

NON-INVASIVE HYDRODYNAMIC CHARACTERIZATION OF SOILS USING INTEGRATED ELECTRICAL RESISTIVITY AND X-RAY COMPUTED TOMOGRAPHY

MIHAI OCTAVIAN CIMPOIAȘU, BSc (Hons)



*Thesis submitted in accordance with the requirements for the degree of
Doctor of Philosophy*

Division of Agriculture and Environmental Sciences
School of Biosciences

June 2020

Abstract

Current world-wide pressures on farming production can be ameliorated by a more efficient use of agronomical resources. As a root zone is a fundamental component of any agrosystem, it is of high importance to develop a deeper understanding of its processes. One of the key elements of the root zone environment is soil structure, which has a great impact on the capacity of soil to conduct or retain water. This plays a vital role in plant's hydration and nutrient accessibility. As agricultural procedures are continuously developing we require novel methods of monitoring and quantifying their effect on soil structure.

Electrical Resistivity Tomography (ERT) is a technique which allows minimally invasive imaging of soil's interior. In the study of soil processes, it is usually applied to monitor changes in soil pore solution concentration, both in space and time. X-ray Computed Tomography (CT) is a method recently adapted for the non-invasive study of soil structure often at high resolutions (e.g. below 50 μm). This research aimed to formulate a methodology that combines the capabilities of ERT and X-ray CT in order to enhance our interpretation of soil hydrodynamics by quantitatively linking soil structure and soil pore solution spatiotemporal variability. Furthermore, it intended to apprehend the effects of soil structure on solute infiltration and retention at three different scales: μm scale (observing soil microaggregates), cm scale (observing soil columns) and dm scale (observing agricultural field plots).

At the smallest scale, different amounts of distilled water were added to receptacles (2.5x2.5x7 cm) filled with soil. This allowed a distinct water redistribution between samples and subsequent measurements enabled the formulation of a relationship between X-ray absorption and electrical resistivity. This param-

eter link enables the quantitative crossover between the two soil assessment techniques. At the intermediary scale, columns of soil were X-ray CT scanned and concurrently subjected to the infiltration of a saline solution in near-real time. This allowed patterns of solution percolation to be directly correlated with air-filled porosity distribution. This methodology was applied to two case studies investigating the hydrodynamics of soil columns 1. at different levels of compaction and 2. extracted from agricultural fields under different durations of zero-tillage (ZT) practices (2, 7 and 12 years). The first application revealed and quantitatively correlated the proportionality between areas of underdeveloped macroporosity and lower solution percolation. The second application revealed that soil under ZT for 7 years experienced an initial increase in bulk density, whereas older, 12 years of ZT soil experienced a macroporosity restoration. However, the overall bulk solute dispersivity increased continuously over time indicating preferential flow, but for the 12 year ZT soil, the amount of immobile water content was reduced. Finally, at field scale, hydrodynamics of charcoal enhanced soils were investigated over the course of six months. ERT revealed this soil type had larger variabilities in electrical resistivity than its naturally occurring counterpart. This effect was explained in the context of the X-ray CT analysis of its structure, which revealed a more developed macroporosity, spatially correlated with standard deviation in electrical resistivity. This work has shown what potential a corroborative assessment between two tomographic methods, ERT and X-ray CT, holds for the study of soil's hydraulic properties, revealing new insights about the effect of compaction, ZT and charcoal. Hereafter, future research can expand this methodology for the assessment of plant-soil interactions and soil hydraulic behaviour under different environmental conditions (e.g. soil texture, temperature, root type). Furthermore, the association between the two tomography methods enables

the user to visualise solute movement in soil in near real-time together with the solute's pathway, determined by the soil's structure. This monitoring approach sets the scene for future work looking to obtain a finer and more discrete parametrization of the soil hydraulic space, which in turn would contribute to a better hydrodynamic representation of soils.

Funding declaration

This work was supported by the Biotechnology and Biological Sciences Research Council; and the Natural Environment Research Council [grant number NE-M009106-1], through the Soils Training and Research Studentships (STARS) Centre for Doctoral Training grant to Mihai Octavian Cimpoiăşu. STARS is a consortium consisting of Bangor University, British Geological Survey, Centre for Ecology and Hydrology, Cranfield University, James Hutton Institute, Lancaster University, Rothamsted Research and the University of Nottingham.

Publications in peer-reviewed journals:

1. Cimpoiăşu, M. O., Kuras, O., Pridmore, T., & Mooney, S. J. (2020). Potential of geoelectrical methods to monitor root zone processes and structure: A review. *Geoderma*, 365. <https://doi.org/10.1016/j.geoderma.2020.114232>
This publication has been used in order to formulate Chapter 2.

2. Cimpoiăşu M.O., Kuras O., Pridmore T. and Mooney S.J. (2020). A Pedophysical Relationship between X-ray Computed Tomography and Electrical Resistivity Data. *Journal of Environmental and Engineering Geophysics*, 25: 181-187. <https://doi.org/10.2113/JEEG19-079>

This publication has been used in order to formulate Chapter 4.

Acknowledgments

Before I began this project never have I imagined just how many wonderful people was I about to meet and how much they were going to impact my life.

Firstly, I am very grateful to my supervisors: Dr. Oliver Kuras, Prof. Sacha J. Mooney and Prof. Tony Pridmore, who offered me continuous advice and moral support. In particular, I would like to express my deepest thanks to Oliver, who believed in me from day one and who showed me what it takes to be a dedicated researcher.

My family: Mama, Tata, Ștefan, Tataie, you were like a rock of great tenacity (a compliment coming from a geophysicist). No matter how hard life was, you were there for me, motivating me to be the best version of myself and for this I thank you.

To my PhD corner fellows and good friends: Jim, Luke, Jimmy, Jess, Tom, thank you for brightening up my days and making me feel that PhD is a journey that we can take on together.

I also want to thank everyone who made STARS doctoral centre possible, especially Phil Haygarth, Andy Tye and Olivia Lawrenson, and my fellow STARS students: Lewis, Dan, Alex, Emily, Chris, Rosanne, Sam, a truly fantastic network of people that promotes inspirational science of the environment.

I must express my gratitude to everyone in the GTom team at the BGS: Jon, Paul, Phil, Russell, Seb, Arnaud, Cornelia and Harry. You will always be my definition of a fantastic team, which I was extremely lucky to be part of.

Further, I wish to thank all the great scientists that supported me with such valuable knowledge in this journey, from the University of Nottingham Hounsfield facility: Craig Sturrock and Brian Atkinson and from the University of Liège: Sarah Garré, Fred Nguyen and Edmundo Placencia.

For my life long friends: Ioan, Alex, Cristi, Anda, Maco, Marius, Robert, Cipi, I am grateful. You have got me through some very tough times just by making me laugh and encouraging me when I felt down. Finally, there are very few words to describe how much I owe to my amazing partner, Gülден Madi. Having such a beautiful relationship made me a better person and every single one of my achievements is because of your devotion.

In the memory of my grandmother

În memoria bunicii mele

Contents

1	Introduction	1
1.1	Project overview	1
1.1.1	The Specific Problem	1
1.1.2	Addressing the problem	1
1.2	Hypotheses	2
1.3	Aims and objectives	3
2	POTENTIAL OF GEOELECTRICAL METHODS FOR MONITORING ROOT ZONE PROCESSES AND STRUCTURE: A LITERATURE REVIEW	6
2.1	Abstract	7
2.2	Introduction	8
2.3	Geoelectrical methods and their variability - general principles .	12
2.3.1	Electrical properties of soils and their variability	12
2.3.1.1	Inorganic constituents	12
2.3.1.2	Organic constituents	13
2.3.2	Methods of measuring soil electrical properties	14
2.3.2.1	Complex electrical impedance	14
2.3.2.2	ERT	15
2.3.2.3	IP	16
2.3.2.4	Relationship between geoelectrical methods . .	19
2.3.3	Translating geoelectrical measurement into root zone properties	20
2.3.3.1	Resolving pedological parameters	21
2.3.3.2	Resolving root system parameters	22

2.4	Monitoring processes and resolving structure in the root zone . .	23
2.4.1	Root zone water dynamics	24
2.4.1.1	Ex-situ studies	24
2.4.1.2	<i>In-situ</i> studies	28
2.4.2	Root structural and functional properties	32
2.4.2.1	Woody roots	32
2.4.2.2	Herbaceous roots	35
2.4.3	Root zone conceptual models	36
2.4.3.1	Modelling root zone water dynamics	37
2.4.4	Other applications	40
2.4.4.1	Resolving pedological parameters	40
2.4.4.2	Plant phenotyping	41
2.5	Discussion and future outlook	42
2.5.1	Choice of geoelectrical method	42
2.5.2	Acquisition set-up and inversion algorithm	44
2.5.3	Electrical response from woody versus herbaceous roots .	45
2.5.4	Knowledge gaps in pedophysical relationships	46
2.5.4.1	Formulating pedophysical relationships in the lab	46
2.5.4.2	On the variability of pedophysical relationships	47
2.5.4.3	Computational approaches in pedophysical cal- ibration	48
2.5.5	Enhancing the geoelectrical characterization of the root zone	49
2.5.5.1	Use of complementary datasets	50
2.5.5.2	A-priori information about the root zone	51
2.5.6	Enhancing root zone conceptualisation	53
2.5.6.1	Root analogue electrical circuit models	53

2.5.6.2	Separating contributors to the electrical response	54
2.5.6.3	Integrating plant hydrology models and geo- electrical measurements	55
2.6	Conclusions	58
3	General method description	61
3.1	ERT	61
3.1.1	Sample selection	61
3.1.2	Forward model	62
3.1.2.1	Model mesh	63
3.1.2.2	Acquisition sequence	64
3.1.2.3	Sensitivity and Noise	65
3.1.3	Error processing	66
3.1.4	Inversion model	67
3.1.4.1	Static inversion	68
3.1.4.2	Time-lapse inversion	68
3.2	X-ray Computed Tomography (CT)	71
3.2.1	Measurement principles	71
3.2.2	Data Acquisition	73
3.2.2.1	Scanner and experiment settings	73
3.2.2.2	Sources of error	73
3.2.3	Data processing	73
3.2.3.1	Appropriate image acquisition	73
3.2.3.2	Image processing	74
3.2.3.3	Soil structural parameters	77
3.3	An experimental design for a joint ERT-CT experiment	78
3.3.1	Resolving a saline tracer using X-ray CT	78
3.3.2	Preliminary conclusions	84

3.4	Outline of experimental work	85
4	A PEDOPHYSICAL RELATIONSHIP BETWEEN X-RAY COMPUTED TOMOGRAPHY AND ELECTRICAL RESIS- TIVITY TOMOGRAPHY DATA	86
4.1	Abstract	86
4.2	Introduction	87
4.3	Theoretical background	89
4.3.1	Basic principles of ERT and X-ray CT	89
4.3.2	Known pedophysical models	90
4.4	Methodology	91
4.4.1	Soil sample preparation	91
4.4.2	Electrical and CT measurements	92
4.4.3	CT image processing	92
4.4.4	Formulating a pedophysical link	94
4.4.5	Enhancing BR predictions based on CT estimates	95
4.5	Results and Discussion	96
4.5.1	MC variability	96
4.5.2	Implications of the pedophysical fit	97
4.5.3	Improving BR calibration	98
4.5.4	CT-ER relationship	99
4.6	Conclusions	99
5	HYDRODYNAMIC CHARACTERIZATION OF SOIL COM- PACTION THROUGH AN INTEGRATED ERT AND X-RAY CT APPROACH	101
5.1	Abstract	101
5.2	Introduction	102

