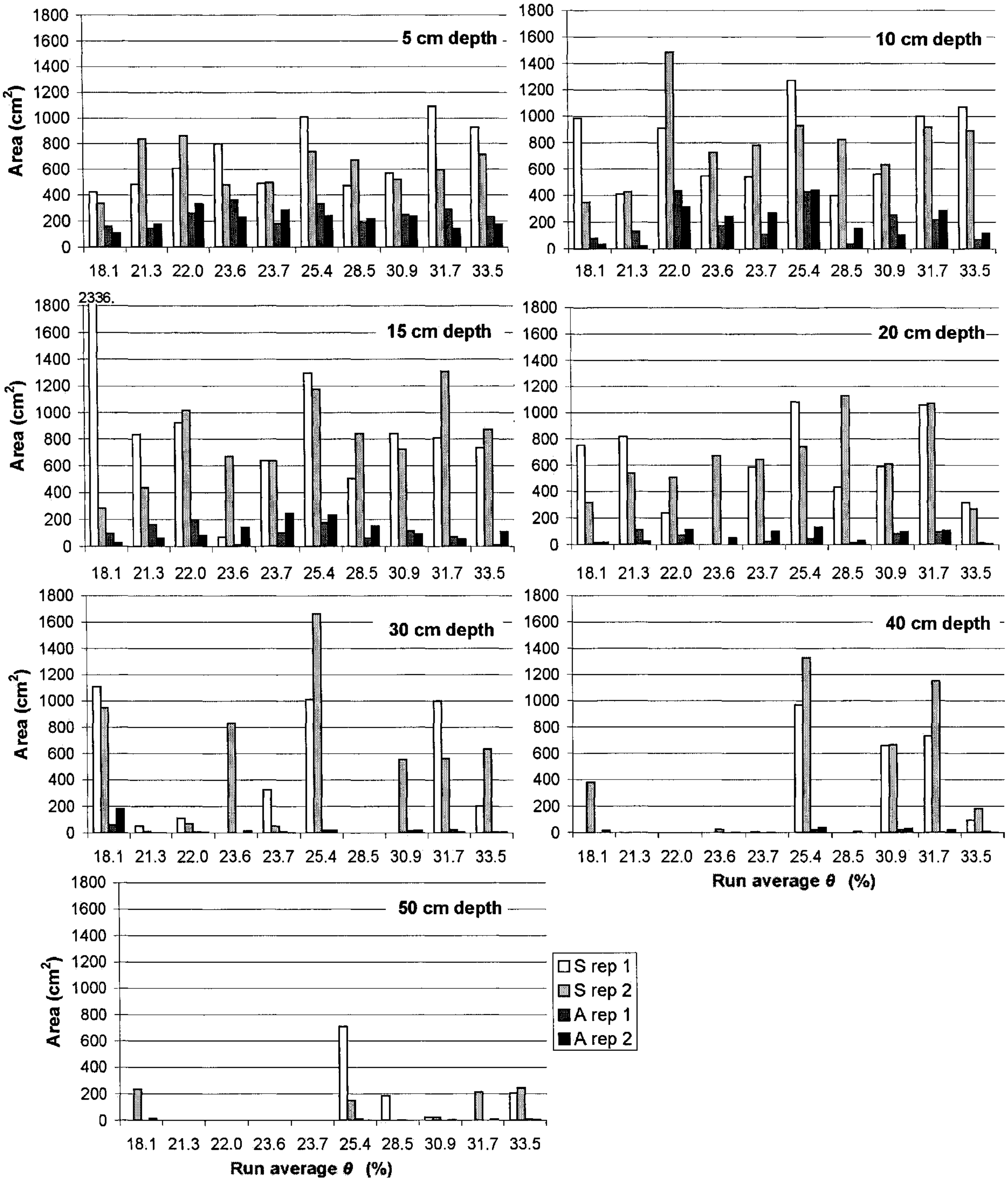

Figure 3.12 Extent of dye spreading and area covered by dye at depth of 5, 10, 15, 20, 30, 40 and 50 cm for the AerWay treatment.

