The aim of this investigation was to experimentally compare the movement of a solute through soils with two field-representative surface geometries: ridge and furrow surfaces versus flat surfaces. X-ray computed tomography (XCT) imaging was undertaken to trace the movement of a soluble iodinated contrast medium, here used as an XCT-visible analogue for field-applied solutes, through soil columns with either a ridge and furrow or flat soil surface geometry. In addition to the soil surface geometry, the experimental treatments included the presence or absence of plants and surface water ponding. Experimental results were compared to existing numerical simulations adapted to represent the present experimental column systems. Similar infiltration patterns were observed in imaging results and the numerical simulations for most treatments. The experimental results suggest that plant roots present a significant localized effect to reduce the infiltration depth of solutes, particularly in planted ridges where the infiltration depth of the contrast medium was minimal. There is variability within the results because the number of replicates was limited to three due to the exploratory nature of the study (testing eight different treatments) and the cost and availability of XCT facilities capable of imaging such physically large samples. Discrepancies between the imaged infiltration depth of the solute and the numerical simulations are attributed to variation in plant root distribution and also spatial soil moisture, as measured using resistive soil moisture sensing. The results of this investigation elucidate the nature of solute movement through soil surface geometries, indicating that plant root water uptake can reduce solute infiltration depth, but surface ponding can negate this. These results suggest that soil surface shape, plant age and the timing of solute application with anticipated rainfall could be important considerations for reducing solute leaching and improving solute application efficiency.
Introduction

Numerous methods are used to cultivate crops in arable systems, including those which alter soil surface geometries (Fahong, Wang, & Sayre, 2004). Two such approaches widely used in the United Kingdom are “flat planting” and “ridge and furrow planting” (Robinson, 1999). Flat planting uses a uniform soil surface with no significant spatial geometric changes, whereas ridge and furrow planting involves the creation of a system of periodic peaks and troughs across an arable field. Determining the most suitable soil surface treatment for a crop system depends on several factors, including, but not limited to, the crop species, soil type, climate, water availability, nutrient status and ease of harvesting (Finch, Samuel, & Lane, 2014). Ridge and furrow planting is the preferred choice for certain crops (e.g., potatoes) because it aids in nutrient replenishment of the soil (Feddes, Kowalik, Kolinskamalinka, & Zaradny, 1976) and the capacity to provide adequate water to plant roots without inducing waterlogging of the rooting region during periods of heavy rainfall (Tisdall & Hodgson, 1990).

Although ridge and furrow systems provide some clear advantages over flat planted systems, studies have shown that the mechanisms of water movement within ridge and furrow systems may make them more vulnerable to solute leaching (Alletto, Coquet, Benoit, Heddadj, & Barriuso, 2010; Kettering, Ruidisch, Gaviria, Ok, & Kuzyakov, 2013). Typical solutes applied in agricultural systems include soluble fertilizers or pesticides. Solute leaching in agricultural systems is of importance as it can cause environmental damage (van der Werf, 1996) and is cost inefficient for farmers. For example, excessive leaching of nitrogenous fertilizers not only means that the crop plants cannot utilize this nitrogen as intended, but can lead to eutrophication of water bodies wherein oxygen depletion can adversely damage populations of aquatic life (Conley et al., 2009; Harper, 1992). Previously, field-scale agronomic studies have identified spatial variation in the solute infiltration depths in an arable ridge and furrow system (Kung, 1988; Leistra & Boesten, 2010; Smelt, Schut, Dekker, & Leistra, 1981). These studies found that solutes present within the furrows moved to a greater absolute depth compared to flat soil surface geometries in all instances. Moreover, a report from the European Food Safety Authority indicated that the severity of leaching in ridge and furrow systems can be up to six times that of flat systems (EFSA, 2013). However, solute management techniques can be employed to mitigate solute leaching in ridge and furrow systems. For example, Jaynes & Swan (1999) observed that leaching was significantly reduced when nitrogen fertilizer was applied only to the ridge and not to the furrow. Such techniques can reduce damaging environmental effects of solute leaching (Hatfield, Allmaras, Rehm, & Lowery, 1998) to the extent at which ridge and furrow systems are less vulnerable to leaching than flat systems (Ressler, Horton, Baker, & Kaspar, 1997).

Duncan, Daly, Sweeney, and Roose (2018a, 2018b) modelled the movement of water and solutes in a ridge and furrow surface and a flat surface geometry (Duncan et al., 2018b), illustrating the effects of dynamic furrow ponding on solute movement. Importantly, these systems were simulated with and without the presence of plant roots. These simulation results indicated that a ridge and furrow geometry could either increase or reduce the infiltration depth of solutes relative to flat systems depending on the rainfall activity following solute application and the presence of roots within the soil. In simulations where solute application to a planted ridge and furrow geometry was followed by a comparatively low frequency and intensity of rainfall, the infiltration depth of solutes was reduced compared to
flat systems. Solute accumulation in ridges in the rooting zone as a result of the root water uptake drawing in solutes via advection. However, when high-intensity rainfall followed the solute application, the infiltration depth of the solute was increased in planted ridge and furrow geometries compared to flat systems. In this instance, water infiltration from ponding was the dominant transport mechanism, thus causing the solutes to infiltrate deeper and increase the likelihood of solute leaching. This effect was more severe in the simulations without plant roots due to a lack of water uptake from roots in the ridges of the system. Although the simulation results elucidate much of the contrasting empirical evidence regarding ridge-furrow systems versus flat systems, there are few measurement techniques that can validate the model.