5.3	Methodology	104
5.3.1	Soil sampling	104
5.3.2	Saline solution infiltration	104
5.3.3	X-ray scanning and image processing	106
5.3.4	Pedophysical model	107
5.3.5	Quantitatively link ERT and X-ray models	108
5.3.6	Inserting X-ray CT derived pore architecture information in the geoelectrical mesh	109
5.4	Results and Discussion	111
5.4.1	ERT monitoring	111
5.4.2	X-ray CT resolved parameters	113
5.4.3	Enhancing time-lapse geoelectrical models of soil mois- ture dynamics with a-priori X-ray CT derived information	115
5.4.4	Correlation between porespace and change in electrical resistivity	117
5.4.4.1	Qualitative assessment	117
5.4.4.2	Quantitative assessment	119
5.5	Limitations and future perspectives	121
5.6	Conclusions	122
6	ASSESMENT OF THE LONG-TERM IMPACT OF ZT AGRI- CULTURE ON SOIL HYDRODYNAMICS	124
6.1	Abstract	124
6.2	Introduction	125
6.2.1	The impact of ZT practives on soil structure and hy- draulic properties	125
6.2.2	ZT and flow parameters	126
6.2.3	ERT and tillage	127

6.2.4	Literature analysis	128
6.3	Methodology	130
6.3.1	Soil sampling	130
6.3.2	Infiltration monitoring	131
6.3.3	X-ray scanning and image processing	131
6.3.4	Effluent conductivity modelling	132
6.3.5	Percolation porosity	134
6.4	Results and discussion	134
6.4.1	X-ray CT analysis of pore structure	134
6.4.2	CDE and MIM models fit parameters	138
6.4.3	Inferences from ERT time-lapse infiltration monitoring .	139
6.4.4	Discussion	143
6.5	Conclusions	145

7 INTEGRATED ERT AND X-RAY APPRAISAL OF PORE WATER DYNAMICS IN CHARCOAL ENRICHED SOILS 147

7.1	Abstract	147
7.2	Introduction	148
7.3	Methodology	149
7.3.1	Soil sampling	150
7.3.2	X-ray scanning and image processing	152
7.3.3	Field-scale ERT	154
7.3.3.1	Measurement acquisition	154
7.3.3.2	Adjacent soil physicochemical indicators	155
7.3.3.3	Electrical resistivity raw data processing and inversion	155
7.3.4	Exploring the electrical polarization	159
7.4	Results and discussion	160

7.4.1	X-ray derived structural indicators	160
7.4.2	Time-lapse difference ERT	165
7.4.3	Correlations between resistivity models, structural pa- rameters and soil physicochemical properties	168
7.4.3.1	Resistivity and weather data	168
7.4.3.2	Resistivity and structural parameters	168
7.4.3.3	Pore structure and macroaggregation	173
7.4.3.4	Pedophysical calibration and electrical polar- ization	174
7.4.4	Limitations and future perspectives	176
7.5	Conclusions	176
8	GENERAL DISCUSSION AND CONCLUSIONS	178
8.1	Geophysical assessment of soil hydraulic properties across scales	179
8.1.1	Small scale interaction between structure and electrical resistivity	180
8.1.2	Observing the impact of macroporosity on column scale flow	181
8.1.3	Perspectives and limitations of field scale assessment . .	183
8.2	Outlook	184
8.2.1	Electrical impedance - the whole picture of the electrical response	185
8.2.2	Roots - observation and monitoring	186
8.2.3	Towards an interdisciplinary study of soil	187
	Appendix A	212
	Appendix B	220

List of Abbreviations

BTC Breakthrough Curve

CEC Cation Exchange Capacity

CHAR Charcoal amended soils \ Title of a University of Liège research project
(Garré et al., 2014)

CT Computed Tomography

ConT Conventional Tillage

EC Electrical capacitance

ECM Electrical Capacitance Method

EIS Electrical Impedance Spectroscopy

EIT Electrical Impedance Tomography

EMI Electro-Magnetic Imaging

ERT Electrical Resistivity Tomography

FDIP Frequency-domain Induced polarization

GPR Ground Penetrating Radar

IP Induced Polarization

RWU Root water uptake

SIP Spectral Induced Polarization

TDIP Time-Domain Induced Polarization

TDR Time Domain Reflectometry

WS Waxman-Smiths model

ZT Zero Tillage

List of Tables

3.1	Studies using KI as a tracer in CT scanning and their corresponding experimental conditions	83
4.1	Laboratory determined parameters used to compute WS and XA relationships	95
A.1	Research articles mentioned in Chapter 2 literature review and corresponding instrumentation settings mentioned in their methodology.	219
B.1	Research articles mentioned in Chapter 2 literature review and corresponding models mentioned in their methodology.	227
C.1	Research articles used in the Chapter 6 literature analysis. ZT or CONT indicates the article quotes a bigger value for the zero-till (no-till) or the convectional-till samples respectively. NC (no change or the difference between ZT and CONT practices is not significant). RT stands for reduced-till.	241

List of Figures

2.1	Diagram of key theoretical characteristics associated to geoelectrical methods described. The dotted line connects the scheme branch with the corresponding geoelectrical method.	20
2.2	Laboratory set-up of a geoelectrical soil column monitoring experiment A) Soil column lateral view B) Horizontal Cross-section view. Adapted from Garré et al. (2011), (Koestel et al., 2007). .	25
2.3	Three dimensional solute concentration distribution in 6 stages of infiltration. Corresponding time-steps are listed in the top-left corner. Extracted from Koestel et al. (2008).	27
2.4	Field acquisition pseudosection line used for ERT surveys. Electrodes are grouped in a Dipole-Dipole sequence.	30
2.5	2D ERT field resistivity distribution variation with time under crops of Maize left and Sorghum right. Extracted from Srayeddin and Doussan (2009).	32
2.6	Resistivity increment percent differences overlapped on 3D rendering of laser-scan point cloud of Pinus Pinea root system. a) 3D view, b) 25 cm below surface, c) vertical section. Extracted from Zenone et al. (2008)	34
2.7	Bar chart indicating number of published articles which use Geoelectrical monitoring methods for the study of root zone processes.	44

2.8	Schematic representation extracted from Postma et al. (2017) representing the model used that couples evapotranspiration, xylem transport and soil water dynamics. a) Soil pedon with the hydraulic head indicated in pseudo-color (left) and three barley root systems (right) taking up water from that column. b) Penman– Monteith equation was used for the simulation of transpiration and evaporation. c) Section of the simulated root network showing its edges and vertices d) Network model used for the simulation of water flow through the roots (Alm et al., 1992) e) Water transport in three dimensions in the soil was simulated by solving the Richards equation, which combines Darcy’s law with mass conservation, using the finite element method.	56
2.9	Stages of an interdisciplinary strategy to perfect root zone geo-electrical monitoring and corresponding conceptual models. In blue: Main steps of the strategy flowchart; In green: Existent auxiliary methods or models that can be used; In orange: Mathematical algorithms needed; Black arrow: Indicates the step succession; Dashed double arrow: Underlines the need of consistency between the two steps; Orange double arrow: Implies a comparison between the results.	58
3.1	Synthetic Electrical Conductivity model. Cartesian grid values are in metres. A: Model outline, B: Model mesh, C: Vertical forward model result clip [S/m]. Color scale indicates the conductivity of the model.	64

3.2	Sensitivity diagrams of electrode configurations (Warm colors indicate higher sensitivity). C1, C2 are the current electrodes and P1, P2 the potential electrodes. Extracted from Dahlin and Zhou (2004).	66
3.3	Error model fit to the apparent resistance reciprocal error and its corresponding weight parameters. Data corresponds to an ERT acquisition on the test column.	67
3.4	ERT inversion models of Electrical Resistivity (Result - [$\Omega.m$]) in 4 stages of KI solution infiltration. The white number indicates the time-step number, recorded 23 minutes apart. The infiltration tube is outlined by the white dotted line and the grey cone.	71
3.5	Examples of two histograms corresponding to the same dry soil sample, but under different scanning conditions.	75
3.6	Scan of kiln sand and further image processing. A: Original scan result, B: Segmented wet sand, C: Classified Connected components, D: Outline of the connected components, E: XY position of the main feature boundary points.	76
3.7	Reconstructed 3D scanned soil volume. Blue depicts the water-filled macropores. Black depicts air-filled macropores.	77
3.8	Scan of sandy loam soil saturated with water and KI. A: the original scan, B: the segmentation results after applying a threshold for water absorption and C: the segmentation results after applying a threshold for KI absorption.	79
3.9	Grayscale image of KI in pure form (A) at 25, 50, 75, 100, 200 mg/ml and in soil (B). Extracted from Grayling (2015).	80

3.10	Scan views of a partly water saturated soil column (Left - top view; Right - lateral view) undergoing KI infiltration. Top view: Veils containing pure water (A), KI solution (C) and infiltration tube containing KI (B). Right view: Veil containing pure water (A) and infiltration tube containing KI (B).	84
4.1	Image showing two cross-sections (I- Widthwise and B- Lengthwise) of a CT reconstructed soil volume. White rectangles indicate the selection area used for image processing. II: Selected area cropped from scan images corresponding to every soil batch. 'A' group corresponds to soil type 1 and 'B' group to soil type 2.	93
4.2	XA: Average GS measurements (circle) fitted by XA estimates (dashed line). Error bars indicate the GS standard deviation within the sample; BR: Resistivity measurements (circle) fitted by BR estimates based on laboratory measurements (dashed line) of MC and based on X-ray CT estimates (down triangle) of MC; Combined: Lab-derived measurements fitted by the new pedophysical relation, Equation (4.5), estimates (dashed line). BR and Combined plots have an assumed 10% error for resistivity estimates.	97
5.1	Schematic of the laboratory soil column experiment. Lateral view: KCl solution infiltration setting. Top view: Electrode arrangement for ERT monitoring.	105
5.2	Soil volume image processing steps. A: Top view cross-section and representative selected area. B: Selected area cropped. C: Sharpen and Median filters applied. D: Threshold applied to segment empty pore space.	107

5.3	Cross-sectional vertical clip of the Left: X-ray CT 3D model of binarized soil. The white structure represents the air-filled pore space on which the surrounding soil in light gray was superimposed Right: model mesh used for resistivity inversion. The red cubes represent the voxel selection used to draw a quantitative correlation between the two datasets. The opaque grey box encloses the sample subvolume subjected to quantitative analysis.	109
5.4	A: Two successive cross-sections of the non-percolating pore space (pores are indicated by black features) B: Pore feature ellipse fitting processing steps - I. Full pore II. Pore outline III. Ellipse fit to the pore outline. C: Reconstruction of the pore channel outline within the geoelectrical model mesh.	110
5.5	Clip of the G1 Column Resistivity model in 4 stages of the high molarity solution infiltration. Dimensions are expressed in cm.	112
5.6	A. Percentage of ERT model cells which changed their resistivity by at least 10 % with respect to the first time-step. Red vertical line denotes time-step 20. B. Effluent breakthrough of solute recorded presented as reduced concentrations. C is measured conductivity, C_i initial conductivity and C_m the 5M KCl tracer conductivity.	113
5.7	Air-filled pore structural parameters as resolved after the soil columns X-ray image processing. In the connectivity density unit formula ΔX denotes the sample's contribution to the Euler number of the sample. * indicates statistical significance (p<0.05)	114

5.8	Extract from a resistivity change inversion model result corresponding to the soil column A: before and B: after including the non-percolating feature zone (green wireframe overlapping the model) in the geoelectrical mesh. The result shows the resistivity change between time step 20 (5 hrs after start) and time-step 1 (15 min after start). Dimensions in cm.	116
5.9	Left: Cropped segmented air-filled pore space. Red outline points towards the areas of interest, areas of underdeveloped porosity. Right: Resistivity model cells which exhibited a change greater than 10% over the top: whole column, bottom: same region cropped for X-ray analysis. Dimensions are expressed in cm.	118
5.10	Relationship between the change in resistivity and soil air-filled porosity. Blue error bars represent the standard error of the mean.	120
6.1	Data distribution of nine soil variables according to previous studies comparing ZT and ConT. <i>N</i> represents the total number of studies referring to every specific parameter. Color legend: 'Green' indicates the proportion of studies which quote an increase for soil under ZT, 'Orange' indicates the proportion of studies which quote an increase for soils under ConT and 'Blue' indicates the proportion of studies which quote No Change (NC).	130
6.2	Top: 2D cross-sectional images (10 cm depth) of three soil samples at different ZT durations. Bottom: Binary correspondent of the same images after the segmentation of air-filled pore space (as detailed in section 6.2.4).	135

