Quantification of preferential flow in undisturbed soil columns using dye tracers and image analysis

Sacha J Mooney and Catherine Morris

Division of Agricultural and Environmental Sciences, School of Biosciences, University of Nottingham, University Park, Nottingham NG7 2RD, UK. http://www.nottingham.ac.uk/biosciences/ah/academic/mooney.html, Email: sacha.mooney@nottingham.ac.uk

Abstract
Solute transport studies are increasingly being used to characterise flow mechanisms in both the field and laboratory. Realisation that solutes may move preferentially through soil into groundwaters has meant that research in this area has increased in importance. Chloride and Brilliant Blue tracers were applied to large undisturbed soil cores (8000 cm^3) inserted with time domain reflectometery probes (TDR). Following the collection of serial digital images, it was possible to examine the nature of the dominant water flow mechanisms in terms of dye-stained pathways and quantify the spatial distribution of dye concentration in two dimensions using image analysis. A high level of variability of flow patterns observed from dye and solute tracers was noted between soil types, between replicates and within replicates. These patterns were further explored using X-ray Computed Tomography to obtain 3-D visualisations of soil macropore architecture.

Key Words
Preferential flow, image analysis, dye tracer, macropores, solute transport, X-ray Computed Tomography.

Introduction
Understanding the complex processes governing transfers of water and chemical agents in soil are key to solving water quality problems. Preferential flow has been observed as rapid by-pass pathways in a range of soils (Bouma and De Laat 1981). Rapid transport processes reduce solute residence time and thus the time available for chemical degradation within the soil and increase sthe risk of agrochemical pollution. A great deal of research over the past four decades has focused on examining the mechanisms of solute transport, and in particular, flow through macropores (Beven and Germann 1982). Mechanisms of preferential flow have been studied in a range of soils both in the field (Droogers *et al.* 1998; Forrer *et al.* 2000) and under laboratory conditions (Aeby *et al.* 1997). Flury *et al.* (1994) found that preferential flow was the rule, rather than the exception in the soils examined, and subsequent studies have shown that as little as *c.* 1-10% of pore space may be utilised during soil water flow (Bouma and De Laat 1981).

Bouma *et al.* (1977) were among the first to use dyes to visualise flow patterns in field soils. Recent research has often used Brilliant Blue FCF as it provides the best combination of mobility, high visibility and low toxicity (Flury *et al.* 1994). Tracers allow flow patterns to be both visualised and quantified at different scales of observation. Their use has an advantage over traditional methods in allowing a distinction between areas of the soil that participate in solute flow and those that do not (Droogers *et al.* 1998). When used in conjunction with image analysis, dye tracing is a useful tool for characterising the interactions between morphological observations and physical processes in soil. At the field scale, image analysis techniques have been used both to visualise the stained pathways and to obtain a semi-quantitative description of flow patterns by determining the concentrations of dye in stained soil (Aeby *et al*. 1997). Until recently, most studies of this type have been conducted on soil samples at the centimetre scale resolutions. However, it is necessary to examine flow at the pore scale in order to derive an improved understanding of the processes of solute flow. Forrer *et al.* (2000) found that flow fingers could appear and disappear within a separation distance of <20 mm. Investigations into water flow pathways require knowledge of the pore connectivity, tortuosity and heterogeneity of the soil. Knowledge to date however is fragmented due to the lack of 3-D information. X-ray Computed Tomography (CT) is a non-destructive imaging technique used to create 3-D visualisations derived from 2-D scans. Perret *et al.* (1999) used CT scans to examine pore geometry and found in one specific sample that 80% of a macropore network was comprised of one independent macropore path.

The aim of this study was to develop a system for the examination of flow pathways in undisturbed soil at the laboratory scale using image analysis of dye tracer patterns and to use quantified data from flow patterns and soil macroporosity to elucidate the underlying flow mechanisms at the macropore scale.