One established method for observing and tracing fluid flow is through the use of radiographic contrast media coupled with imaging via X-ray computed tomography (XCT). For example, Heijns, Ritsma, & Dekker (1996), Larsbo, Koestel, & Jarvis (2014) and Sammartino et al. (2015) used XCT imaging to trace contrast media solutions through porous media to assess preferential solute transport in the context of macropore structure and characteristics. These methods offer opportunities to obtain information that cannot be captured using traditional destructive methods such as dissections or soil coring. These methods allow for the examination and quantification of 3D patterns of fluid movement in an intact soil system containing live plants. In particular, non-ionic iodinated contrast media are commonly used as a fluid flow tracer; for example, for gastrointestinal and vascular flow imaging in biomedicine (Blachar, Federle, & Dodson, 2001; Gertz, Wisneski, Chiu, Akin, & Hu, 1985; Lusic & Grinstaff, 2013). These contrast media are used as flow tracers because they possess several favourable traits. Firstly, they are generally less reactive compared to alternative contrast media; for example, ionic iodinated contrast media (Aspelin, 2006; Lusic & Grinstaff, 2013). This is advantageous when the contrast media are required to translocate freely and for applications involving organic tissues. Additionally, non-ionic iodinated contrast media are highly soluble and possess a viscosity similar to water (Lusic & Grinstaff, 2013). These attributes make these contrast media an ideal surrogate for mobile solutes in soil under variable agricultural settings.

The objective of this study was to experimentally observe the patterns of solute movement through ridge and furrow or flat soil surface geometries. This was achieved via XCT imaging, used to trace the flow of a soluble non-ionic iodinated contrast media through soil columns with ridge and furrow or flat soil surfaces. The experimental imaging results were compared to numerical modelling simulations originally developed by Duncan et al. (2018a, 2018b), but adapted to represent the specific experimental system here. Resistive soil moisture sensing (RSMS) was also then used to record spatiotemporal soil moisture. Planted and non-planted treatments were incorporated, as well as treatments that vary in watering regime following solute application. These different watering regime treatments represented either no rainfall or excessive rainfall scenarios. By demonstrating that solute infiltration observed in the XCT imaging can be reproduced using numerical models, the conclusions of this work may lead to better informed management of solute application in areas exposed to intermittent heavy rainfall.

As informed by previous modelling results (Duncan et al., 2018a, 2018b), we hypothesized that the advection of water uptake by plant roots would cause the contrast media to accumulate close to the soil surface for both soil surface geometries. We predicted that this accumulation would take place to a greater extent in ridge and furrow systems that were not exposed to heavy watering following the addition of the contrast media. This was because it was anticipated that the advective force of root water uptake would be able to exert greater influence in ridges, in accordance with the results of Duncan et al. (2018a, 2018b). We also hypothesized that where ponding is present ponding could force deeper infiltration of solutes. We predicted that this would take place as a result of the pressure exerted by ponded water.

2 | MATERIALS AND METHODS

2.1 | Experimental system

In order to trace the movement of the contrast media through the soil using imaging experiments, column mesocosm systems, designed to be suitable for XCT, were constructed (Figure 1). The requirements for achieving compatibility with XCT were: (a) radial symmetry of the sample, (b) a constrained density and scale of the sample so that sufficient X-ray transmission and resolution could be achieved, and (c) low X-ray attenuation of the materials relative to contrast media. Consequently, experimental column systems used for this investigation were largely constructed from unplasticized polyvinyl chloride (uPVC) components.

The major structural component of the mesocosm columns was a uPVC tube with an internal diameter of 10.2 cm and total height of 36 cm. On the basal end of the uPVC tube was a uPVC end-cap, which featured 10 evenly spaced holes of 5 mm diameter. A single layer of nylon mesh with an aperture of 300 μm (Plastok, Birkenhead, UK) was laid into the base of the tube immediately over the holes in the end-cap to prevent soil and sand aggregates from leaking out of the column via the holes. Coarse
sandpaper of 40 Grit (Flexovit, Conflans-Sainte-Honorine, France) lined the inside of the uPVC tube, with the abrasive surface facing soil-ward to increase surface connectivity at the interface between the edge of the soil and the inner wall of the tube. This would minimize the chance that preferential fluid flow pathways emerged. Sand of British Standard Fraction A (1.18–2.36-mm grain size) was placed onto the basal nylon mesh to a depth of 45 mm, the height of the end-cap. A sand-textured Eutric Cambisol field soil (collected from a surface plot at Abergwyngregyn, north Wales) was sieved to below 1 mm and placed on top of the sand until the soil was 25 cm deep. A sheet of the nylon mesh was laid onto the surface of the soil.

Two soil surface geometries were considered: a ridge and furrow geometry and a flat geometry. Additionally, an inverted ridge and furrow surface geometry was used to assess the significance of an edge effect (see Supplementary Information in File S1). For the flat soil surface geometry, another 6-cm-deep layer of Eutric Cambisol soil was placed above the nylon mesh. For the ridge and furrow geometry a central mound was formed of the Eutric Cambisol soil, which was 6 cm in height from peak to trough. This resulted in a ridge width to ridge height ratio equivalent to that which can typically be found in agricultural field systems, where this ratio can vary from 1:1 to 1:4 (X. Y. Li & Gong, 2002; Tian, Su, Li, & Li, 2003). This central mound formed a radially symmetrical representation of the ridge and furrow geometry. Pregerminated rice seedlings (*Oryza sativa* subsp. *Indica* var. IR64) were placed in planted treatments into these top regions of the soil. This is discussed in more detail in the section “Growth Conditions for Planted Treatments” and Supplementary Information in File S1. The upper layer of nylon mesh, buried 6 cm under the soil surface, confined root growth to this top region of soil because it was necessary to downscale the soil system such that it would be XCT compatible. In particular, the roots were not to grow to a greater relative depth than would be the case in a field system. Soil bulk density of all columns was recorded prior to watering and addition of plants. The method used to calculate soil bulk density and results are given in the Supplementary Information (Table S1 in File S1).