6.3	CT resolved structural parameters corresponding to different ZT ages. * indicates statistical significance ($p < 0.05$)	136
6.4	Percolation pore volume structural parameters corresponding to every ZT age. * indicates statistical significance ($p < 0.05$) . . .	136
6.5	Volume subsections of the pore networks corresponding to different ZT ages. Effective percolation (orange) overlaps total porosity (gray).	137
6.6	CDE model fit (blue line) to effluent electrical data (blue dots) with corresponding standard deviations (red discontinuous lines). 0 min marks the start of the high molarity infiltration.	138
6.7	CDE and MIM estimated model flow parameters corresponding to every ZT age. * indicates statistical significance ($p < 0.05$) . .	139
6.8	Comparison between resistivity values resolved from ERT models and effluent recordings. 0 min marks the start of the high molarity infiltration.	140
6.9	Percentage of ERT model cells which changed their resistivity by at least 30 % with respect to the first time-step. 0 min marks the start of the high molarity infiltration.	141
6.10	Soil column ERT inversion results corresponding to the 3 ZT durations at 3 different TS. Minute labels indicate time after start of the last high molarity infiltration stage.	143

6.11	Methods (CT - X-ray CT, ERT - ERT, Flow mod - Flow modelling, Percolation - Percolation analysis) and their corresponding measurable parameters (CT1 - Total porosity, CT2 - Average Pore Size; ERT1 - Bulk soil electrical resistivity, ERT2 - Tracer lateral distribution; Flow mod1 - MIM water content ratio, Flow mod2 - Pore water velocity, Flow mod3 - Dispersivity; Percolation1 - Surface connected porosity, Percolation 2 - Pore critical diameter) evaluated in this chapter. Color legend: Red - Decrease with ZT duration; Yellow - Decrease for 7 yr ZT followed by an increase; Green - Increase with ZT duration. The dark points indicate that a correlation was established between specific parameters.	144
7.1	Top: Aerial view of CHAR observatory. Red symbols mark the sampling locations and areas of interest: OBC and REF. Adapted from Zanutel (2019). Bottom: Schematic of sampling locations along ERT survey line of electrodes	150
7.2	One of the five soil sampling locations with its corresponding triplicate cylindrical soil cores.	151
7.3	Representative scan image window selections before (left) and after (right) applying a binary threshold for air-filled space. They correspond to the A horizon of one sample from charcoal soil and one sample of reference soil.	153
7.4	Contour plot of an ERT 2D field survey pseudosection.	154
7.5	Triangular 2D mesh used for ERT inversions. Depth axis length is exaggerated for visual purposes.	156
7.6	Time-lapse error model fit to the distribution of reciprocal errors. Dark points represent the bins average.	159

7.7	Soil sample modified to accommodate SIP measurements. Annotations indicate different components of the set-up.	160
7.8	3-Dimensional volume of pixels corresponding to air-filled pore space segmented from the X-ray digitally reconstructed images.	161
7.9	Boxplots showing the distribution of 4 pore structural parameters corresponding to the 4 sampling groups: charcoal enhanced soil - horizon A (CHAR A), horizon B (CHAR B) and reference soil - horizon A (REF A), horizon B (REF B).	162
7.10	Histograms showing the pore size distribution. Values represent the totals over 6 samples in each category (CHAR A, B; REF A, B)	164
7.11	Time-lapse difference inversion sensitivity models (corrected for topography) corresponding to all time-steps. OBC5- top 6; REF5 - bottom 6. X-Y axis scale is in metres.	166
7.12	Time-lapse difference inversion resistivity models (corrected for topography) corresponding to all time-steps. OBC5 - top 6; REF5 - bottom 6. X-Y axis scale is in metres.	167
7.13	Weather data acquired on the CHAR monitoring field site during 2019. Numbers displayed are the average net precipitation values represented graphically by the violet bars.	168
7.14	Average resistivity of inversion model cells above 25 cm depth - A horizon (left) and below 25 cm depth - B horizon (right) . . .	170
7.15	Areas of model cell selection corresponding to soil core sampling locations	171
7.16	SP selected model cells average resistivity values and their variation in time (top) and depth (bottom)	172

7.17	Apparent correlation between average porosity (left) and Resistivity standard deviation ($\Omega.m$) corresponding to the 5 SP . . .	173
7.18	Top: Total surface area corresponding to air-filled pores grouped by the size of their equivalent diameter. Bottom: Fraction weight of macroaggregates - data analysis produced by PhD candidate Victor Burgeon - University of Liège. Macroaggregate fraction (Macro) represents particles larger than 250 μm , Microaggregate fraction (free micro) represents particles 50-250 μm and Silt and Clay fraction (S&C) represents particles smaller than 50 μm	174
7.19	Spectral electrical response during desaturation. The legend indicates the day (07/11 - 7th November 2019) each phase spectrum was recorded.	175
8.1	Synthesis diagram of project results across three scales.	180

1 Introduction

1.1 Project overview

1.1.1 The Specific Problem

Knowledge about soil processes is essential in the attempt to make agricultural practices more sustainable and efficient. In particular, soil hydraulic properties dictate water infiltration and retention, which in turn dictates nutrient availability and transport (Sparling and West, 1989). Because soil is a highly heterogeneous medium, parametrizing and quantifying soil hydraulic processes is very challenging to a high resolution in both space and time. In addition, soil structure is known to be a major controller of soil hydrodynamics (Bouma et al. (1981); Germann et al. (1984)), but an effective direct quantitative link between them has not been established. Therefore, we require novel methodologies that capture this complex dynamic behaviour in soils without modifying its natural integrity.

1.1.2 Addressing the problem

This project sets out to enhance our interpretation of soil hydraulic properties by associating descriptors of soil physical structure with spatiotemporal changes in the pore solution concentration. Electrical Resistivity Tomography (ERT) is a geoelectrical method successfully applied for the assessment of soil properties (Samouëlian et al., 2005). It non-invasively measures and subsequently images electrical resistivity of the subsurface. Because pore solution acts like an electrolyte, ERT is particularly sensitive to changes in its concentration (Everett, 2013). X-ray Computed Tomography (CT) is a 3D visualization technique, which has proven to be effective in non-invasively appraising soil

internal structure (Peyton et al., 1992). The incentive is therefore to combine the respective capabilities of these two methods and to generate a more robust interpretation of soil hydrodynamic behaviour. It is hypothesized that their combined assessment in both time and space at a high resolution will enable us to observe and quantify directly how soil structural indicators influence solute transport in near real time. This will enable us to understand the underlying mechanisms and inform further research on what are the key drivers behind such hydraulic processes.

1.2 Hypotheses

The overarching hypotheses of this project are:

1. ERT and X-ray CT can be used in conjunction to better describe the hydrodynamical behaviour of soils across scales
2. The complementary abilities of these two technologies can be used to explore the impact of soil structure on solute hydrodynamics in soil

A number of questions accompanying these statements were considered. The chapters containing corresponding work aimed are listed in parenthesis.

1. What is the utility and state of the art of ERT in root zone research ?
(Chapter 2)
2. What are the experimental conditions under which a joint ERT-CT experiment is viable and most fruitful? (Chapter 3)
3. Can we formulate a direct pedophysical relationship to link ERT and X-ray CT data ? (Chapter 4)

4. Can we formulate a methodology which makes use of both ERT and X-ray CT capabilities in order to study soils in a controlled laboratory environment ? (Chapter 5)
5. Can we use such a methodology to obtain better understanding of the effect of soil compaction? (Chapter 5)
6. Can we use a ERT and X-ray CT in conjunction in a column experiment to obtain a better understanding of the long term effect of Zero Tillage practices ? (Chapter 6)
7. Are X-ray CT and ERT complementary at the field scale ? (Chapter 7)
8. Can we combine CT and ERT at field scale to study the hydrodynamic properties of charcoal enhanced soils? (Chapter 7)

1.3 Aims and objectives

In order to assess the hypotheses and answer the questions listed above a list of aims was conceived. These are accompanied by their corresponding objectives:

1. Understand how current geoelectrical technology can be applied in root zone research
 - Derive the benefits of using geoelectrical methods in the study of soil
 - Derive the limitations geoelectrical studies have and how can their interpretation be improved
2. Find the conditions for a conjunct ERT-X-ray CT experiment to be possible

- Determine the appropriate soil sample size at which both methods are effective
 - Run a series of preliminary tests to assess the compatibility of the various measurement conditions (e.g. electrode configuration, X-ray energy, time of measurement)
 - Determine the correlation between their measurable parameters
 - Formulate a relationship that quantitatively links their measurable parameters
3. Formulate and apply an experimental methodology involving both technologies for the study of soil hydrodynamics
- Redesign the experimental settings to accommodate ERT and X-ray CT measurements
 - Scan and digitally reconstruct the soil core's pore architecture
 - Monitor solute infiltration through the soil medium using ERT
 - Use resulting parameters to explain the effect of different levels of compaction on soil
 - Use resulting parameters to explain the effect of long term Zero-Tillage (ZT) on soil
 - Use resulting parameters to explain the hydraulic properties of charcoal enhanced soil

In what follows, Chapter 2 examines the current potential of geoelectrical methods, such as ERT, for root zone research. It also underlines how the output of such methods can greatly be enhanced by complementary information, such as knowledge about the soil structure, supplied by X-ray CT. This sets the scene for a collaborative methodology between ERT and X-ray CT. Chapter

3 then outlines the theoretical background of the two methods, providing details about data acquisition, processing, error sources and model interpretation. This is followed by four experimental chapters where this collaborative study is facilitated across three scales. In chapter 4 a small scale study is presented, where a property transfer relationship was derived between X-ray absorption and electrical resistivity, the effective measurable parameters of X-ray CT and ERT respectively. In chapters 5 and 6 the methods were used at column-scale and combined their outputs in order to understand how solute flow is impacted by the pore network size and architecture. Their conjunct application was used for the evaluation of soil properties, where the effects that compaction (chapter 5) and ZT (chapter 6) have on soil hydrodynamics were explored. Finally, in chapter 7, field scale experimental efforts are described, where the bulk soil electrical resistivity variability of charcoal enhanced agricultural soils was explored. Information about soil pore size distribution obtained through X-ray CT scans is used in order to understand the source and scale of such variability. Through all these correlations, the construction of a robust methodology for studying the hydrodynamic character of soils was attempted, which in turn contributes to our understanding of how human interaction affects soil physical properties (by exploring case studies on compaction, tillage and charcoal deposition).

2 POTENTIAL OF GEOELECTRICAL METHODS FOR MONITORING ROOT ZONE PROCESSES AND STRUCTURE: A LITERATURE REVIEW

The work in this chapter was published in the scientific journal Geoderma:

Cimpoiasu, M. O., Kuras, O., Pridmore, T., & Mooney, S. J. (2020). Potential of geoelectrical methods to monitor root zone processes and structure: A review. *Geoderma*, 365. <https://doi.org/10.1016/j.geoderma.2020.114232>

End user license: CC-BY 4.0.



Author contributions:

Cimpoiasu M.O. and Kuras O. conceptualised the paper and decided on its core structure. Cimpoiasu M.O. carried the literature analysis, wrote the first draft of the manuscript and created the figures. Kuras O. contributed to the sections referring to theoretical aspects of geoelectrical monitoring and further improved the manuscript's conciseness. Mooney S.J. contributed to the sections referring to soil physics and further edited the general structure, language and conciseness. Pridmore T. contributed to the sections referring to computational statistics and imaging technology and further edited the general structure, language and conciseness.