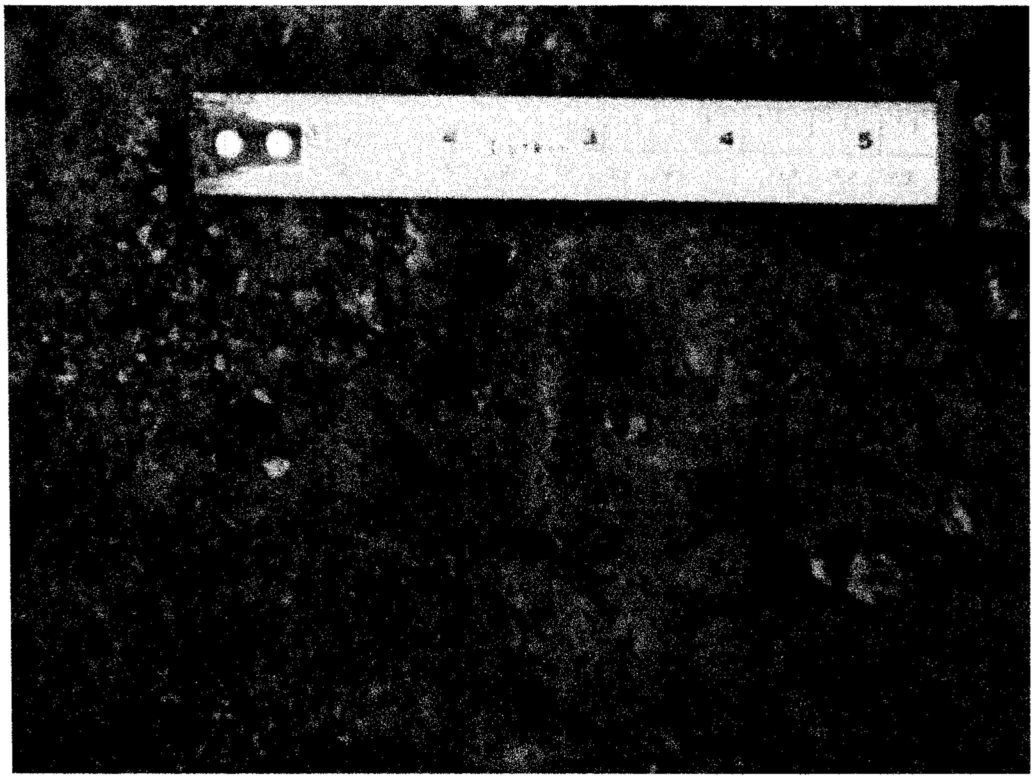

Figure 3.13 Dye surrounding earthworm burrows (≈ 0.5 cm diameter) at depth of 30 cm.

TABLES

Table 2.1 Summary of descriptive statistics of hydraulic conductivity, volumetric water content and bulk density for undisturbed and disturbed Kongskilde treatments.