The entire column was moved onto a raised central ridge in a “base holder” consisting of a cylindrical uPVC tray of 15 cm internal diameter and 7.5 cm height. Three bolts of 4 cm length, which were radially evenly spaced, were drilled through the side of the larger cylinder at a height of 2 cm from the cylinder’s top edge. Bolts were tightened such that the column was held securely and straight. Distilled water was then poured into the cylindrical tray to a depth of 4 cm around the outside of the column. The raised central ridge, which the column base rested on, allowed water in the tray to enter the column through holes in the basal end-cap and thus passively provide water to the soil system. The base holder featured an additional smaller cylinder, 6.2 mm internal diameter and 2.5 cm height, which extended downward from beneath the tray. This smaller additional cylinder allowed the base holder, which held the column, to later be secured in place on the stage of the XCT scanner using a three-jaw chuck.

### 2.2 Experimental treatments

The main treatments were combinations of either planted or non-planted systems, ridge and furrow soil surface geometries or flat soil surface geometries and either with ponding of water on the soil surface or without, summarized in Table 1. This combination of treatments is similar to those previously modelled by Duncan et al. (2018a, 2018b). There were three replicate columns for each of the eight treatments (total 24 columns).

### 2.3 Growth conditions for planted treatments

*Indica* rice cultivar IR64 (*Oryza sativa* subsp. *Indica* var. IR64) was selected for planted treatments due to its high water-uptake rate (Kramer, 1983; S. Li et al., 2017) and
shallow root architecture (Uga et al., 2013; Uga, Okuno, & Yano, 2011). Therefore, this rice cultivar was likely to be capable of successful development when the roots were confined by nylon mesh, as was necessary to downscale the soil system suitable for XCT imaging, whilst maintaining approximate root distribution and water mechanics of a field system. Prior to transplanting into columns, the rice was pre-germinated. This germination involved submerging the seeds in water for 10 days using a photoperiod of 12 hr per day at a temperature of 30°C/27.5°C during the “daytime” and “night-time,” respectively, controlled in a Conviron CMP6010 Growth Chamber ( Controlled Environments Ltd, Winnipeg, Canada). The humidity inside the chamber remained at 70% throughout the germination period.

Once germinated, rice seedlings were transplanted into the columns and placed 0.5 cm beneath the soil surface in the centre, orientated such that the leaf shoot emerged through the surface of the soil. In the ridge and furrow systems the seedlings were transplanted into the ridge. The entire column setup was then moved into the growth chamber, including the base holders in which the columns were held. The columns remained in the growth chamber for a total of 4 weeks until imaging. The water in the base holder trays was refilled regularly to maintain the provision of water to the columns of soil through the end-cap. Additionally, 15 mL of distilled water was mist-sprayed in a fine droplet size onto the soil surface of each column every other day until 2 days before imaging to ensure the plants received sufficient water. Supplying the plants with water through the basal end-cap and through mist-spraying reduced the risk of soil erosion from large water droplets on the soil surface. After the imaging experiments had concluded, the plants were immediately harvested and fresh/dry mass values were recorded for each plant. Full details of the methods and results for harvested plant mass can be found in the Supplementary Information in File S1.

2.4 X-ray computed tomography imaging

An initial contrast assessment was undertaken to ascertain the concentration of contrast media required for sufficient contrast. This assessment also provided the XCT parameters used for the column imaging. All XCT and radiography imaging was accomplished using the Custom 450kVp Hutch at the λ-VIS X-ray Imaging Centre, University of Southampton, UK. The contrast assessment column was set up in the same system as the main experimental treatments. The contrast medium used for these experiments was Niopam 370 (Bracco, High Wycombe, UK), an iopamidol-based contrast medium containing 370 mg iodine mL$^{-1}$. A dilution series of the contrast media with distilled water from 370 to 37 mg iodine mL$^{-1}$ was produced in 2-mL Eppendorf tubes (Eppendorf, Hamburg, Germany). The tubes containing the contrast media and one tube of distilled water were embedded into the soil of the contrast assessment column in a ring. Further information on the contrast assessment can be found in the Supplementary Information in File S1.

During all XCT imaging, the columns were affixed to the XCT scanner stage by placing the smaller cylinder on the underside of the base holder (as shown in Figure S1 in File S1) into a three-jaw chuck. For the contrast assessment imaging, the stage was raised such that the top 8-cm region of soil, which included the Eppendorf tubes containing contrast media, was imaged. The stage was lowered for the experimental columns to ensure that scans captured the region from 2 cm above the soil surface through to 12 cm below. Capturing this region would ensure that the top 10 cm of soil would be clearly visible, whilst allowing an additional 2-cm zone of nonessential image information at the top and bottom of the scan. This was because cone beam artefacts were expected to form within these 2-cm zones at the top and bottom, creating streaks of high grey values, which would make later image processing more complex.

The contrast medium was added to the experimental column soils 1 min before the start of image acquisition. A 25-mL volume of the contrast medium was sprayed evenly over the surface of the soil at a concentration of 185 mg I mL$^{-1}$, as determined as most appropriate by the contrast assessment. For the treatments with ponding, 15 mL of water was then sprayed onto the soil surface such that ponding occurred above the soil surface. The treatments without ponding did not undergo the addition of water to the soil surface after contrast media application.

The XCT imaging utilized an X-ray tube with a tungsten target to generate X-rays of 400 kVp in energy. An aluminium bow tie filter was applied to reduce edge effects and artefacts resulting from greater X-ray transmission at the edges of the columns. A comprehensive list of imaging parameters is given in Table 2.