Materials and Methods

Soil Collection & Tracer Analysis

Soil samples were obtained from the University of Nottingham's experimental farms at Sutton Bonnington and Bunny and comprised four contrasting textural groups; Newport, a light sand, (brown soil) and Worcester, a heavy clay (argillic pelosol), Fladbury, a clay loam (Pelo-alluvial gley soil), and a sandy loam, Dunnington Heath series (Stagno Gleyic Luvisol). Selected physical properties for the soil types examined are listed in Table 1. Three intact soil blocks per soil series (250 × 250 × 250 mm) were collected following methods similar to those described by Quisenberry *et al.* (1994). The soils were sampled four to eight weeks after sowing with wheat, with the exception of the Worcester series which was under established grassland. Pedestals of soil were carved from the surface to a depth of *c.* 250 mm and a wooden box placed over the soil. The sides of the box were injected with polyurethane foam and left overnight to cure. After 24 h, the soil columns were carefully removed and transported to the laboratory. The columns were placed under a drop applicator and leached with 0.01M $Ca(NO_3)_2$ until equilibrium was reached. The volumetric water contents at three depths (50, 130 and 210 mm) was recorded by three rod 200 mm TDR probes (0.48 cm diameter and 4.5 cm spaced) installed horizontally within the soil columns (TDR100 Reflectometer, Campbell Scientific Inc.). A chemical breakthrough curve was obtained for chloride by adding an 80 ml (2 mm) pulse of 0.1 M $CaCl_2$ and collecting the solute using a fraction collector. Samples were taken over a 24 h period, resulting in 200 samples per column. Chloride concentration was determined by automated colorimetry. Brilliant Blue FCF dye was applied to the intact soil columns using a peristaltic pump. The flow was maintained through 30 tubes equally distributed over the soil surface, at a rate of 280 mL h^{-1} or 7 mm h^{-1}. The dye solution was applied at a concentration of 3 g L^{-1} and leached for two hours (560 mL) to enable the dye to provide complete coverage. Complete dye breakthrough was not achieved in any of the soils. Hydrophobicity was measured in each soil type using the WDPT method (Dekker & Ritsema 1994).

Table 1. Selected Soil Physical Properties for the studied soils

Soil Series	% Sand	% Silt	% Clay	Bulk Density (g cm^{-3})	Organic Matter (%)	K_{sat} (cm s^{-1})
Newport	78.7	9.4	11.9	1.49	2.26	3.69×10^{-3}
Dunnington Heath	66.4	18.0	15.6	1.56	4.53	1.86×10^{-3}
Worcester	31.1	34.5	34.4	1.40	5.49	6.31×10^{-5}
Fladbury	9.0	30.9	60.1	1.12	5.79	6.85×10^{-5}

Image Capture & Analysis

Digital images were acquired in a dark room illuminated with a tungsten filament lamp. Sources of variability in soil images were minimised by fixed environmental conditions. The exposed soil faces were prepared carefully by hand by removing thin layers of the soil with a knife in the vertical orientation. Approximately 40-50 serial images were taken from each soil column separated by a maximum thickness of *c.* 5 mm. High-resolution (1600 × 1200 pixels) digital images were collected in the TIFF file format and transferred to a PC. The images were analysed using *analySIS 3.0*© (SIS Germany). Corrections were made for colour differences between images in order to standardise the images for comparison. Threshold values for colour calibration were set using soil samples of known concentrations (Aeby *et al.*, 1997) and by removing small amounts of dyed soil from the surface of an image for extraction (Forrer *et al.*, 2000). One hundred sub-samples of the stained soil were removed from one soil face per soil column in order to calibrate image brightness to enable conversion into a concentration map of dye in the soil. The samples were taken by placing a 10 ×10 mm grid over the surface of the soil face and removing a small amount of soil (*c.*1g) from each sampling portal. The method used for extracting the dye from the soil was adapted from Forrer *et al.* (2000) where soil samples were dried for 24 h at 80 °C before being weighed out. The samples were added to 10 mL of an aqueous-acetone solution (1:4 ratio), shaken for 12 h and centrifuged for 20 min at 2500 rpm. The concentration of Brilliant Blue dye was then measured in the supernatant solution using a spectrophotometer at a wavelength of 630 nm. These results were used to calibrate the images and produce a concentration map of dye for each soil.