Run	Hydraulic conductivity (data transformed in log) (cm/s)					Water content (% vol.)					Bulk density (g/cm^3)				
	Mean	SEM	Min.	Max.	N	Mean	SEM	Min.	Max.	N	Mean	SEM	Min.	Max.	N
Undisturbed Kongskilde treatment															
1	-2.04	0.101	-2.98	-1.59	16	31.1	0.3	26.9	35.7	46	1.40	0.01	1.33	1.48	15
2	-2.38	0.174	-3.77	-1.34	16	35.0	0.4	28.0	38.8	48	1.34	0.02	1.25	1.49	16
3	-2.25	0.140	-3.23	-1.31	15	29.5	0.4	23.6	34.2	45	1.40	0.02	1.27	1.50	15
4	-2.18	0.134	-3.83	-1.26	16	32.9	0.3	25.1	35.8	48	1.39	0.02	1.25	1.47	16
5	-1.87	0.077	-2.25	-1.14	16	28.1	0.4	22.5	32.3	48	1.37	0.01	1.29	1.43	16
7	-2.54	0.049	-2.93	-2.23	16	30.2	0.3	23.4	34.2	48	1.46	0.02	1.20	1.53	16
8	-1.91	0.183	-2.71	-1.20	7	30.9	0.5	27.5	34.4	15	1.37	0.02	1.30	1.43	7
9	-1.88	0.156	-3.53	-0.99	16	25.4	0.3	20.2	29.5	48	1.49	0.02	1.28	1.61	16
11	-1.15	0.149	-1.84	-0.70	8	21.1	0.7	15.4	26.4	18	1.38	0.04	1.29	1.49	5
12	-1.49	0.208	-2.33	-0.78	8	28.9	0.3	26.6	33.1	24	1.40	0.02	1.34	1.46	8
Disturbed Kongskilde treatment															
1	-3.09	0.195	-4.42	-1.78	16	32.7	0.4	22.5	37.9	48	1.46	0.02	1.31	1.55	16
2	-2.45	0.190	-4.06	-1.67	15	34.5	0.3	30.9	37.7	45	1.38	0.02	1.21	1.51	15
3	-1.96	0.094	-2.64	-1.41	14	29.9	0.4	23.5	35.6	42	1.32	0.03	1.12	1.44	14
4	-2.04	0.118	-2.77	-1.43	16	31.2	0.2	28.0	34.8	48	1.40	0.04	0.95	1.55	15
5	-2.08	0.129	-3.22	-1.32	16	29.6	0.2	26.9	33.0	48	1.33	0.04	1.02	1.56	16
7	-2.65	0.133	-3.46	-1.89	16	30.6	0.3	27.6	34.5	48	1.43	0.02	1.27	1.64	16
8	-2.57	0.215	-3.35	-1.93	7	32.6	0.3	30.1	34.7	21	1.51	0.07	1.29	1.88	7
9	-2.26	0.078	-2.95	-1.80	16	29.1	0.2	26.0	34.2	48	1.45	0.01	1.35	1.53	16
11	-1.68	0.149	-2.76	-0.94	11	22.7	0.4	19.0	26.9	30	1.40	0.03	1.20	1.57	10
12	-1.97	0.193	-3.04	-1.19	8	29.2	0.5	25.2	34.0	24	1.32	0.02	1.23	1.42	8

Table 2.2 One-way ANOVAs results of the effect of "run" on θ (Kongskilde).

Variability source	Sum-of-Squares	*df*	Mean-Square	F-ratio	*p*
Undisturbed					
α	1595.526	9	177.281	45.733	0.000
ϵ	480.680	124	3.876		
Disturbed					
α	1100.193	9	122.244	42.556	0.000
ϵ	359.066	125	2.873		

Table 2.3 One-way ANOVAs results of the effect of "run" on log K_{fs} (Kongskilde).

Variability source	Sum-of-Squares	*df*	Mean-Square	F-ratio	*p*
Undisturbed					
α	16.861	9	1.853	7.389	0.000
ϵ	31.105	124	0.251		
Disturbed					
α	21.434	9	2.382	7.879	0.000
ϵ	37.783	125	0.302		

Table 2.4 Significance of mean θ difference between runs as determined by a Bonferroni post-hoc test for U_K and D_K. - = $P > 0.05$; Y = $P < 0.05$.

U_K

Run	1	2	3	4	5	7	8	9	11	12
1	-									
2	Y	-								
3	-	Y	-							
4	-	-	Y	-						
5	Y	Y	-	Y	-					
7	-	Y	-	Y	-	-				
8	-	Y	-	-	Y	-	-			
9	Y	Y	Y	Y	Y	Y	Y	-		
11	Y	Y	Y	Y	Y	Y	Y	Y	-	
12	-	Y	-	Y	-	-	-	Y	Y	-

D_K

Run	1	2	3	4	5	7	8	9	11	12
1	-									
2	-	-								
3	Y	Y	-							
4	-	Y	-	-						
5	Y	Y	-	-	-					
7	Y	Y	-	-	-	-				
8	-	-	Y	-	Y	-	-			
9	Y	Y	-	Y	-	-	Y	-		
11	Y	Y	Y	Y	Y	Y	Y	Y	-	
12	Y	Y	-	-	-	-	Y	-	Y	-

Table 2.5 Significance of mean log K_{fs} difference between runs as determined by a Bonferroni post-hoc test for U_K and D_K. - = $P > 0.05$; Y = $P < 0.05$.