One XCT scan was captured of each contrast assessment column. The experimental columns were imaged once before the application of the contrast medium to
produce a "control" image. The contrast medium was then applied and 4 hr later the columns were imaged again to produce a "final" image. The resulting XCT images were reconstructed using the software CTPro 3D (Nikon, Tokyo, Japan) with a fine-scale dual centre of rotation detection. The images were reconstructed as 32bit 3D image stacks.

2.5 | Image analysis

2.5.1 | Segmentation of contrast media

The image segmentation of the XCT data was undertaken using the Fiji distribution of the image processing software ImageJ (Rueden et al., 2017; Schindelin et al., 2012).

The image segmentation workflow is summarized in Figure 2. First, a 3D Gaussian blur operation with a radius of 6 pixels in each dimension was applied to the "control" image (the image captured before contrast medium was applied). This reduced speckle from individual particles or pores and variation in localized contrast, particularly at the soil surface and in ridges, where total linear attenuation can be variable. The next stage in the workflow was the subtraction of the smoothed control image from the "final" image (the image captured approximately 4 hr after the contrast medium was applied). This removed the contrast resulting just from the attenuation of the soil and not the contrast medium and allowed the contrast medium distribution to be segmented.

The post-subtraction image stack was then cropped and a "clear outside" operation was performed, which removed image data outside an oval outline such that the image stack only included the area inside the column. This oval outline around the inside of column was set by segmenting the uPVC tube using a grey value threshold, obtaining the dimensions of the inner wall of the tube and using this to set the oval. A "Li" binary threshold (C. H. Li & Tam, 1998) was applied to the image stack to segment the high grey value pixels of the contrast media from any remaining pixels of soil or column material. The "Li" binary threshold is an iterative method, which uses a one-point iteration to determine the threshold that minimizes the cross entropy of the unsegmented image and the segmented image (C. H. Li & Lee, 1993; C. H. Li & Tam, 1998). This was followed by a 3D ball dilation, followed by erosion of 1 pixel in each direction using the FIJI "Morphological Filters 3D" from the plugin package "MorphoLibJ" (Legland, Arganda-Carreras, & Andrén, 2016). A "remove outliers" was then applied to the stack to reduce any groups of pixels of less than 3 pixels in diameter. Both the "dilation"/"erosion" and "remove outliers" operations were intended to reduce

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**TABLE 2** The parameters used for the X-ray computed tomography (XCT) imaging. All XCT and radiography imaging was accomplished using the Custom 450kVp Hutch at the μ-VIS X-ray Imaging Centre, University of Southampton, UK

| Parameter       | Value           |
|-----------------|-----------------|
| Voltage (kV)    | 400             |
| Amperes (μA)    | 513             |
| Power (W)       | 205.2           |
| Exposure (mS)   | 88              |
| Analogue gain   | 2               |
| Binning         | x2              |
| Number of projections | 1,201         |
| Frames per projection | 2               |
| Target material | W               |
| Detector        | Flat panel (2000 × 2000 pixels) |
| Filtration      | Al (bow tie)    |
| Resulting voxel size (μm) | 130            |

**FIGURE 2** A flowchart outlining the workflow for image segmentation of the contrast media distribution. The red ellipses represent the first and last images in the segmentation workflow. The green parallelograms are output images, with the title of the images in bold and in quotation marks. The black rectangles are the operations that were applied [Color figure can be viewed at wileyonlinelibrary.com]
“speckle” from individual pixels of high grey value resulting from particularly attenuating soil grains that had been over-segmented.

Following contrast media segmentation, a “180° rotation vertical reslice” stack was produced for each column (Figure S2 in File S1). The reslice stacks would enable analysis of vertical contrast media infiltration depth in the context of the radial symmetry of the column systems. These stacks were produced by first duplicating the segmented image stack. The duplicate stack was then rotated by one degree and resliced along the centre line of the vertical (Z) axis to produce a 2D reslice image. This duplication and reslicing was repeated 180 times and each time the angle of rotation performed on the duplicate stack was increased by one. A stack was produced from the 2D reslice images of the full 180° rotation. A “find edges” operation was performed on the stack of reslices in preparation for the next stage of analysis and this stack was then saved.

Finally, the infiltration depth of the contrast media within the columns was quantified. To achieve this, each 2D image of the vertical reslice image stack was read into Matlab (MathWorks, Natick, MA, US) as arrays of pixel values. A custom script calculated the difference between the top (soil surface) and bottom edge position (deepest point of solute infiltration) for every column within the arrays. This calculated value was the approximate infiltration depth vertically down columns by the contrast media. This calculated value was then averaged across the rotation images and the radial mean average infiltration depth of the contrast media was plotted from the outside rotation images and the radial mean average infiltration depth of contrast media were then averaged across the media within the 4 hr. The values for the infiltration depth of contrast media were then averaged across the rotation images and the radial mean average infiltration depth of the contrast media was plotted from the outside edge to the centre of the columns. The overall mean infiltration depth for each replicate was also calculated in addition to the standard deviation [SD] also using Matlab. SD is reported alongside the mean infiltration depth in the format: mean infiltration depth ± SD.

2.5.2 Additional image processing

To ensure that there was no formation of preferential contrast media flow paths due to the presence of macropores, the pore size distribution (PSD) was calculated for each sample. Correlation analysis determined the likelihood of a correlation between PSD and the distribution of contrast media. The details of the image processing methodology and results for the PSD and image correlation can be found in the Supplementary Materials in File S1.