2.1 Abstract

Understanding the processes that control mass and energy exchanges between soil, plants and the atmosphere plays a critical role for understanding the root zone system, but it is also beneficial for practical applications such as sustainable agriculture and geotechnics. Improved process understanding demands fast, minimally invasive and cost-effective methods of monitoring the shallow subsurface. Geoelectrical monitoring methods fulfil these criteria and have therefore become of increasing interest to soil scientists. Such methods are particularly sensitive to variations in soil moisture and the presence of root material, both of which are essential drivers for processes and mechanisms in soil and root zone systems. This review analyses the recent use of geoelectrical methods in the soil sciences, and highlights their main achievements in focal areas such as estimating hydraulic properties and delineating root architecture. We discuss the specific advantages and limitations of geoelectrical monitoring in this context. Standing out amongst the latter are the non-uniqueness of inverse model solutions and the appropriate choice of pedotransfer functions between electrical parameters and soil properties. The relationship between geoelectrical monitoring and alternative characterization methodologies is also examined. Finally, we advocate for future interdisciplinary research combining models of root hydrology and geoelectrical measurements. This includes the development of more appropriate electrical models of the root system , careful separation between different root zone contributors to the electrical response and integrating spatial and temporal geophysical measurements into plant hydrological models to improve the prediction of root zone development and hydraulic parameters.

2.2 Introduction

Root zone is a term used to describe the region of soil that is directly influenced by plant roots and all its inherent physicochemical processes. It links directly to human activity; for example, agriculture is typically based on anthropic interactions with the root zone. In addition to its economic importance, studying the root zone provides the tools to protect and to nurture a sustainable environment. In order to understand soil-plant interactions, a detailed appreciation is essential of processes such as: root water uptake (RWU), growth of micro-organism communities, nutrient fixation, carbon sequestration and soil structure. This requires the development and routine use of well-defined investigation and quantification methods in order to translate the measurable observations into meaningful soil and root parameters, including hydraulic conductivity, porosity, root length, root biomass or soil respiration. Assessment of root zone processes can take place in-situ or ex-situ, with both experimental settings serving different purposes. Laboratory studies allow the creation of a controlled environment with defined media where experimental parameters are carefully planned and adjusted. This can help understand soil processes on a specific, localized scale (typically sub-metre). By contrast, field surveys facilitate the study of processes in an undisturbed setting. In addition, they provide the necessary benchmarks for translating laboratory results into the real environment. They allow evaluation of methods for monitoring natural and man-made inputs to the root zone system, including agricultural strategies such as inter-cropping or crop rotation, which can only be tested at the field scale (100s of metres) (Garré et al., 2012).

Over recent decades, a range of assessment methods for the root zone has been developed. These can be split into invasive/destructive and minimally/non-invasive approaches. Invasive methods disturb the integrity of the soil in order

to determine soil (moisture content, calcium content, pH) and root (elongation, mass) properties. Examples include the core-break method (Moreno et al., 2005; Escamilla et al., 1991; Bland, 1989) and the use of minirhizotron tubes (Hendrick and Pretigzer, 1996; Garré et al., 2011). Whilst the results obtained in this way are accurate, useful and do not require ground-truthing, they reflect conditions at the test locality only. Achieving meaningful experimental coverage therefore requires many sampling points, which can be time-consuming and laborious. Furthermore, altering the soil properties through sampling reduces the opportunities for continuously monitoring the soil-plant system.

The literature offers many examples of minimally-invasive methods such as TDR (Michot et al., 2001) and non-invasive methods, including X-ray Computed Tomography (CT) (Peyton et al., 1992), Neutron Probe Imaging (Vrugt et al., 2001) or Magnetic Resonance Imaging (MRI) (Segal et al., 2008). These methods provide important insights concerning soil structure (Peyton et al., 1992), or soil water transport (Amin et al., 1996), and more recently they have allowed imaging of the plant root architecture in situ (Mooney et al., 2012). Even though these technologies provide high resolution 3D results, they are expensive to deploy and maintain. Also, at the current state of technology, they restrict the user to a laboratory environment. The exception is TDR, which is frequently employed in field surveys. However, the spatial coverage and resolution achievable with TDR and other non-invasive methods based on point sensors is comparatively poor.

Geoelectrical tomography represent a relatively recent, but fast growing set of tools for soil assessment and monitoring (Everett, 2013). In particular, efficient methods for investigating soil-plant interaction are increasingly in demand. Geoelectrical methods are minimally invasive and involve the use of sensors that penetrate the soil surface only (top 10 cm), thus not disturbing the in-

tegrity of the volume under investigation. Well-established methods include: Electrical Resistivity Tomography (ERT), Electrical Impedance Tomography (EIT), Electrical Capacitance Method (ECM) and Induced Polarization (IP) with some conceptual overlap between them. A significant body of research has focused on ERT, due to its robustness and ease of use, particularly in the field. Geoelectrical techniques facilitate both *in-situ* and *ex-situ* assessments of soil. The methodology allows comparatively rapid data acquisition which enables near real-time measurements (Loke et al., 2013; Samouëlian et al., 2005). It also allows practically continuous measurements over time, which provides an important capability for the long-term monitoring of soil processes.

The physical principles governing this family of methods involves electrical current signals driven into the soil through electrodes and subsequent recording of differences in electrical potential associated with the subsurface current flow. Larger arrays of multiple electrodes are typically used to acquire geoelectrical data, with individual measurements made consecutively on small subsets of electrodes. Electrical parameters such as conductivity, polarization or capacitance are measured. The systematic collation of datasets with multiple point measurements allows the application of tomographic imaging techniques, which can generate 2, 3 or even 4 dimensional images of the subsurface distribution of electrical properties. This enables quantification of spatial and temporal property variations within soils.

Whilst many factors can influence soil electrical properties (e.g. porosity, density, clay content), a particularly useful application is their use as a proxy for soil water content (SWC; Michot et al. (2001)). SWC quantification is critically important for most soil studies. Firstly, it is indicative of plant water availability (Denmead, 1961) and secondly, it is a major factor controlling soil respiration (Davidson et al., 1998) or soil aggregates stability (Haynes and

Beare, 1997). Geoelectrical monitoring is able to quantify temporal variations in SWC, and has been used to monitor plant water uptake in the laboratory (Werban et al., 2008) and in the field (Michot et al., 2003), as well as to monitor soil water availability (Brillante, 2016; Srayeddin and Doussan, 2009).

A direct correlation has been found between electrical permittivity and root biomass (Dalton, 1995). Therefore, root presence and activity can be quantified directly from electrical measurements. Moreover, organic matter has the ability to polarize electrical current (Schwan, 1957). Researchers have exploited this for assessing the architecture of root systems by measuring not only conductivity (Amato et al., 2009), but also chargeability (Mary et al., 2017).

In this study we review the main opportunities for geoelectrical monitoring in root zone research and discuss the key questions that may be addressed in this way. We also seek to highlight the information each method delivers to the user and appraise the state of the art in terms of geoelectrical instrumentation and methodology for root zone research. Current gaps in knowledge and research needs are identified, covering issues such as the variability of pedo-transfer functions, the use of a-priori information to constrain the geoelectrical result and the advantages of complementing geoelectrical information with GPR or EMI data in a joint field surveying strategy. We conclude with an outlook to future research opportunities within the experimental observation and conceptual modelling of the root zone. Therefore, with a view to advancing our understanding of root zone processes, we suggest the root system requires a more comprehensive electrical analogue representation, the contributors to the geoelectrical response need to be appropriately separated and a coupled research framework aimed to improve root zone parametrization which jointly includes geoelectrical measurements and simulations of plant growth and hydraulic properties.

2.3 Geoelectrical methods and their variability - general principles

2.3.1 Electrical properties of soils and their variability

The application of geoelectrical methods in root zone research aims at determining the electrical properties of soils, namely, conduction and polarization. Electrical conduction represents the movement of electrically charged particles through liquid and solid phases of the soil medium. Their flow will depend on the amount of available charge, the distribution of conducting paths and the charge mobility. Electrical polarization represents the redistribution of positive and negative charges when exposed to an exterior electric field. In consequence, this will determine regions of charge accumulations across the soil medium.

Variability in soil electrical properties can be caused by either inorganic or organic constituents of the soil system. Soil electrical conduction is generally determined by pore fluid and mineral surface conductivity. Soil electrical polarization is determined by the pore architecture and water-mineral interface capacity of ion aggregation (Everett, 2013). Therefore, a number of properties intrinsic to the soil (i.e. its inorganic constituents) have a direct effect on the electrical response. Further essential contributors to the electrical response are components of the root zone with an organic origin, such as decomposed plant material, collectively known as humus, and plant root systems.

2.3.1.1 Inorganic constituents **Pore fluid.** Electrical conduction in soils is mostly electrolytic, ions in the pore fluid being the charge carriers (Everett, 2013). The amount of charges increases either with fluid ionic concentration given a constant volumetric water content or with the volumetric water content given a constant fluid conductivity.

When an electrolyte comes in contact with a charged surface of a soil particle, an electrical double layer (EDL) forms and ions are adsorbed onto the solid surface (Revil and Glover, 1997), therefore affecting ion mobility which gives rise to electrical polarization (Lyklema et al., 1983).

Solid soil. Generally, the solid matrix acts like a semi-conductor with some exceptions such as the surface of clay minerals. Their inherently negative surface charge constitutes another electrical conduction pathway. Also, soils with a predominantly clay texture tend to exhibit a larger specific surface area than soils consisting primarily of sand (Pennell, 2016). Therefore, clay content implies a larger conductive particle surface which leads to an important contribution to the soil electrical conductivity (Fukue et al., 1999).

Air Filled pore space. The volume (porosity) and connectivity of the pore network determine a soil's water holding capacity, which in turn affects the bulk soil electrical conduction. Also, the tortuous nature of the pore system generates complex patterns of fluid flow which can determine electrically conductive and non-conductive regions. As for polarization, due to the formation of EDLs, narrow pore channels may cause charge accumulation and localized disequilibria in ionic concentration (Revil, 1999).

Temperature. An increase in pore fluid temperature causes a decrease in pore fluid viscosity, which in turn increases the ion agitation in the solution. Alternatively, in freezing conditions, molecules of salt are rejected into unfrozen pore water, thus changing the concentration of the pore solution (Banin and Anderson, 1974). Superficial soils are exposed to diurnal and seasonal fluctuations in temperature, therefore neglecting such variability may lead to serious errors in geoelectrical data interpretations (Samouëlian et al., 2005).

2.3.1.2 Organic constituents Organic matter (OM). The capacity of the soil to retain ions (or ion exchange capacity) is a measure of soil surface

charge (Zelazny et al., 1996). A considerable proportion of soil cation exchange capacity (CEC) is associated with soil organic matter. Interactions between OM and soil minerals result in a decrease in ion mobility, and thus a decrease in polarization (Schwartz and Furman, 2015).

Plant roots. The living root system has a very complex electrical response that depends on root characteristics, such as: mass, length, structure, type (woody or herbaceous) or tortuosity. Woody root tissue does not contain charge carriers, therefore their presence in the soil system will reduce the overall bulk electrical conductivity (Vanderborght et al., 2013). However, electrical current will flow through the root xylem as the fluid contains electrical charges. EDLs form both at the contact between the outer and inner root surface, therefore the magnitude of root polarization relates to their overall surface area (Weigand and Kemna, 2018).

2.3.2 Methods of measuring soil electrical properties

A range of geoelectrical methods is available to measure soil properties. In this section we aim to provide a short introduction to the physical and functionality principles governing these methods.