U_K

Run	1	2	3	4	5	7	8	9	11	12
1	-									
2	-	-								
3	-	-	-							
4	-	-	-	-						
5	-	-	-	-	-					
7	Y	-	-	-	Y	-				
8	-	-	-	-	-	-	-			
9	-	-	-	-	-	Y	-	-		
11	Y	Y	Y	Y	Y	Y	Y	-	-	
12	-	Y	Y	-	-	Y	-	-	-	-

D_K

Run	1	2	3	4	5	7	8	9	11	12
1	-									
2	-	-								
3	Y	-	-							
4	Y	-	-	-						
5	Y	-	-	-	-					
7	-	-	Y	-	-	-				
8	-	-	-	-	-	-	-			
9	Y	-	-	-	-	-	-	-		
11	Y	Y	-	-	-	Y	Y	-	-	
12	Y	-	-	-	-	-	-	-	-	-

Table 2.6 Linear regression equations of log (K_{fs}) vs. θ for each treatment.

Treatment	Linear regression equation	R^2	Significance F
U_A (h = 5cm)	$\log(K_{fs}) = -0.051\ \theta - 0.9424$	0.1676	6.81E-07
U_A (h = max)	$\log(K_{fs}) = -0.0367\ \theta - 1.0392$	0.1847	2.18E-07
D_A (h = 5cm)	$\log(K_{fs}) = -0.0271\ \theta - 1.2876$	0.1391	4.85E-06
D_A (h = max)	$\log(K_{fs}) = -0.0244\ \theta - 1.2097$	0.1977	2.37E-08
U_K	$\log(K_{fs}) = -0.0446\ \theta - 0.6737$	0.1061	1.56E-4
D_K	$\log(K_{fs}) = -0.0948\ \theta + 0.6054$	0.2509	8.23E-10

Table 2.7 Summary of descriptive statistics of hydraulic conductivity, volumetric water content and bulk density for undisturbed AerWay treatment.

Run	Hydraulic conductivity (data transformed in log) (cm/s)					Water content (% vol.)					Bulk density (g/cm^3)				
	Mean	SEM	Min.	Max.	N	Mean	SEM	Min.	Max.	N	Mean	SEM	Min.	Max.	N
	@ pressure head of 5 cm														
1	-2.88	0.176	-3.86	-1.35	15	28.1	0.3	23.8	35.7	45	1.40	0.02	1.27	1.52	15
2	-2.85	0.212	-4.08	-1.46	16	34.8	0.3	29.6	38.5	48	1.40	0.02	1.34	1.55	16
3	-2.51	0.122	-3.44	-1.60	15	28.4	0.3	23.7	33.3	48	1.39	0.02	1.22	1.50	16
4	-2.24	0.110	-2.98	-1.52	16	28.7	0.4	21.5	32.9	48	1.44	0.02	1.34	1.56	16
5	-2.02	0.144	-3.00	-1.27	15	21.7	0.5	15.5	29.0	48	1.36	0.02	1.14	1.54	16
6	-2.96	0.200	-4.42	-1.65	15	36.1	0.2	33.5	37.7	48	1.38	0.02	1.15	1.48	16
9	-1.90	0.177	-3.42	-0.96	16	22.2	0.5	16.5	27.9	36	1.45	0.02	1.30	1.59	16
10	-1.97	0.196	-3.77	-1.05	16	22.2	0.4	15.3	29.6	45	1.34	0.02	1.11	1.51	16
11	-2.21	0.154	-2.83	-1.56	8	17.7	0.5	15.3	22.5	16	1.35	0.03	1.25	1.53	8
12	-2.18	0.208	-3.35	-1.14	12	31.5	0.4	20.9	34.9	36	1.37	0.01	1.27	1.45	12
	@ pressure head of 12 cm														
1	-2.50	0.128	-3.40	-1.46	15										
2	-2.34	0.114	-3.06	-1.69	16										
3	-2.09	0.092	-2.80	-1.46	15										
4	-1.91	0.094	-2.67	-1.51	16										
5	-1.77	0.101	-2.58	-1.38	15										
6	-2.56	0.153	-4.16	-1.81	14										
9	-1.88	0.145	-3.56	-1.37	16										
10	-1.89	0.155	-3.23	-1.23	16										
11	-1.97	0.209	-3.15	-1.45	8										
12	-2.10	0.178	-3.00	-1.27	12										

Table 2.8 Summary of descriptive statistics of hydraulic conductivity, volumetric water content and bulk density for disturbed AerWay treatment.