Additional image processing segmented the roots and quantified root surface area density for one flat system (replicate one of the planted flat system without ponding). These data were used to parameterize root surface area density in an additional modelling simulation, rather than the homogenous root distribution used in all other simulations of this investigation and used in previous modelling studies (Duncan et al., 2018a, 2018b). The purpose of this was to investigate whether using root surface area density information from the XCT imaging might address discrepancies between the imaging results and simulations that used homogeneous root distribution for the flat surface geometry. This additional modelling simulation and details of the image processing methodology for the root segmentation and surface area density quantification are detailed in the Supplementary Materials in File S1.

2.6 Resistance sensors for spatial soil moisture

Resistive soil moisture sensing (RSMS) was applied here to assess spatial soil moisture (Zazueta, Xin, Smajstrla, & Carrillo, 1994). Duplicate columns were made for the RSMS experiments as RSMS probes are physical structures that could create macropores in soil. RSMS-related macropores could act as preferential pathways that would enable faster movement of contrast media and bias the measured distances in the images. The RSMS experiments featured the same combination of treatments as the imaged columns (Table 1). The custom-built RSMS system consisted of a Raspberry Pi Zero W (Raspberry Pi Foundation, Cambridge, UK) connected to a soil moisture probe (The Pi Hut, Haverhill, UK) via an analogue to digital converter (ADS1015, Adafruit, New York City, NY, USA) that recorded analogue voltage impedance between forks of the probe as a proxy for soil moisture. In each column were three soil moisture probes, which each had a width of 2 cm and fork length of 3 cm. The first probe was placed in the column centre, the second halfway to the outside of the column and the third 1 cm in from the column edge. Probes were placed vertically down through the soil so that soil just covered the top of the probe fork.

The RSMS system was constructed from the design by The Pi Hut (The Pi Hut, 2019) and the Python code (Python version 2.7) used for recording voltage impedance values was based upon the Python code “Adafruit_ADS1x15” (Adafruit), which is open source and available on GitHub (Fried, Townsend, & Sklar, 2013). Similar methodologies have been used numerous times for soil moisture sensing applications (Chate & Rana, 2016; Ishak, Abd Malik, Latiff, Ghazali, & Baharudin, 2017; Jadhav & Hambarde, 2016). The published Python code was modified for this experiment to take voltage recordings on the hour for 5 days, 4 weeks after transplanting seedlings into the columns for
planted treatments (equivalent to the time of XCT imaging in imaged columns). The device was calibrated to ensure the accuracy of recordings and correspond the measured voltage to soil moisture values. Full details of the RSMS probe calibration and specifics of the data recorded by probes are in the Supplementary Information in File S1. SD is reported alongside the mean volumetric water content (VWC) in the format: mean VWC ± SD. A one-tailed t-test assuming unequal variance was used to assess significant difference where significant difference was considered $p < .05$.

### 2.7 Implementation of model

We used the water-solute-pond model developed in Duncan et al. (2018a), which is used to study water and solute movement in a cross-section of a ridge and furrow (or flat) soil surface geometry. The model consists of a coupled system of partial differential equations (PDEs) and ordinary differential equations (ODEs) that describe water and solute movement, and surface ponding in a ridge and furrow system.

Within the model the movement of water in soil is described by the effects of capillary forces, pressure gradients and gravity, all of which are coupled via a feedback loop to the pond depth on the soil surface. The pond depth is described by a combination of surface runoff, rainfall and infiltration into the soil. Furthermore, the transport of solutes, that is, contrast media in soil under the influence of water movement, is also included. The mechanisms driving solute movement are described by the processes of diffusion and advection, which are influenced by the movement of water and the resulting pressure gradients that form in the soil. The diffusivity of the solutes considers the diffusivity of iodine in free water under different soil saturation conditions and a tortuosity impedance factor. This allows for a coupled system of equations to describe the simultaneous movement of water and solutes in soil. It should be noted that we assume solutes do not create osmotic pressure gradients influencing fluid flow, that is, water movement influences solute movement, but not vice versa. Furthermore, for the scales and rates of the fluid flow and the consideration of advective fluxes in the model, we neglect hydromechanical dispersion, which could more significantly impact solute transport on larger scales.

The model described is developed for a generalized curved soil surface, that is, to account for the ridge and furrow geometry. However, this can be easily adapted for a flat surface. The details and necessary equations for the model used for this investigation can be found in the Supplementary Information in File S1. For a full derivation and validation, see Duncan et al. (2018a).

### 3 RESULTS

#### 3.1 Contrast assessment

The contrast assessment of the XCT images revealed that the contrast media provided adequate contrast against both the soil and the Eppendorf tube containing the distilled water at all concentrations of the dilution series (Figure 3). However, it was found that concentrations of 222 mg iodine mL$^{-1}$ and above were vulnerable to crystallization. For these reasons, the 185 mg iodine mL$^{-1}$ contrast media concentration was determined to be the suitable concentration for application in this investigation: it produced sufficient contrast against both soil and the tube of distilled water whilst not being vulnerable to crystallization. Concentrations as low as 37 mg iodine mL$^{-1}$ at least (a fifth of the concentration applied to the soil surface in the imaging experiments) provided sufficient contrast against soil and water so as to be segmented by the grey value threshold during the image processing.