X-ray Computed Tomography (CT)
Three smaller soil columns (170 mm length x 90 mm diameter) for each series were scanned using a Siemens X-ray CT-scanner. The X-rays were generated with an exposure factor of 120kV and 100 mA using a standard spiral scan routine. The resolution of the scanners output device was 512 x 512 and the final spatial resolution of each volume unit (voxel) was 0.46 mm x 0.46 mm x 0.46 mm (0.08 mm^3). Hence, analysis was restricted to macroporosity only. Each column scan took less than 10 seconds and generated 144 vertically orientated images (240mm x 240 mm). After columns had been scanned at field capacity, the procedure was repeated, without moving the soil columns, three minutes after a sprinkler application of 50 ml at a rate of 10 mm h^{-1}. Using public domain software ImageJ 1.21 (National Institutes of Health, USA), it was possible to reconstruct 3-D representations of pore space and quantify the spatial arrangements of soil components for a given density by using automated segmentation tools. Air-filled and water-filled porosity were segmented with mean Hounsfield units of *c.*310 and *c.*1055 respectively, which are similar to previously published data (Adderley *et al.* 2001). CT images of soil columns at field capacity and after infiltration were matched to enable the visualisation of water pathways and segmentation of air and water filled pore spaces.

Results and Discussion

Solute Transport
Water content dynamics and chloride breakthrough results both show evidence that preferential flow channels may be responsible for a significant portion of the total flow in the different soils. For example, the Dunnington Heath soil showed a rapid increase in water content at the start of the experiment until a constant (almost saturated) state was reached at around 7 hours (≈2 L) from the start of rainfall (Figure 1a). Both the 50 mm and 210 mm probes recorded an almost instantaneous response to the chloride application noted by the rise in water content suggesting a preferential flow of solute however, the results given by the 130 mm depth probe continued to increase subsequent to this indicating that only a proportion of the water flow was affected. This pattern was not observed at the 210 mm depth. The Worcester and Fladbury soils behaved in a similar way to the Dunnington Heath soils, whereas a much slower recovery of chloride akin to a more uniform wetting was found in the Newport series. Differences in the overall water contents may be due to localised differences in the soil structural characteristics (small outcrops of the heavy clay subsoil were identified within the Fladbury soil columns) or from partial bypassing of the soil matrix. As shown in Fig. 1b, following the chloride application, around 2.2 pore volumes of water were applied, measurements showed that 90-95% of applied chloride was recovered by this method with peak breakthrough prior to the application of one pore volume. This indicated the occurrence of preferential flow processes at the column scale. WDPT data indicated that none of the soils studied exhibited signs of hydrophobicity.

Visual Observations
The dye tracer experiment yielded > 500 images which were each initially subjected to a visual examination based primarily on the morphology of the dye tracer pattern and any associated soil features. Example images with the dye tracer highlighted are in Figure 2. Although texturally the Newport and Dunnington Heath soils have some similarity (predominantly sandy), the dye tracer profiles were quite different with a greater depth of dye penetration generally noted in the Dunnington Heath columns. Although the overall staining patterns between the Fladbury and Worcester series soils were different, preferential flow paths associated with structural cracks and fissures as observed visually were identified in both. Although highly variable, the Worcester series columns exhibited much greater dye coverage than the Fladbury. In the Fladbury soil, virtually all of the observed flow appeared to be via preferential flow channels, with typically > 5 fingers per image, compared to *c.* 2 in the Worcester series.