2.3.2.1 Complex electrical impedance In practice an electrical measurement on soil involves a measurement of the complex impedance $\hat{Z}$ of the material, a frequency f dependent function expressed as:

$$\hat{Z} = (Z'(\omega) + iZ''(\omega)), \quad (2.1)$$

where i is the imaginary unit, $\omega = 2\pi f$, Z' and Z'' are the real and imaginary parts of the impedance respectively. This can, in turn, be translated into effective material properties by taking into account the dimensions and spatial

geometry of the measurement, represented through the geometric factor K . Therefore we can obtain an expression for the 'apparent' complex conductivity $\hat{\sigma}_a$ and its inverse, complex resistivity $\hat{\rho}_a$, which describe how well a material conducts electrical current flow:

$$\hat{\sigma}_a = (K \times \hat{Z})^{-1} = \sigma' + i\sigma'' = |\rho_a| \times e^{-i\phi}, \quad (2.2)$$

where the real part σ' quantifies conduction and σ'' quantifies polarization. ϕ is the phase angle that represents the phase shift between the injected current and measured voltage.

2.3.2.2 ERT For this review we selected 72 articles spanning across 22 years (1996-2018) which feature the application of geoelectrical methods in root zone research (Complete list in Appendix A and B). We found that ERT was one of the most extensively used near surface geophysical methods, very popular for the study of soil-plant interaction. 65% of the studies reviewed for this paper employed ERT as the primary method of imaging soil-plant interaction. ERT applications inject DC or low-frequency current into the soil and tend to measure the magnitude $|\hat{Z}|$ of the electrical impedance only (Everett, 2013). Provided that the geometric factor K is known, the bulk resistivity of the soil can be calculated according to Ohm's law:

$$\rho = K \times \frac{\delta V}{I}, \quad (2.3)$$

where δV is the observed potential difference and I is the injected current. The primary concern is with the strength of the received signal, rather than its phase relationship. A standard procedure is to use a pair of electrodes for current injection and separate pair of electrodes to record the potential dif-

ference (Samouëlian et al., 2005). After making multiple spatially distributed measurements, the recorded data is used to generate a tomographic image of the subsurface, in order to determine the spatial distribution of soil electrical properties. These are interpreted in the context of a heterogeneous subsurface structure. Inverse modelling is used to fit an earth model to the measured dataset. The inversion procedure uses adjustments to the predicted model parameters to achieve convergence between the measured and predicted datasets. A typical approach is to change the model until the misfit reaches a minimum (Kemna, 2000). The model is build upon a digital mesh (dimensionality is case dependent) which follows a pre-defined discretisation of the target geometrical space and other constraints (e.g. limit values, smoothing factor, boundary conditions). The model cells have corresponding cartesian coordinates and a parametric value associated, in this case a geoelectrical parameter (e.g. resistivity, phase). Additional a-priori information about the environment (e.g. soil structure, temperature, topography) will significantly improve the inversion result. However, inherent problems with geoelectrical inversion are:

1. Non-linearity. The relation between parameters and data is often non-linear, therefore a linear approximation is required to help solve the system of equations.
2. Solution stability. A small perturbation in the initial conditions can cause very different outcomes.
3. Non-uniqueness. Multiple models fit the data to the same degree of accuracy, hence choosing the "correct" model is a challenge both conceptually and practically. These limitations of geoelectrical inversion apply to all geoelectrical techniques that employ tomographic reconstruction of the data.

2.3.2.3 IP In the absence of polarization, a sudden switch off of the current injected in the target medium should cause the voltage between a pair

of potential electrodes to drop from an initial value V_0 instantaneously to 0. However, if the soil exhibits polarization, a gradual decay of the voltage can be observed over a finite time period, which is known as the IP effect (Everett, 2013). In practice, this behaviour can be measured both in the time-domain and in the frequency domain.

Time-domain IP. The acquisition principle here is technically similar to the one used for ERT. From the IP recorded discharge curve we can obtain measurable quantities such as apparent polarizability η (Equation 4) or partial chargeability m (Equation 5):

$$\eta = \frac{V(T)}{V_0}, \quad (2.4)$$

where V_t is the voltage measured at time T after current switch off.

$$m = \frac{1}{V_0} \int_{t_1}^{t_2} V(t) dt, \quad (2.5)$$

where t_1 and t_2 are the two limits of a time window during the voltage decay (Everett, 2013).

Frequency domain IP. FDIP is often referred to as SIP or EIS and uses a range of (typically discrete) frequencies for current injection. The complex resistivity in both magnitude and phase is a function of the frequency of the injected current signal. Polarization causes a phase shift between injected and recorded currents, therefore in addition to ERT, FDIP method is able to measure the IP effect through its phase angle.

Empirical models such as Debye (Debye, 1929) or Cole-Cole (Equation 6) (Cole and Cole, 1941) have been developed to describe the complex resistivity fre-

quency dependence.

$$\rho^*(\omega) = \rho_0[1 - m(1 - \frac{1}{1 + (i\omega\tau_0)^c})], \quad (2.6)$$

Fitting the Cole-Cole model parameters to experimental data yields values for the chargeability m , relaxation time τ_0 and frequency exponent c . It is worth mentioning this model can also be applied in the time-domain on chargeability curves (Pelton et al., 1978) in order to extract corresponding parameters.

EIT. EIT is a method which uses the measurement principles of IP, and therefore used to determine complex resistivity, but in addition incorporates a tomographic reconstruction capability, such as ERT (Zimmermann et al., 2008). Therefore, EIT brings together information about the signal strength, shape and timing. Ultimately, it uses the data to construct a tomographic distribution.

For soil research purposes the method is still in the incipient stages. It was successfully applied previously for detecting electrical phase differences (Kelter et al., 2015), the low-polarizability of a water submerged root system (Weigand and Kemna, 2017) and changes in polarization due to diurnal cycles and gradual nutrient deprivation (Weigand and Kemna, 2018).

ECM. Chloupek (1972) found a direct correlation between root parameters, such as dry mass and surface area, and the EC of root systems. The basic measurement procedure involves the connection of an LCR (Inductance-Capacitance-Resistance) meter between an electrode attached to the base of the plant stem and another one inserted into the soil. Previous studies established such correlations at a single measurement frequency (Dalton, 1995; Ellis et al., 2013) or using a broader range of frequencies (Ozier-lafontaine and Bajazet, 2005). Primarily, the measured quantity for ECM is still complex impedance. However, the impedance measurements are interpreted in terms

of an analogue electrical circuit. Dalton (1995) envisioned root segments as capacitor-resistance pairs connected in parallel. The root segment capacitor has three components: xylem as an internal electrode, soil nutrient solution surrounding the root as a second electrode and a poorly conducting plant tissue acting as a dielectric. Therefore, the complex impedance can be expressed in terms of the equivalent root system capacitance C and resistance R as:

$$\hat{Z}^{-1} = \frac{1}{R} + i\omega C = \frac{1}{R} + i\omega \frac{\epsilon A}{4\pi r_2 \ln(\frac{r_2}{r_1})}, \quad (2.7)$$

where ϵ is the dielectric constant, A is the geometrical surface area of the root tissue, r_1 and r_2 are the radius of the inner root xylem channel and the root segment, respectively.

2.3.2.4 Relationship between geoelectrical methods Considering what was previously enunciated, one may reach the conclusion that there is a certain degree of interconnectivity between all the geoelectrical methods. The main common denominator is the measurement of complex electrical impedance, but different methods have different ways of mathematically expressing the recorded data, such as the magnitude of complex impedance (ERT), polarizability and chargeability (IP) or electrical permittivity (ECM). Secondly, methods differentiate by the type of current they use (DC or AC) or the domain they operate in (time-domain or frequency-domain). In Figure 2.1 we formulated a summary diagram describing the relationship between different methods and their corresponding measured quantities. This will potentially serve as an aid to better understand how the geoelectrical methods were used to resolve parameters of the root zone in the studies we review in the following section 3.

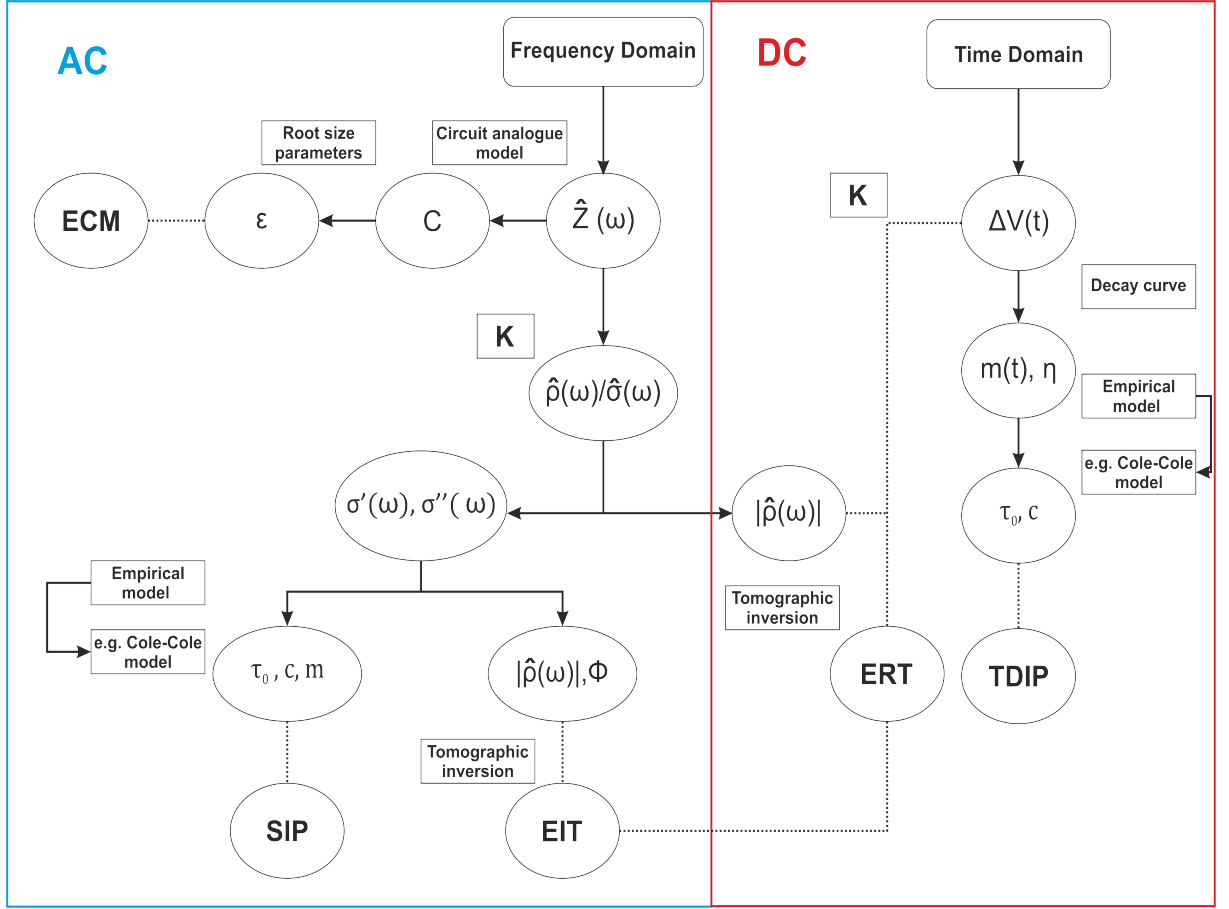


Figure 2.1: Diagram of key theoretical characteristics associated to geoelectrical methods described. The dotted line connects the scheme branch with the corresponding geoelectrical method.

2.3.3 Translating geoelectrical measurement into root zone properties

It is important to note that geoelectrical methods do not quantify root zone properties directly. For this purpose an additional calibration measurement is required to allow direct translation of electrical measurements into root zone properties. This can be illustrated using the example of SWC. As mentioned, electrical measurements are sensitive to changes in SWC, but the relationship is a function of multiple factors and no analytical expression is readily available to describe it. Therefore, a dedicated method for estimating water content (e.g.