#### 3.2 Ridge and furrow geometry overview

#### 3.2.1 Experimental results

The XCT image results of non-ponded treatments indicated that roots impede the infiltration depth of the contrast media (Figure 4). In the ridge and furrow system with a plant but without ponding, the contrast media
infiltrated to an average depth of $3.88 \pm 2.53$ mm and a maximum depth of 10 mm over the course of the 4 hr (Figure 4b). When no plant was present, the infiltration of the contrast media was greater - to an average depth of $9.98 \pm 3.3$ mm (Figure 4a). In ridge and furrow treatments with ponding and plants, the impedance of contrast media infiltration depth was varied (Figure 4d). In the ridge, the infiltration depth was less than 10 mm in two of the three replicates. However, in the furrow the infiltration depth was between 15 and 25 mm. This is further than in the planted systems without ponding (Figure 4b). The pattern of contrast media infiltration in the planted system with ponding (Figure 4d) was in many cases similar to that of both the ponded and non-ponded systems with no plant (Figure 4a,c). There is some variation between replicates within the imaging experiments (Figures 4 and 7).

**3.2.2 | Simulation results**

In the model, the transport depths for the planted ridge and furrow simulations without the addition of ponding was uniformly 10 mm from ridge to furrow (Figure 5), which is similar to the maximum depth observed in the imaging (Figure 4b). However, the
numerical simulations did not capture variation in contrast media infiltration depth from ridge to furrow as observed in some imaged replicates for this treatment. Also, unlike the imaging results, the depth of contrast media infiltration observed in simulation results was the same in the systems with no plant and no ponding as in the systems with a plant and no ponding. Images of the planted ridge and furrow system with ponding displayed some differences in contrast media infiltration pattern compared to the numerical simulations. The 2D resliced images showed that the infiltration depth in the furrow was generally greater than in the ridge (Figure 4d), which is consistent with the numerical simulations (Figure 5). The imaged contrast media
infiltration pattern was observed to be similar for the systems with a plant and ponding (8.99 ± 4.76 mm), with ponding but no plant (11.61 ± 6.99 mm) and the system with no plant and no ponding (9.98 ± 3.3 mm) (Figure 4a,c,d). This was not true of the simulations where the results for these treatments were different. In the simulation for the system with a plant and no ponding the solute in the furrow remained considerably nearer to the surface than for the other two treatments.

3.3 | Flat geometry overview

3.3.1 | Experimental results

The infiltration pattern was complex for the flat treatments. There was evidence of an inward movement of contrast media horizontally toward the centre of the column in the flat planted treatment without ponding (Figure 6); this is particularly visible in the time lapse images of this treatment (Figure S9). The contrast media...
at the edges of the columns, that is, furthest from where the rice seedling was planted, appeared to move freely downward in the column (Figure 7b). In the planted system with ponding the infiltration depth of the contrast media was greater (16.19 ± 6.99 mm) than in systems without ponding (5.41 ± 3.38 mm) (Figure 7d). The infiltration patterns observed in the imaged flat system with no plant and no ponding were variable (Figure 7a) and the SD for infiltration depth was high (6.99 ± 4.25 mm).

3.3.2 | Simulation results

When the patterns and depth of contrast media infiltration in imaged flat systems were compared to those of the simulated flat systems with homogeneous root distribution, disparities in infiltration patterns were apparent. The depth of infiltration was generally observed to be non-uniform from the edge to the centre of the column in the imaging experiments (Figure 7), whereas the simulation results showed no horizontal variation in infiltration depth (Figure 8). In the imaging results, the infiltration depth in the centre of the planted system with no ponding was up to 10 mm in the centre and 20 mm at the edges, whereas in the simulation results the infiltration depth was horizontally uniform. However, in the additional simulation, which instead used root distribution data extracted from XCT imaging results, a non-uniform infiltration depth can be observed (Figure S7 in File S1). The simulation results for the planted flat system with ponding suggested that contrast media infiltration would be uniform and to a greater depth (60 mm) than observed in the imaging experiments (16.18 ± 6.99 mm) (Figures 7d and 8b).

3.4 | RSMS spatial soil moisture

The soil moisture values indicated two trends. Firstly, soil in both flat systems and ridge and furrow systems containing plants was significantly drier than in the systems without plants. For soil moisture values captured 1 hr before each watering event, there was significant difference between the soil moisture in the planted (11% VWC ± 0.057) and non-planted systems (20.4% VWC ± 0.026). This was true of both flat ($p = 8.65 \times 10^{-8}$) and ridge and furrow ($p = .0006$) surface geometries.

The second observable trend was that in planted systems, with either surface geometry, the probes nearest to the centre of the columns recorded the lowest soil moisture values. The central region of the columns was likely to be the most root-dense, as was observed in the image analysis of the root surface area density for replicate one of the planted flat system with ponding (segmented to parameterize the additional model simulation with non-homogenous root distribution). Due to the labour-intensive nature of this image processing, it was not possible to segment the root surface area density in other planted columns. However, most roots were found in the central region of the columns upon visual inspection of the other planted replicates. In the intervals between watering events the soil in the centre of the columns dried at a faster rate than at the edges of the columns. For soil moisture values captured 1 hr before each watering event, there was significant difference between the soil moisture in the centre of the column and at the edges of the column for both planted flat ($p = .00115$) and planted ridge and furrow ($p = .00257$) systems. The full data are displayed in Figure S6 in File S1.
4 | DISCUSSION

The aim of this study was to capture the movement of a solute through ridge and furrow and flat soil surface geometries using XCT imaging of contrast medium as it infiltrated soil columns. The treatments applied to the experimental systems were similar to those investigated using mathematical modelling by Duncan et al. (2018a, 2018b). The contrast medium iopamidol (trade name: Niopam) was applied to the surface of each of the columns. The position of the contrast medium was traced over a period of 4 hr using XCT. These experimental results were then compared to numerical simulations, initially developed by Duncan et al. (2018a, 2018b), although adapted to directly represent the experimental system.