Run	Hydraulic conductivity (cm/s)					Water content (% vol.)				
	Mean	SEM	Min.	Max.	N	Mean	SEM	Min.	Max.	N
	@ pressure head of 5 cm									
1	-1.94	0.072	-2.44	-1.51	16	25.4	0.6	16.5	33.3	46
2	-1.97	0.049	-2.17	-1.35	16	31.7	0.4	26.7	41.4	48
3	-1.80	0.058	-2.15	-1.39	16	22.0	0.5	15.0	28.9	48
4	-1.74	0.082	-2.36	-1.28	16	28.5	0.5	20.2	33.7	48
5	-1.94	0.046	-2.27	-1.66	16	23.7	0.4	18.4	29.4	48
6	-2.61	0.083	-3.15	-2.23	14	33.5	0.3	29.4	36.2	42
9	-2.47	0.159	-3.90	-1.55	16	21.3	0.3	17.0	25.3	48
10	-2.21	0.123	-3.24	-1.44	16	23.6	0.3	19.4	27.8	48
11	-1.62	0.075	-2.08	-1.26	12	18.1	0.4	11.9	20.5	32
12	-2.10	0.091	-2.55	-1.48	11	30.5	0.5	19.4	34.5	33
	@ maximum pressure head									
1	-1.79	0.048	-2.10	-1.49	16					
2	-1.90	0.039	-2.17	-1.67	16					
3	-1.73	0.045	-2.07	-1.45	16					
4	-1.65	0.059	-2.21	-1.45	15					
5	-1.74	0.034	-2.17	-1.52	16					
6	-2.39	0.060	-2.78	-2.03	14					
9	-1.92	0.071	-2.63	-1.50	16					
10	-1.84	0.067	-2.39	-1.46	16					
11	-1.54	0.054	-1.93	-1.32	12					
12	-2.05	0.086	-2.43	-1.54	11					

Table 2.9 One-way ANOVAs results of the effect of "run" on θ (AerWay).

Variability	Sum-of-Squares	*df*	Mean-Square	F-ratio	*p*
Undisturbed					
α	4402.173	9	489.130	113.975	0.000
ϵ	575.068	134	4.292		
Disturbed					
α	3220.172	9	357.797	81.026	0.000
ϵ	613.801	139	4.416		

Table 2.10 One-way ANOVAs results of the effect of "run" on log K_{fs} (AerWay).

Variability source	Sum-of-Squares	*df*	Mean-Square	F-ratio	*p*
Undisturbed (5 cm head)					
α	21.825	9	2.425	5.435	0.000
ϵ	59.791	134	0.446		
Undisturbed (maximum head)					
α	10.128	9	1.125	4.366	0.000
ϵ	34.281	133	0.258		
Disturbed (5 cm head)					
α	12.819	9	1.424	11.437	0.000
ϵ	17.311	139	0.125		
Disturbed (maximum head)					
α	6.864	9	0.763	16.038	0.000
ϵ	6.563	138	0.048		

Table 2.11 Significance of mean *θ* difference between runs as determined by a Bonferroni post-hoc test for U_A and D_A. - = $P > 0.05$; Y = $P < 0.05$.

U_A

Run	1	2	3	4	5	6	9	10	11	12
1	-									
2	Y	-								
3	-	Y	-							
4	-	Y	-	-						
5	Y	Y	Y	Y	-					
6	Y	-	Y	Y	Y	-				
9	Y	Y	Y	Y	-	Y	-			
10	Y	Y	Y	Y	-	Y	-	-		
11	Y	Y	Y	Y	Y	Y	Y	Y	-	
12	Y	Y	Y	Y	Y	Y	Y	Y	Y	-

D_A

Run	1	2	3	4	5	6	9	10	11	12
1	-									
2	Y	-								
3	Y	Y	-							
4	Y	Y	Y	-						
5	-	Y	-	Y	-					
6	Y	-	Y	Y	Y	-				
9	Y	Y	-	Y	-	Y	-			
10	-	Y	-	Y	-	Y	-	-		
11	Y	Y	Y	Y	Y	Y	Y	Y	-	
12	Y	-	Y	-	Y	-	Y	Y	Y	-