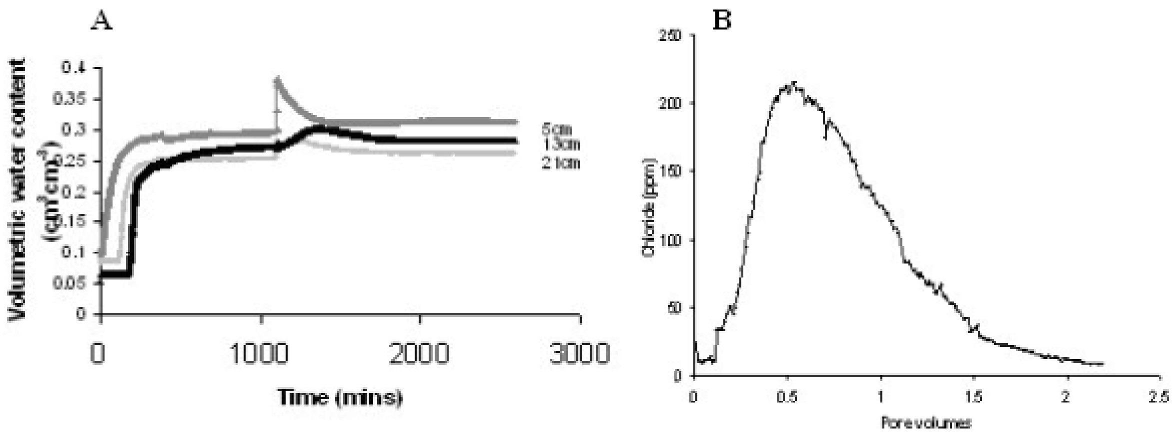

Figure 1. Example of a) volumetric water contents at different depths and b) a column-scale chloride breakthrough curve for a soil column of the Dunnington Heath soil series

Semi-Quantitative Analysis

The average percentage dye coverage for three columns for each soil type did not suggest any obvious relationship between the soil types and the respective flow pattern, although there was a clear significant difference between how the different soils behaved (P<0.001)(Figure 3a). A hypothesised difference with respect to soil texture (i.e. decreasing dye coverage with increasing clay content) was not observed since the two soil types with the greater dye coverage were the Newport and Worcester series. The within soil type variance was highly significant (P<0.001) for all of the soils, with the exception of the Worcester series, indicating that the depth of dye penetration varied greatly between columns of the same soil type. The within soil column variation (between replicates) (Figure 3b) was in general low (SD < 7%), especially in the Dunnington Heath series, with one main exception (Worcester column 3). A variance components analysis revealed the main variance was associated with the soil types (56%), with 21% attributed to the within soil type variation and 23% attributed to the within soil column variation.

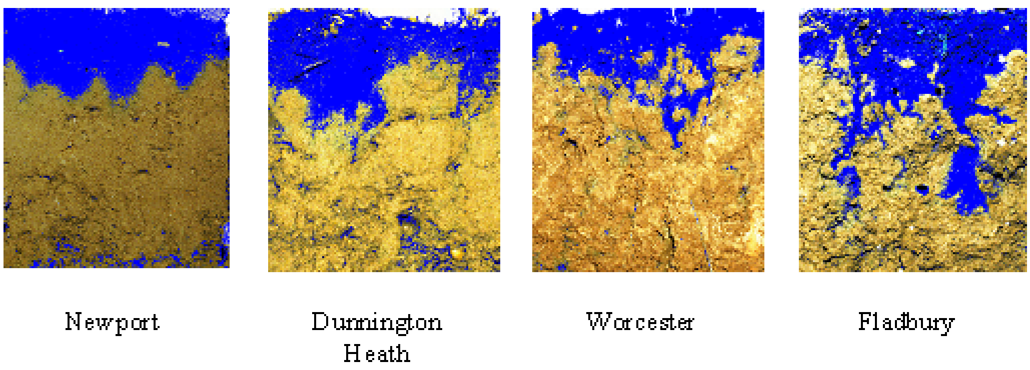

Figure 2. Example vertical orientated images of dye tracer patterns from the middle of columns for the four examined soil types. (Dimensions = c. 250 mm length x c. 200 mm width).

1-D & 2-D Flow Measurements

For each soil, the dye coverage (%) and average dye concentration (mg g-1) were computed at 10 depths in the soil profile (Figure 4). In the Newport soil, the peak dye concentration was recorded below the surface at 30 mm followed by an abrupt tailing of the dye front at *c.*130 mm depth with low average concentrations. The former appeared to be related to incorporated plant residues observed near the surface soil facilitating flow in the upper part of the profile. This observed flow pattern was similar to what might be expected by a uniform wetting mechanism. In the Dunnington Heath series, the staining pattern was shallow but with the same abrupt front tailing off seen in the Newport series. The tailing off of the dye front in the Worcester series was long with dye recorded at the column base. Non-uniform flow activity was observed in the Fladbury series where maximum dye coverage in the surface soil was > 60%, suggesting that preferential flow channels may have been initiated above 30 mm. The Worcester soils predominantly had a maximum dye coverage and concentration at, and just below, the immediate surface layer which maybe explained by plant material and/or worm burrows observed near the soil surface initially facilitating the transport of dye below the surface layer, changes in texture causing storage (incorporation of clay subsoil from depth), and surface measurement affected by the presence of organic matter. A possible cause of the tailing off phenomena could be attributed to the adsorptive / desorptive properties of Brilliant blue as described by Ketelsen & Meyer-Windel (1999). However, while adsorption isotherms (not published here) confirmed dye adsorption in the soils studied comparisons between chloride breakthrough curves and dye tracer profiles suggest it had a limited effect.