4.1 | Ridge and furrow surface geometry

In the planted ridge and furrow treatment without ponding the infiltration depth of the contrast media was minimal and the contrast media accumulated near the soil surface in the ridge as was hypothesized (Figure 4b). The infiltration depth of the contrast media in the non-planted ridge and furrow system was substantially greater in both the ridge and furrow regions (Figure 4a). However, in the simulation results the infiltration was the same in the systems with no plant and no ponding as in the systems with a plant and no ponding. This is possibly because of the difference in soil moisture in experimental columns compared with model simulations. The RSMS results had suggested that the ridge of planted columns was significantly drier than non-planted columns, which is likely to be the result of root water uptake. If this were the case then the advection induced by the root water uptake could have also influenced the reduced vertical infiltration in the planted systems. This is in agreement with previous modelling investigations (Duncan et al., 2018a, 2018b). However, it should be noted that, although RSMS results can give some insights into soil moisture, the RSMS results do not directly distinguish between the effects of root water uptake and evaporation. Therefore, in future it would be useful to explicitly record transpiration rate and/or root water uptake data in order to better decipher the influence of these factors.

In planted ridge and furrow systems with ponding, the infiltration depth in the furrows was greater than in the planted ridge and furrow systems without ponding (Figure 4b,d). The infiltration depth in the furrow was more similar to the columns that contained no plant at all when ponding took place (Figure 4a,c). This suggests that ponding can negate the capacity of roots to hold the solute near the surface of the soil. This deeper infiltration of contrast media in the furrow for ponded systems was also observed in the simulation results (Figure 5). This suggests that the roots can have an observable effect on reducing the solute transport depth, particularly in regions nearest to where the rice seedling was planted. It should also be noted that in Replicate 1 of the ridge and furrow system without a plant or ponding there was the appearance of some minimal initial ponding in the furrow. This was likely to be caused by soil surface run-off of contrast media from the ridge into the furrow. This soil surface run-off was not captured in the model as it assumed solute application is normal to the soil surface. These results could explain why some previous agronomic studies have found ridge and furrow geometries to be particularly susceptible to solute leaching (Kung, 1988; Leistra & Boesten, 2010; Smelt et al., 1981). A period of significant rainfall or soil surface run-off of solutes during these agronomic studies could have exacerbated the solute leaching effect in the furrow.

4.2 | Flat surface geometry

The pattern of contrast media infiltration captured during XCT imaging of the planted flat system without ponding did not reflect that of the model simulations which featured homogenous root distribution. The contrast media accumulated in the centre of the column in the imaging experiments (Figure 6). The numerical simulations for this treatment had suggested that the contrast media infiltration would be horizontally uniform (Figure 8). In the additional simulation for the planted flat system without ponding, which featured the root distribution from the imaging results, this pattern of accumulation in the root-dense centre of the columns can be observed, suggesting a greater density of roots may have influenced this accumulation (Figure S7 in File S1). This would appear to support the suggestion that a greater density of plant roots in the centre of the imaged columns could induce an accumulation in the centre of the columns. However, given that the small number of replicates and the labour-intensive nature of the root segmentation procedure meant that only one column could be analysed, this cannot be stated with certainty.

In the planted flat system without ponding the centre of the columns was also the driest region, as indicated by the RSMS results (Figure S6 in File S1). This central accumulation of contrast media in this treatment may have been further influenced by the significantly drier soil surface in the experimental samples than in the model simulations prior to contrast media applications. This was likely to be due to a combination of drainage,
surface evaporation and root water uptake effects (Hanks, Klute, & Bresler, 1969; Nye & Tinker, 1977). The low soil water matric potential may have contributed to this water redistribution analogous to soil water sorptivity effects (J. Philip, 1957; J. R. Philip, 1969; Wooding, 1968). The drier soil subdomain could have induced a strong water potential gradient (Nye & Tinker, 1977), hence, the contrast medium was redistributed through the soil toward the dry central region. This could explain why an inward movement of contrast media is experimentally observed in the flat planted system without ponding (Figure 6). In the system without ponding, the contrast media near to the centre was likely to be drawn further inward by this water potential gradient, which resulted from the advective root water uptake.

In this treatment the contrast media was also observed to infiltrate to a depth of up to 30 mm through the soil at the edges of the column (Figure 7b). It is possible the contrast medium at the edges of these columns could have been too far from where the rice seedling was planted to be observably influenced by the roots and so was able to move freely deeper into the soil. It is also possible that the deeper infiltration at the edges of the column is the result of an edge effect at the column wall, as this is also observable in the flat system without a plant or ponding. However, it should also be noted that in the RSMS experiments for both the flat system with a plant and without a plant the soil in the centre of the columns was frequently drier than at the edge (Figure S6 in File S1), possibly a result of surface evaporation. If the central soil was drier prior to the application of the contrast medium then the capillary action of the soil may have held more of the contrast medium fluid in the centre nearer to the surface. However, there is ultimately too much variation between the three replicates to determine the cause with certainty.

In the systems with a plant and ponding the contrast medium appears to infiltrate to a greater depth, particularly in the centre of the columns, than in those with no plant but which undergo ponding (Figure 7c,d). This is potentially a result of the ponded water forcing the contrast medium deeper into root-generated pores (Millere, Le Bayon, Lamy, Gobat, & Boivin, 2009; Phillips, 2007; Ruiz, Or, & Schymanski, 2015). This enhanced flow through root-generated pores is not included in the model. When there is no ponding treatment applied to the soil surface, advection of the root water uptake remains dominant. However, when water is applied to the soil surface for the ponding treatment it is possible that the hydrostatic pressure of this surface water drives the contrast medium down through these root-generated pores. Therefore, advection driven by root water uptake to hold the contrast medium near the surface may be negated by the hydrostatic pressure from ponding water. In the equivalent ridge and furrow systems this is potentially not observed because the pond in those systems largely accumulates in the furrow, whereas in the flat systems the ponding occurred across the surface. Therefore, in the flat systems the ponding is over the area of the surface from which the plant emerges and is able to enter root-generated pores with more ease, thus forcing the contrast medium deeper. This is not captured by the continuum-based modelling methodology used in this study because it assumes uniform root distribution and does not consider anomalous pore structures that might have been caused by root-induced bioturbation.