TDR, neutron probe, destructive sampling) is usually used in parallel to the geoelectrical method, in order to determine the dependency of the electrical response on SWC variation by empirical means. The outcome of this exercise is a calibration curve, which can subsequently be used to translate the geoelectrical measurements into SWC for the specific material and under the specific circumstances. Unfortunately, a universal transfer function is unlikely to exist, due to the large number of potential input factors, used to parametrize the root zone, such as porosity, saturation status or root mass. Different calibration strategies have been adopted over the years. Earlier studies established simple linear regression correlations between measured resistivity and SWC or root biomass, respectively (Michot et al., 2003 and Amato et al., 2008). However, the calibration process has recently become more systematic and new research is looking into its simplification using deep learning prediction algorithms (Brillante et al., 2016).

2.3.3.1 Resolving pedological parameters A more robust strategy involves the use of quantitative conceptual models to link electrical parameters and soil properties (known as pedotransfer functions or PTFs). One of the first relationships of this kind described the resistivity behaviour of a brine-saturated sandstone in the context of borehole logging and was developed by Archie (1942). However, Archie's law did not take into account surface conductivity, which becomes essential in samples with an increased clay content. Based on Archie's relation, the Waxman-Smits (WS) model, established for shaly sands, incorporates the presence of clay particles with surface conductivity effects (Waxman and Smits, 1968). More comprehensive models have been developed based on both laws. The model proposed by Rhoades et al. (1989) relies on the assumption of two separate electrical pathways, a continuous one through waterfilled macropores and a series linked soil-liquid one. A model

by Mualem and Friedman (1991) is based on the fact that the tortuosity factor affecting the bulk electrical conductivity is identical to the one predicting hydraulic conductivity. Revil et al. (1998) assumes surface conduction to be restricted to the part of the EDL where ions are adsorbed to the material surface (Stern layer). The Linde et al. (2006) model takes into consideration the different behaviour of ions in the pore space. The transport regime of anions is independent of salinity as opposed to that of cations, which have a different regime for high and low salinity.

The decision over which model to apply is subjective for any given application, as more than one model may fit the requirements. Laloy et al. (2011) compared existing pedotransfer models and suggested that the Linde model performs better for a low resistivity regime ($<100 \text{ Ohm.m}$), whilst WS performs better in the high resistivity regime.

As one can realize from early PTSs such as Archie's law, they were not initially intended for applications in the root zone but for oil exploration. Therefore, the factors describing them are strictly pedological. In order to offer a more comprehensive view of how geoelectrical methods can resolve root zone properties, the following subsection briefly presents research efforts of describing the root electrical signature.

2.3.3.2 Resolving root system parameters An electrical model developed by Dalton (1995) suggested that roots can be represented by a parallel resistance-capacitance (RC) circuit. More roots will imply more RC pairs connected in parallel. Therefore, the effective capacitance of a root system will depend on its structure and size. Ellis et al. (2013) concluded that capacitance was significantly related to root mass, length and surface area, but as a measurable quantity its predictive power is poor. They also obtained the best predictions for root length, which was significantly related to the ratio

between capacitance and density. However, the Dalton model was tested and inconsistencies were found by both Ellis et al. (2013) and Dietrich et al. (2012), questioning the validity of a linear correlation between capacitance and root mass. Upon the removal of roots from a hydroponic solution it was realized that the capacitance of the solution was much higher than the capacitance of the root tissue. Arguably, the studies have shown that capacitance is correlated to root mass, but is not a direct means of measuring it.

Cao et al. (2010) also measured the electrical resistance of a root system submerged in a hydroponic solution. The resistance decreased with an increasing contact surface area of the root with the solution. These measurements contributed to the formulation of analogue circuits where the root system is realized as series of electrical resistors. Building on these results, Cao et al. (2011) used a spectrum of frequencies to analyse the elements of the root system analogue circuit. The study found that capacitance is a more useful parameter than resistance when it comes to root size estimation. Regression models were used in Amato et al. (2008, 2009) in order to link root mass density to resistivity measurements. The strong correlations led to the formulation of a logistic-growth model which later gave accurate predictions on field data acquired by Rossi et al. (2011).

2.4 Monitoring processes and resolving structure in the root zone

Geoelectrical methods are able to (1) monitor processes in near real time and (2) resolve structure, which is important for the study of soil-plant interactions because of the high significance of water content changes (Samouëlian et al., 2005), for these interactions and the presence of root organic matter (Amato et al., 2008) in the medium of investigation. Given that access to water plays a

key role in plant survival, quantitative monitoring of water dynamics is helpful for defining the requirements and constraints, such as water availability, influx access points, transport parameters, flow pathways and for characterizing the environmental conditions, including soil texture, soil porosity, root characteristics, climate, geological setting and others. Detecting and quantifying root activity is crucial for understanding the extent of plant development and their reactions to stimuli (Mooney et al., 2012). Root architecture development is a visible indicator of the quality of the impact root system has on the plant's health and productivity, or on surrounding plants. The following subsections present an overview of the current state-of-play in geoelectrical monitoring research in three main application areas, namely: (1) water dynamics, (2) the detection of root organic matter and (3) the modelling of root zone processes.

2.4.1 Root zone water dynamics

Much geoelectrical research is focused on monitoring root water dynamics. A considerable body of literature focuses on monitoring root water dynamics underlining its importance for soil studies.

2.4.1.1 Ex-situ studies We examine studies performed ex-situ (in a laboratory environment), many of which were undertaken to try to illustrate the suitability of geoelectrical methods for monitoring solute transport in soils, or to determine soil properties in a controlled experiment, which would not be possible on a larger scale. The majority of studies have adopted a similar experimental set-up, whereby the soil volume of interest is surrounded by electrodes in order to enable electrical current flow throughout the sample (Figure 2.2).

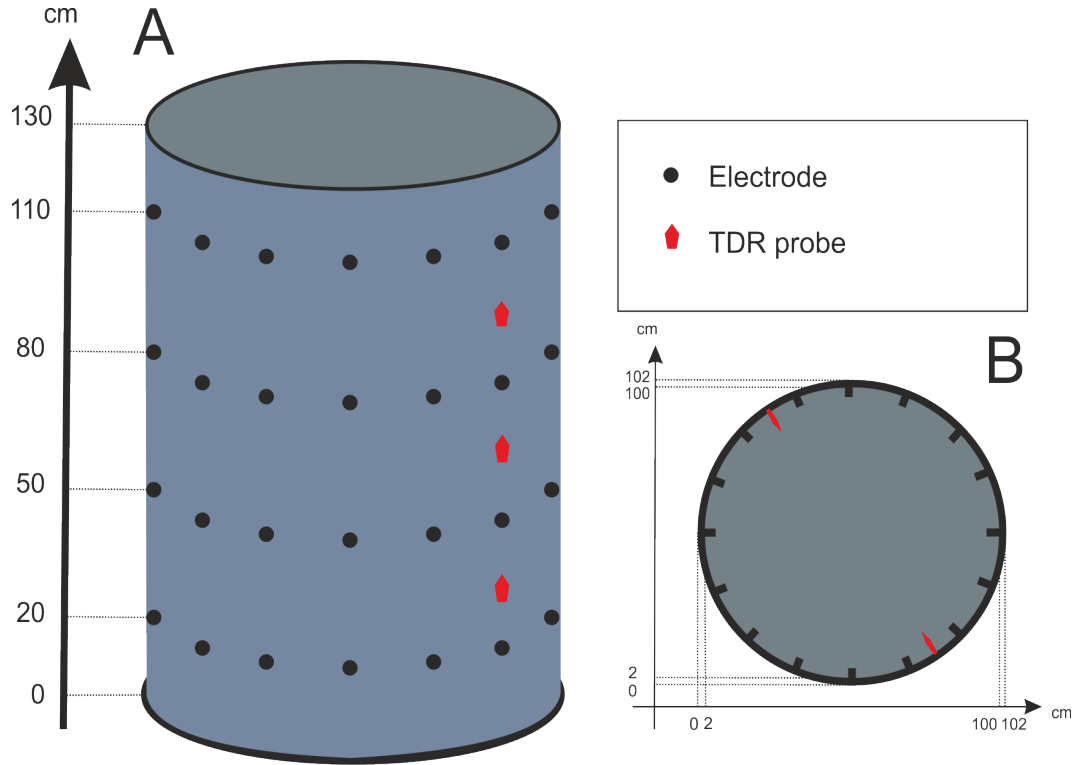


Figure 2.2: Laboratory set-up of a geoelectrical soil column monitoring experiment A) Soil column lateral view B) Horizontal Cross-section view. Adapted from Garré et al. (2011), (Koestel et al., 2007).

The signature of rootless soil

It is important to acknowledge that the studies mentioned here focus on the soil as a medium which does not contain a root system, disregarding the effect such a system has on neighbouring physicochemical properties. The existence of roots in soil adds a further layer of complexity to the geoelectrical attempt of monitoring hydrodynamic processes. Therefore, we present an initiatory body of literature that aims to decipher the contribution of rootless soil separately before expanding to applications which take roots into consideration.

Binley et al. (1996) used a dye staining experiment to show the ability of ERT to reconstruct flow pathways in soil. Olsen et al. (1999) used ERT in conjunction with X-ray CT for the purpose of solute transport characterisation. A rapid transport mode was detected through geoelectrical monitoring and was

explained by the properties of the macropore system detected by X-ray tomography. However, macropores could not be directly related to the electrical tomogram because of the gap in spatial resolution, hence a causal link between the two observations could not be established. Similarly to Binley et al. (1996), Koestel et al. (2007) demonstrated the benefits of using dye as a tracer for electrical conductivity monitoring experiments. This was extended to a two-step tracer infiltration experiment through a cylindrical soil column (Koestel et al., 2008), in which bulk electrical conductivity was translated to solute concentrations. Figure 2.3 shows the evolution of concentration illustrating the ability of ERT to track the dynamics of solute injection and transport at the laboratory scale. However, this type of observation was only possible when a hydraulic steady-state existed and there was no spatial variation in the saturation states of the soil. Cassiani et al. (2009) used SIP for the purpose of monitoring organic pollutants in soils, looking at DC and chargeability responses from samples at different levels of water saturation obtained after the injection of air and a non-aqueous phase liquid (NAPL). The study observed differences between the NAPL and air samples, which were attributed to phase distributions across the samples and not to chemical interaction between solutes and surrounding liquid/solid phases.

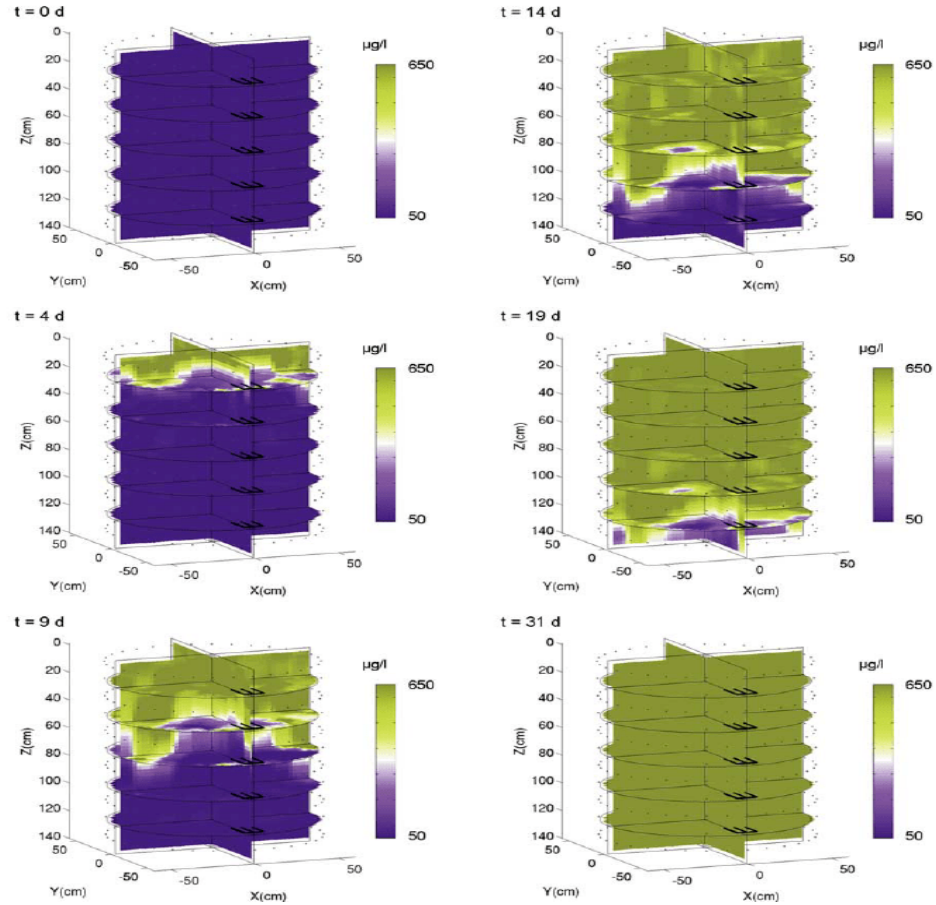


Figure 2.3: Three dimensional solute concentration distribution in 6 stages of infiltration. Corresponding time-steps are listed in the top-left corner. Extracted from Koestel et al. (2008).