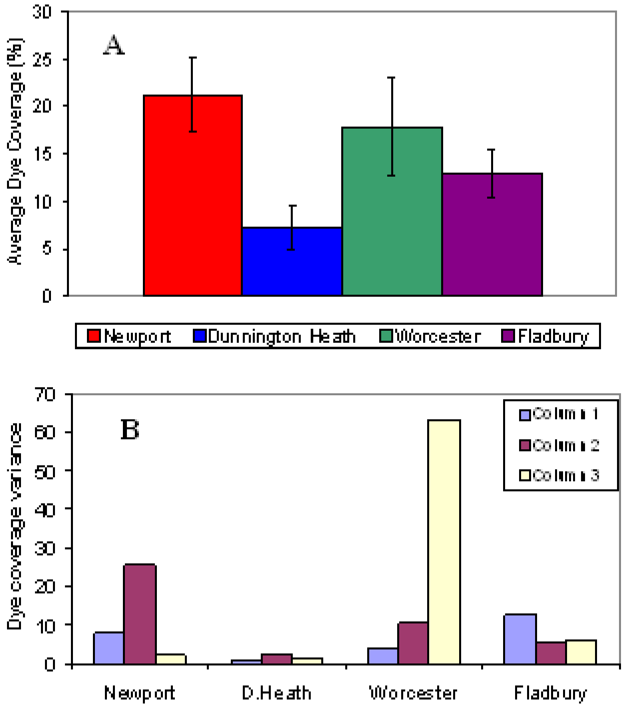

Figure 3. Variation in dye coverage percentage between a) soil types and b) within soil columns.

3-D Flow Observations

From the initial X-ray CT data, it was observed that the Dunnington Heath soil contained the greatest total (macro) porosity (air-filled porosity)(40% derived from portion of air-filled voxels that comprised the total soil volume) for the given spatial resolution. This was greater than that of the Newport series (31.5%) and the Worcester and Fladbury series' (24.5% and 21.6% respectively). The soils reacted to the infiltration of water in quite distinctive ways. The subsequent re-classification identified that in the Dunnington Heath series c.90% of the pore volume was active in water storage (i.e. 37.2% water-filled pore volume). This provided a quantitative measure of water retention for a given albeit large spatial resolution and small time period. Although representative only at this particular resolution, this is significantly different to previously published data in this area (Bouma & De Laat 1981). By contrast, after infiltration, the Newport series comprised *c.*53 % water filled voxels (47% air-filled voxels). This contradicts the dye tracer profiles, where it was suggested that water storage was greater in the Newport series, with an increase frequency of small scale preferential flow channels observed in the Dunnington Heath series. The X-ray CT data for the predominantly clay textured soils (Fladbury and Worcester series) also failed to support the dye tracer profiles in that following infiltration, the percentage of water filled voxels was similar, *c.* 80% of the total pore space. However, it must be noted that the X-ray CT data represents 'snap shots' taken a short time frequency (3 minutes) compared to the tracer profiles over several hours. From visual observation of the reconstructed pore space and quantified by 1-D porosity measured along horizontal transects (chord analysis)(Fig. 5d), a clear structural discontinuity was observed in the Newport series column, illustrating a highly porous upper layer (*c.*30%) that reduced significantly with depth.

Conclusions

The dye tracer method provided a cheap and simple way to obtain field condition samples for laboratory experimentation which yielded images which could be easily examined both by eye and using image analysis techniques. The results suggested a significant variability in the mechanisms of water and solute flow between and within the different soil types. Comparing the analysis across the different techniques and resolutions, it was observed that the predominantly sandy soil (Newport series) had the greatest dye coverage in the upper layer and among the lowest dye concentrations in the lower layers. This suggested a more uniform wetting and greater water storage than the other soils, which was supported by the X-ray CT data. Preferential flow was recorded in each of the other soils examined by both chloride and dye tracer analysis, although the dye coverage suggested slightly more uniformity of flow in the Worcester series. Such information as to how a soil dynamically rewets is important both in terms of cultivation practice and pollution modeling. This is especially significant when considering a wetting mechanism, such as preferential flow, that cannot be adequately described by conventional soil physics. By combining techniques such as tracer concentration mapping and 3-D structural visualisation, the successful prediction of the multi-scale, heterogeneous processes of soil water flow may soon be realised.