4.3 Agricultural implications and further work

The results of this work have several implications for the application of soluble agrochemicals to soil systems with either flat or ridge and furrow surface geometries. However, these potential implications should be viewed in the context of the limitations of the scale and technology deployed in this investigation. For example, there is variation between replicates within the imaging experiments (Figures 4 and 7 and Figure S4 in File S1). The use of XCT technology meant that the replicate number was constrained to three. Given the exploratory nature of the study (testing eight different treatments), we were limited by the cost and availability of XCT facilities capable of imaging samples as physically large as the soil columns. Individual scenarios that are more specific in nature warrant focus on individual treatments with a greater number of replicates. This would also facilitate a greater use of statistical testing to analyse trends between treatments that could not be validly implemented within this investigation.

In addition, the physical downscaling of the ridge and furrow system, necessary for XCT imaging, has implications for the applicability of the results of this investigation to agricultural field systems. We maintained a ridge height to ridge width ratio that was equivalent to that of field systems; however, in field systems the height of ridges is typically between 15 and 60 cm, whereas the width of ridges is typically between 30 and 60 cm (X.Y. Li & Gong, 2002; Tian et al., 2003). This physical downscaling would have, for example, reduced the surface area of the soil surface, which would have had implications for evaporation of water from the soil. The heterogeneous aspects of soil systems also have implications for comparisons. For example, the soil aggregate sizes used in this investigation were more homogenous than would be expected in the field, although this was a necessary
control measure for the reproducibility of the experiments. This could have implications for some aspects of the hydromechanics of the system, such as the extent of capillary action taking place as well as hydromechanical dispersion. Previous studies have indicated that the relative influence of soil heterogeneity on solute movement can be considerable, for example compared to advection from root water uptake mechanisms (Koch et al., 2019; Schroder, Javaux, Vanderborght, Steffen, & Vereecken, 2012). A final additional suggestion for future studies is that it could be worthwhile to incorporate the interaction between evapotranspiration and the influence it has on mobilizing contrast media in soil. By utilizing a root transpiration model, the Penmen Monteith equation (Monteith, 1965) could potentially be linked to the transport of contrast media in the soil domain.

Given that the results indicate that when ponding takes place in a ridge and furrow system solutes will infiltrate to a considerable depth, it might be important to consider the timing of solute application with respect to anticipated rainfall. Results suggest that farmers may wish to consider how early into the growing season they need to apply solutes, particularly in ridge and furrow systems. If solutes are applied early in the growing season when root systems are less developed, then the capacity for the advective force of plant roots to hold the solute near the soil surface may be reduced (Crush, Waller, & Care, 2005; Somma, Hopmans, & Clausnitzer, 1998).

With regards to flat planting systems, the density of planting and accuracy of solute application could be important for reducing solute leaching. The results of this investigation suggest that the effect of plant roots on preventing solute leaching could be localized to root zones. In addition to our observations, previous agronomic studies have observed that greater root density reduces solute leaching (Hauggaard-Nielsen, Ambus, & Jensen, 2001; Mariotti, Masoni, Ercoli, & Arduini, 2015). As such, if solutes are applied to areas of soil with low root density then leaching could be exacerbated.

5 | CONCLUSIONS

It was hypothesized that for treatments containing a plant, the contrast media would accumulate near to the soil surface. It was also hypothesized that where ponding is present, it could force deeper infiltration of solutes. In summary, we observed that plant roots have a significant impact on reducing the depth of vertical solute transport. This is particularly true of plants growing within ridge and furrow systems; where plants were absent from these systems the depth of contrast media infiltration was observed to be greater. The effect of roots on solute infiltration was, however, observed to be relatively localized to root-dense regions. We also observed that ponding induced deeper solute infiltration in flat soil surface geometries that contained a plant, thought to be a result of hydrostatic pressure from ponding forcing contrast media into root-generated bio-pores. The results indicate that plant roots, soil surface structure and soil moisture can affect the infiltration depth of solutes. These results indicate that the timing of solute application with anticipated rainfall could be an important consideration for the agricultural industry. However, there is variability within the results because the number of replicates was limited to three due to the exploratory nature of the study and the availability and cost of XCT facilities capable of imaging physically large soil column samples. Giving consideration to the limitations imposed by the scale of the system and technology used for this investigation, further work is required before implications for agriculture can be stated with certainty.

DATA AVAILABILITY STATEMENT
Data supporting this study are publicly available from the University of Southampton repository via the doi: https://doi.org/10.5258/SOTON/D1137

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CONFLICT OF INTEREST
The authors have no competing interests.

AUTHOR CONTRIBUTIONS
C.P.S., S.J.D. and T.R. designed the study. C.P.S. collected the XCT image data. C.P.S. developed the image processing protocol with advice and input from K.W. C.P.S. undertook the image processing and analysis of XCT data. S.J.D. developed and undertook the modelling with input from S.R. C.P.S. constructed the Raspberry Pi soil moisture probe setup and undertook the RSMS experiments. C.P.S. wrote the manuscript and all other authors provided critical revision and approval before submission and publication.
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**SUPPORTING INFORMATION**

Additional supporting information may be found online in the Supporting Information section at the end of this article.

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