The signature of the root zone

By periodically irrigating a ginkgo tree, Wu et al. (2013) detected spatial and temporal variations in capacitance with increasing water content. Also, the tomographic images provided visual representation of the process of saturation and subsequent drying. Werban et al. (2008), in a pot experiment containing a *Lupinus* plant grown in fine sand, set out to monitor spatial heterogeneity of water movement. Diurnal variations were found, which were assumed to be a manifestation of RWU triggered by plant transpiration. Building on this, Garré et al. (2011) used a 3D ERT to quantify water content changes in soil due to RWU and evapotranspiration. Resistivity variations were correlated here with

minirhizotron measurements of root development. Newill et al. (2014) demonstrated the feasibility of using capacitive coupling insulated electrodes whose purpose is to reduce corrosion and avoid polarization of the probes. The study presented a more efficient acquisition system for measuring impedance, which resulted in the technique being able to resolve water content fraction changes of up to 20%. However, it is important to note that their study measured the magnitude of the complex impedance only, without consideration of polarization effects.

2.4.1.2 *In-situ* studies In an industrialized world with a rising demand for food in both quantity and quality, effective soil management for agriculture is becoming increasingly critical. The majority of *in-situ* root studies have therefore focused on water dynamics exhibited by agricultural crops. In this kind of setting it is difficult to separate the effect of rootless soil as it was previously done for *ex-situ* studies. This underlines the necessity of laboratory trials that attempt to understand and parametrize the more localized behaviour of the root zone, which will subsequently support and serve as reference for field trials.

One of the first studies that assessed the effectiveness of the ERT method in an agricultural context was by Panissod et al. (2001). It revealed the existence of high resistivity patches under cover crops, and these patches were inferred to be linked to plant water uptake. In the absence of appropriate pedotransfer functions, which create the link between water content and electrical resistivity, the water distribution could not be estimated. Also, no ground truth was available for comparison. The study was able to map anomalies in the resistivity distribution, thus showing the potential of the ERT method, but the causal link between resistivity variation and water content depletion remained an assumption. Michot et al. (2001) presented a more robust experimental

design using TDR measurements in parallel with ERT. Resistivity variations with time were observed under crops similar to the ones identified by Panisod et al. (2001). Moreover, a wetting front was localized from the electrical tomogram and preferential flow directions were identified. Michot et al. (2003) subsequently conducted a very similar field trial. The resistivity-estimated water content was compared to that obtained from TDR. The %RMS (Root Mean Square) error was less than 5 and the correlation factor around 0.8, which suggests good agreement between both techniques. Consequently, the work proves the suitability of ERT to monitor soil available water reserves on the field scale. One of the reference works for root zone water dynamics was presented by Srayeddin and Doussan (2009), who conducted a field monitoring study of water uptake under sorghum and maize fields subjected to different watering regimes. The study showed heterogeneous patterns of water depletion in the moderated and poorly irrigated fields. Direct field water content measurements were used to calibrate the resistivity results. The water uptake was found to have a quantitative (and not just qualitative) relationship with resistivity.

The field studies follow a similar experimental set-up to the studies mentioned in section 3.1.1. Figure 2.4 shows an example of a typical survey arrangement on a linear profile. 2D resistivity images resulting from such an acquisition scenario are presented in Figure 2.5. They demonstrate the extent to which ERT resolved the spatial distribution of resistivity. Here, both the lateral and the vertical variability was likely caused by the plant water uptake.

Celano et al. (2011) compared two different soil management regimes, tillage and cover cropping, and found a significant water reserve in the soil beneath the cover crops. The authors used laboratory derived calibration curves between soil moisture and resistivity. The correlation coefficients between resistivity-estimated and directly measured water content was found to be stronger than

that observed by Srayeddin and Doussan (2009). However, the latter measurements were carried out in situ, whereas the former ones were undertaken ex situ, which typically requires additional experimental time and effort. All applications of geophysical monitoring represent a trade-off between time, effort and data quality.

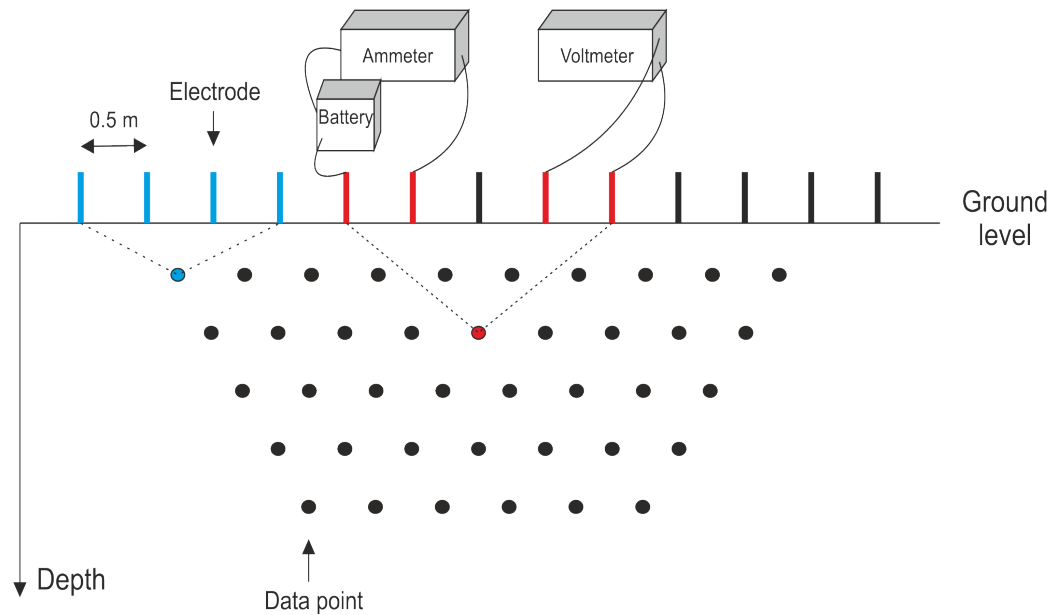


Figure 2.4: Field acquisition pseudosection line used for ERT surveys. Electrodes are grouped in a Dipole-Dipole sequence.

Nijland et al. (2010) presented a case study that used geoelectrical methods to quantify water availability in a Mediterranean soil ecosystem. The study highlighted the power of the roots to penetrate the fractured bedrock to reach water. Robinson et al. (2012) underlined the ease of use and convenience of data collection that an ERT survey provides. They conducted a 3D survey to monitor moisture content in an oak-pine forest, which suggested moisture stability in tree-covered areas and moisture instability in open areas. Beff et al. (2013) monitored WC under a maize field through a joint assessment of ERT and TDR. The latter was used to achieve spatial coverage and the former to

achieve temporal coverage. The resistivity distributions reflected the maize row arrangements in the field. Garré et al. (2013) monitored resistivity changes in mixed cropping systems showing a smaller depletion depth for chili cultures compared to maize and *Leucaena*. Also, a higher depletion was detected close to the intercrop hedges which implied a competition for water between different crop species. Garré et al. (2012) used semivariogram interpretations of WC spatial distribution, indicating moisture variability is highly influenced by soil heterogeneity. Kelly et al. (2011) monitored water migration beneath crops. The resulting resistivity tomograms were compared with WC values obtained using a capacitance probe. Moreover, the study recommended that ERT monitoring should be integrated into irrigation programmes.

ERT monitoring was also used by Musgrave and Binley (2011) to characterize the stratigraphy of a wetland site. The 2D characterization with ERT was performed in combination with GPR. The study highlighted the suppression of temporal changes in resistivity, which was explained by the occurrence of groundwater recharge, providing a means of identifying such recharge areas.

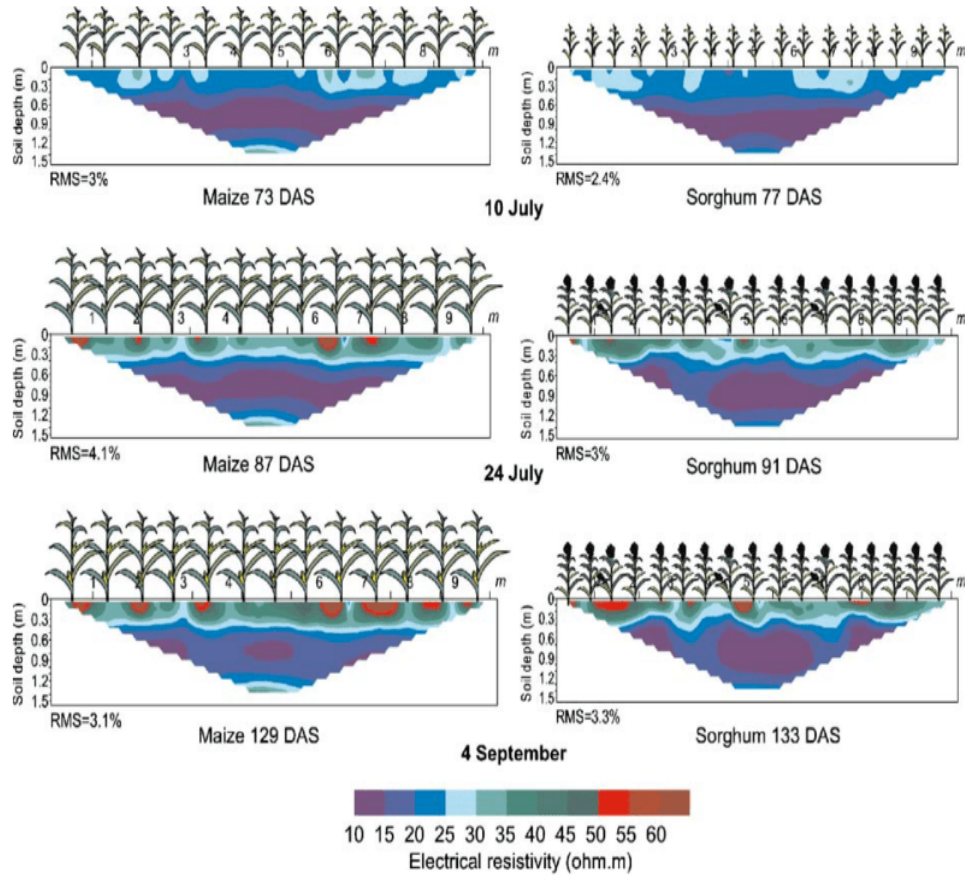


Figure 2.5: 2D ERT field resistivity distribution variation with time under crops of Maize left and Sorghum right. Extracted from Srayeddin and Doussan (2009).