Published on CDROM. Website www.regional.org.au/au/asssi/

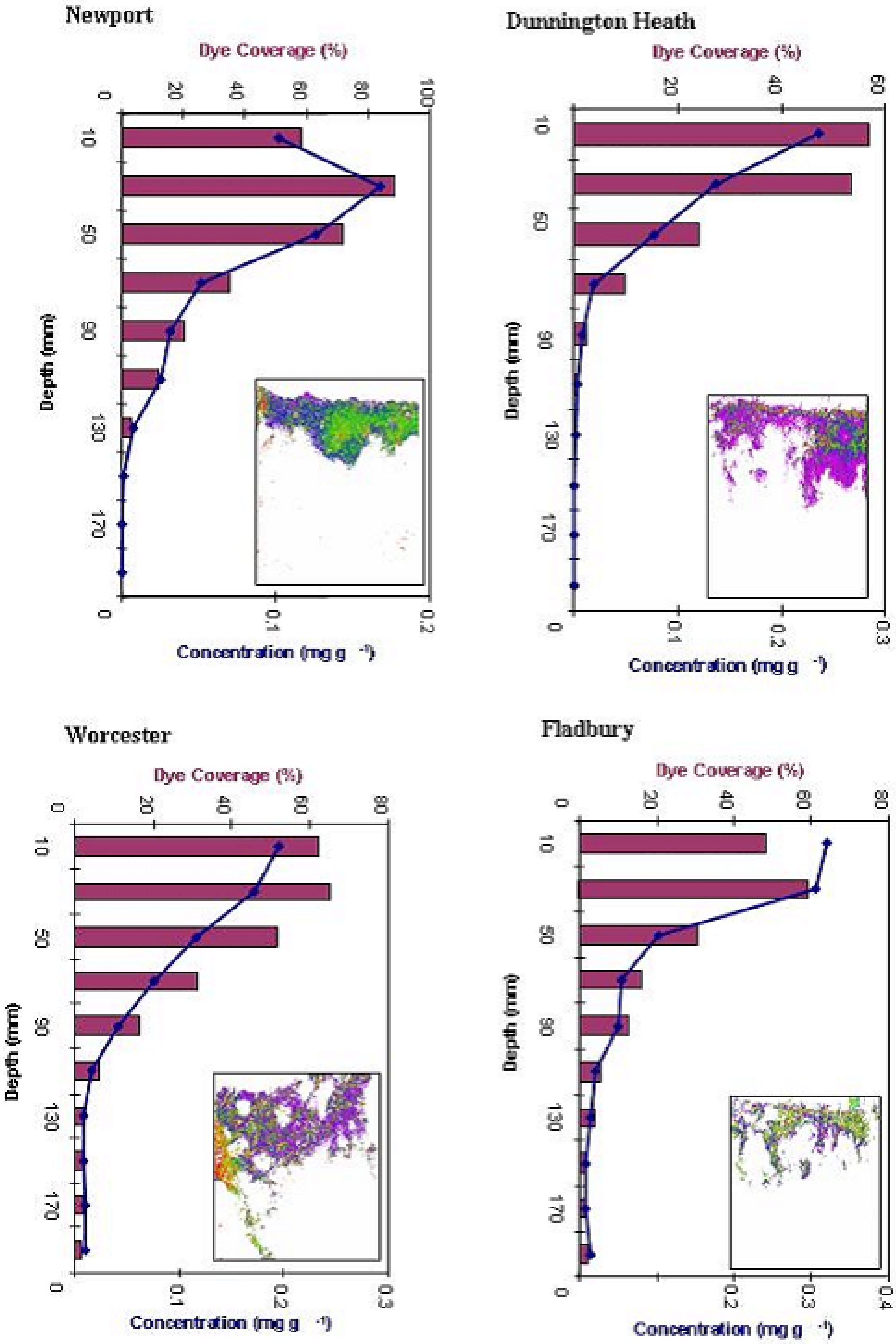

Figure 4. Two-Dimensional measurements of average dye concentration (mg g^{-1}) and dye coverage (%) with depth for each soil type with a typical concentration map (0.16 mm $pixel^{-1}$).