Table 2.12 Significance of mean log K_{fs} difference between runs as determined by a Bonferroni Post Hoc Test for U_A 5 cm head (a), U_A maximum head (b), D_A 5 cm head (c) and D_A maximum head (d). - = not significant; Y significant (0.05 level).

a)

Run	1	2	3	4	5	6	9	10	11	12
1	-									
2	-	-								
3	-	-	-							
4	-	-	-	-						
5	Y	Y	-	-	-					
6	-	-	-	-	Y	-				
9	Y	Y	-	-	-	Y	-			
10	Y	Y	-	-	-	Y	-	-		
11	-	-	-	-	-	-	-	-	-	
12	-	-	-	-	-	-	-	-	-	-

b)

Run	1	2	3	4	5	6	9	10	11	12
1	-									
2	-	-								
3	-	-	-							
4	-	-	-	-						
5	Y	-	-	-	-					
6	-	-	-	Y	Y	-				
9	Y	-	-	-	-	Y	-			
10	-	-	-	-	-	Y	-	-		
11	-	-	-	-	-	-	-	-	-	
12	-	-	-	-	-	-	-	-	-	-

c)

Run	1	2	3	4	5	6	9	10	11	12
1	-									
2	-	-								
3	-	-	-							
4	-	-	-	-						
5	-	-	-	-	-					
6	Y	Y	Y	Y	Y	-				
9	Y	Y	Y	Y	Y	-	-			
10	-	-	-	Y	-	-	-	-		
11	-	-	-	-	-	Y	Y	Y	-	
12	-	-	-	-	-	Y	-	-	-	-

d)

Run	1	2	3	4	5	6	9	10	11	12
1	-									
2	-	-								
3	-	-	-							
4	-	-	-	-						
5	-	-	-	-	-					
6	Y	Y	Y	Y	Y	-				
9	-	-	-	Y	-	Y	-			
10	-	-	-	-	-	Y	-	-		
11	-	Y	-	-	-	Y	Y	Y	-	
12	-	-	Y	Y	Y	Y	-	-	Y	-

Table 3.1 CART regression trees results for AerWay. D = depth (cm) of dye penetration, S = spreading (cm^2) of dye and corresponds to the N-S multiplied by the E-W extent of dye contamination, A = area (cm^2) corresponds to the true area covered by dye. Letters are accompanied with number, which represent the depth of measurement in cm. Depth not shown in the table did not produce split.

	Terminal node	Condition	Split	Av	Stdev	N
D	1	<=	19.7	67.00	3.00	2
	2	>	19.7	43.35	9.33	10
	3	>	29.7*	81.33	12.53	6
S20	1	<=	31.3	559.89	259.59	14
	2	>	31.3	1064.95	8.05	2
	3	>	32.6*	293.80	23.10	2
S30	1	<=	19.7*	1027.20	79.30	2
	2	<=	31.3	167.62	256.82	12
	3	>	31.3	600.10	282.16	4
S40	1	<=	29.7*	34.38	104.25	12
	2	<=	32.6	801.53	203.77	4
	3	>	32.6	138.45	44.05	2
A5	1	<=	21.65*	148.18	24.53	4
	2	<=	23.65	297.93	52.15	4
	3	<=	31.3	227.53	36.50	6
	4	>	31.3	211.13	55.75	4
A10	1	<=	21.65*	66.58	42.99	4
	2	<=	22.8	375.05	60.85	2
	3	<=	32.6	185.45	78.31	10
	4	>	32.6	92.00	24.50	2
A20	1	<=	29.7	48.10	37.55	12
	2	>	29.7	96.65	8.58	4
	3	>	32.6*	10.55	2.95	2
A30	1	<=	19.7*	121.60	60.60	2
	2	<=	29.7	3.72	4.32	10
	3	>	29.7	13.82	7.77	6
A40	1	<=	19.7	9.25	9.25	2
	2	>	19.7	1.16	2.45	10
	3	>	29.7*	16.30	11.39	6

* Primary split