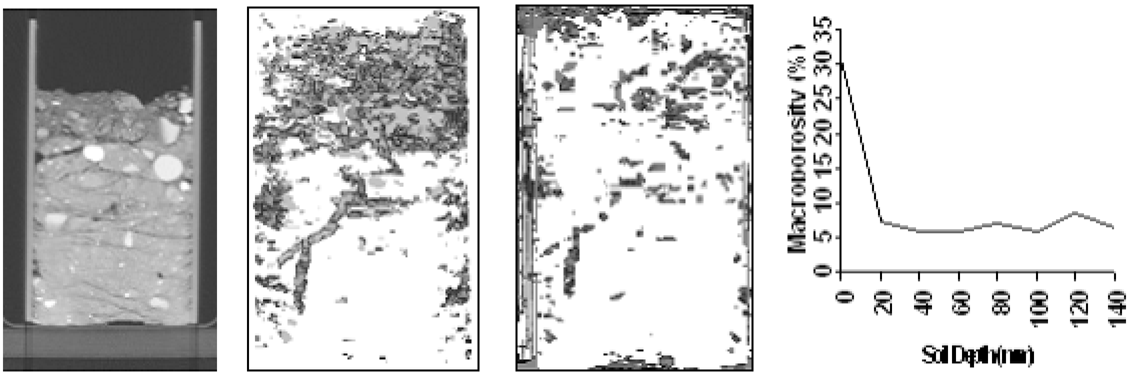

Figure 5. Examples of reconstructed X-ray CT scans of soil macropore space for the Newport soil series and illustration of variation with depth (Image resolution = c. 0.1 mm^3, column size = 170 mm x 90 mm)
a) original scan b) total macroporosity c)water filled porosity d) macroporosity v depth

References

Adderley WP, Simpson IA, MacLeod GW (2001) Testing high resolution X-ray computed tomography for the micromorphological analyses of archaeological soils and sediments. *Archaeological Prospection* 8, 107-112.

Aeby PJ, Forrer C, Steinmeier D, Flühler H (1997) Image analysis for determination of dye tracer concentrations in sand columns. *Soil Science Society of America Journal* 61, 33-35.

Beven K, Germann P (1982) Macropores and water flow in soils. *Water Resources Research* 18, 1311-1325.

Bouma J, Jongerius A, Boersma O, Jager J, Schoonderbeek D (1977) The function of different types of macropores during saturated flow through four swelling soil horizons. *Soil Science Society of America Journal* 41, 945-950.

Bouma J, De Laat PJM (1981) Estimation of the moisture supply capacity of some swelling clay soils in the Netherlands. *Journal of Hydrology* **49**, 247-259.

Dekker LW, Ritsema CJ (1994) How water moves in a water repellant sandy soil. 1. potential and actual water repellency. *Water Resources Research* **30**, 2507-2517.

Droogers P, Stein A, Bouma J, De Boer G (1998) Parameters for describing soil macroporosity derived from staining patterns. *Geoderma* 83, 293-308.

Flury M, Flühler H, Jury WA, Leuenberger J (1994) Susceptibility of soils to preferential flow of water: A field study. *Water Resources Research* 30, 1945-1954.

Forrer I, Papritz A, Kasteel R, Flühler H, Luca D (2000) Quantifying dye tracers in soil profiles by image processing. *European Journal of Soil Science* 51, 313-322.

Ketelsen H, Meyer-Windel S (1999) Adsorption of brilliant blue FCF by soils *Geoderma* 90, 131-145

Perret J, Prasher SO, Kantzas A, Langford C (1999) 3-D quantification of macropore networks in undisturbed soil cores. *Soil Science Society of America Journal* 63, 1530-1543.

Quisenberry VL, Phillips RE, Zeleznik JM (1994) Spatial distribution of water and chloride macropore flow in a well-structured soil. *Soil Science Society of America Journal* 58, 1294-1300.

Vogel H-J (1997) Morphological determination of pore connectivity as a function of pore size using serial sections. *European Journal of Soil Science* 48, 365-377.

Published on CDROM. Website www.regional.org.au/au/asssi/