2.4.2 Root structural and functional properties

2.4.2.1 Woody roots

Correlating root properties and geoelectrical measurements. Amato et al. (2008) and Rossi et al. (2011) found a strong positive correlation between resistivity measurements and root biomass. Rossi et al. (2011) also observed a dominating effect of the root biomass over other root zone properties, such as root length density (root length per unit volume), which raised the concern that this has to be taken into account by future studies to avoid bias.

In an *in-situ* experiment, Čermák et al. (2006) successfully estimated tree root absorption surface area with resistivity measurements. Also, the study showed a positive correlation between stem area and root absorption area. In addition, Mares et al. (2016) used ERT to capture the spatiotemporal variability in an active sapwood, which reflects the sapflow upscaling. Guyot et al. (2013) attempted to estimate sapwood area with the use of resistivity monitoring. However, the R^2 correlation between resistivity derived estimates and actual area was low. Jones et al. (2009) used ERT as a means of visualizing tree-induced subsidence. Leveling data indicating subsidence and ERT profiles were in agreement, both being influenced by climatic conditions. As the study did not include quantitative models to accompany and fit the resistivity datasets, the correlations are qualitative.

Mapping tree root systems. Mary et al. (2018) showed the potential of ERT and the Mise-à-la-masse (MALM) technique for mapping woody root system distribution in soil. The concept of MALM measurements is to inject electrical current into a conductive body and make surrounding measurements of voltage. Based on these measurements the extent of the body can be calculated. The assumption is made that the roots are the conductive body and that the current injected through the plant stem will eventually be passed into the subsoil through the root terminations (root hairs). Another study by Zenone et al. (2008) combined ERT reconstruction and GPR sections for the purpose of root detection. Figure 2.6 shows the level of performance that can be expected from ERT when imaging root architecture. The root system is not resolved accurately, but the potential to localize roots is undeniable and the overall shape of the root system is captured well. The study also concluded that combining electrical resistivity with GPR data is useful in the investigation of root shape and behaviour. It was shown that the contemporaneous use of multiple geo-

physical methods improves the quality of the results. GPR was successful for identifying the distribution of the roots in the subsoil, whereas ERT was useful for estimating the root volumes. Leucci (2010) used ERT, GPR and seismic refraction to produce 3D images of tree-root distribution. GPR revealed the extent of the root system, seismic refraction delineated the subsurface layers and ERT distinguished the roots from an old pipe system. The study reinforced the utility of the methods for this application emphasized the benefits of combining the techniques.

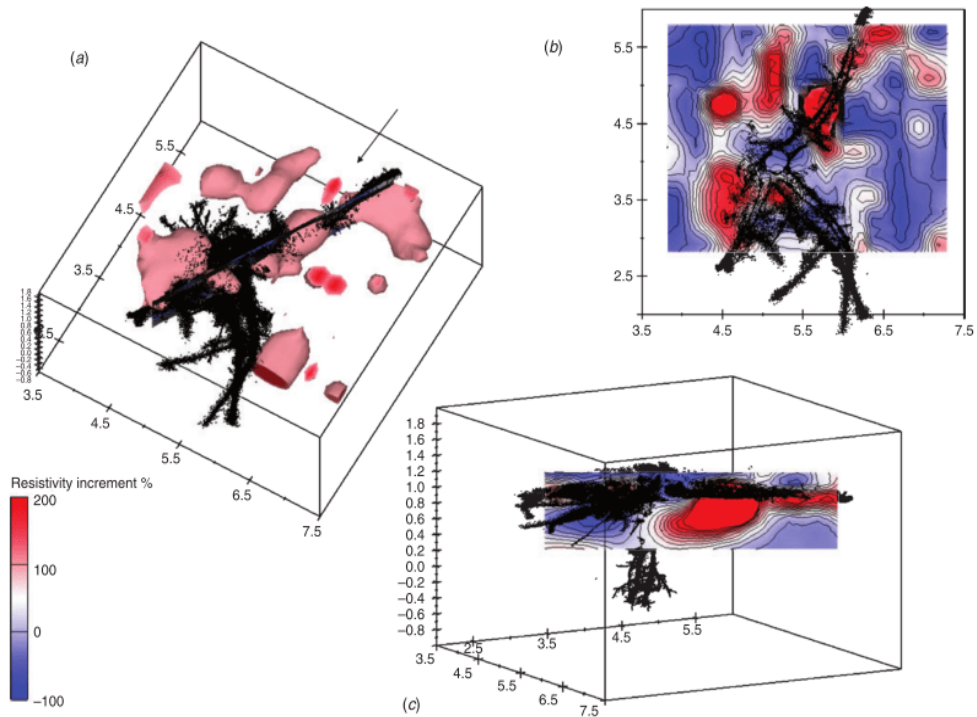


Figure 2.6: Resistivity increment percent differences overlapped on 3D rendering of laser-scan point cloud of Pinus Pinea root system. a) 3D view, b) 25 cm below surface, c) vertical section. Extracted from Zenone et al. (2008)

Root polarization Zanetti et al. (2011) observed the complex conductivity signature of multiple samples of dead roots in three different soil textural environments dominated by gravel, sand and silt, respectively. Additionally, the methodology was able to indicate the presence, type, size and orientation

of buried material. However, measurements were limited to 1D, hence no information about the spatial distribution of the buried samples could be obtained. Polarization effects have also been observed by Martin (2012) when studying wood, suggesting that the methodology was able to identify infection damage in wood cells, which could add significant value to the technique.

Mary et al. (2016, 2017) demonstrated the feasibility of using IP for root detection, whilst performing *in-situ* experiments. Mary et al. (2016) concluded that a dry soil medium is more appropriate for IP measurements as the contrast between the response from roots and surrounding soil is higher. Mary et al. (2017) concluded that, at low frequencies (1 Hz chosen as adequate), significant effects of polarization are dependent on root per soil volume ratio and are sensitive to root orientation. Furthermore, Mary et al. (2017) suggests root WC is proportional to the amplitude of polarization. These results suggest that there is an increasing prospect of using this method in the study of soil-plant interactions.

2.4.2.2 Herbaceous roots Aulen and Shipley (2012) identified a significant relationship between root mass and capacitance. Unfortunately this was too weak without prior species specific calibrations ($R^2 = 0.3$). Ellis et al. (2013) confirmed a weak predictive power of ECM ($R^2 = 0.21 - 0.31$), but suggest an empirical model as a reasonable predictor of root length ($R^2 = 0.56$). Amato et al. (2009) tested the ability of resistivity tomography to detect low-density root systems. They concluded that, although promising for more developed root systems, the resistivity contrast is not sufficient for a low-density regime.

Sabo et al. (2016a,b) proposed the use of capacitance tomography to assess the difference between healthy and dead roots by their ability to absorb water containing nano-particles of iron. Healthy roots showed capacitive readings

that were up to three times lower than diseased ones. A series of pot experiments demonstrated the capability of capacitance measurements to monitor root system properties (e.g. dimensions, mass, root surface) when subjected to herbicide aceochlor (Cseresnyés et al., 2012), mycorrhizal fungal colonization (Cseresnyés et al., 2013), different RWU rates (Cseresnyés et al., 2014; Cseresnyés et al., 2016) and SWC changes together with mycorrhizal activity under field conditions (Cseresnyés et al., 2018). The latter study concluded that EC dependency on SWC is plant species dependent, which underlines the importance of root system architecture through its impact on RWU rate of change. Weigand and Kemna (2017) applied EIT to monitor the root activity of oil seed plants, which were grown in hydroponic conditions. The study discovered a low-frequency polarization response associated to root presence, and the methodology was able to delineate the extension of the root system. The study also observed changes in electrical properties due to root physiological stress imposed by nutrient deprivation.

2.4.3 Root zone conceptual models

Root zone processes and structure are vastly complex. Formulating both conceptual and quantitative models of the root zone is important to help develop our understanding of their complexity. Improved root zone models may help fulfill the long-term ambition to be able to predict future states of the soil-plant system. However, existing root zone models are not universally valid and dependent on locally derived parameters, such as soil texture, porosity, temperature fluctuations, root mass and others.

Geoelectrical monitoring can help improve root zone modelling. As discussed in sections 2.3.1 and 2.3.2, geoelectrical methods have demonstrated their capability to assess root water dynamics and root structure. The recorded variation in

electrical properties reflects root functions (e.g. water uptake) or root-system structural indicators (e.g. mass, length, density). In this section we discuss how this information was in turn used as a basis for models of the root zone in order to 1. estimate the water balance determined by the soil-vegetation interaction 2. estimate effective water uptake in order to optimize irrigation practices and 3. improve conversion between electrical data and crop-scale root zone parametrization. A list of cited articles and corresponding models used can be found in supplementary materials (Appendix A and B).

2.4.3.1 Modelling root zone water dynamics

Interaction between vegetation cover and soil water balance Cassiani et al. (2012) used ERT in conjunction with EMI method and TDR to investigate the effect of vegetation upon water dynamics. A strong correlation was found between the presence of vegetation and the variability of SWC. It was suggested that spontaneously grown vegetation on the bare soil influences the degree of soil compaction, which led to a slow infiltration of meteoric water in the upper layers. This is one of the few studies that have attempted to model vegetation-soil interaction based on electrical monitoring data. This approach holds promise for future research and opens the door for more comprehensive modelling which should take into account the dynamics of vegetation growth. Michot et al. (2003) demonstrated the effectiveness of combining ERT and TDR, in 2D some 10 years prior, but Cassiani et al. (2012) undertook 3D reconstruction of SWC distribution. Whilst geoelectrical methods alone are capable of providing time-lapse information, TDR can be useful for its superior temporal resolution. It is also worth noting ERT systems with permanently deployed sensor arrays and instrumentation are actively being developed, providing superior repeatability and high temporal resolution from ERT measure-

ments alone (Chambers et al., 2014).

Boaga et al. (2014) used ERT to demonstrate flooded plants are able to create aerated layers below the flooded surface when transpiration rate was high. The study found the results were in agreement with the model previously developed by Tosatto et al. (2009), which solved the 2D two-phase flow equations in porous media. Ursino et al. (2014) showed that in fallow plots infiltration is heterogeneous, water redistribution takes place below ground where roots have access to the active volume and the root-soil interplay reduces runoff and increases evapotranspiration. Their study promoted the integration of measurements of soil properties such as electrical resistivity, moisture content and vegetation density in order to develop a comprehensive soil-plant interaction model. However, the study did not employ a meaningful quantitative translation between electrical measurements and soil properties.

Contributing towards irrigation efficiency Boaga et al. (2013) used ERT for temporal monitoring in order to characterize water balance exchanges in the subsoil under an apple orchard. Root growth was closely connected to the geometry of the irrigation system as roots developed in a shallow area, and were aligned with the irrigation lines. Cassiani et al. (2016) built on this approach by developing a model of the unsaturated zone flow using 3D Richard's equations (Richards, 1931). This revealed the potential of the method for monitoring and possibly predicting the time at which fresh irrigated water replaced saline water already present in the soil.

Cassiani et al. (2015) used a 3D ERT system to monitor the root zone of an orange tree. Other measurements of sap flow, eddy covariance and evapotranspiration were used, in combination, to develop a 1D model based on Richard's equation, which described the water dynamics of the monitored soil volume. This calibration was successful and predicted a much smaller water volume

than the resistivity-derived estimation. The implication was that over 50 % of irrigated water was not taken up by plants, illustrating the importance of quantitative modelling to help interpret electrical monitoring data. Furthermore, Consoli et al. (2017) monitored and compared the impact of full versus partial irrigation, based on a reduction of water input by 50%. The study showed that water efficiency and fruit yield increased when a partial irrigation regime was used, which also implied that overirrigation affected productivity.

Enhancing the pedotransfer calibration In an effort to avoid site-specific calibrations and to make the irrigation process more efficient, Brillante et al. (2014) developed a pedotransfer function to estimate WC from ER data. The function is obtained through the use of a learning algorithm and estimated soil water wetness. It performed moderately well, showing a correlation of 0.67 between measured values and resistivity derived estimates of WC. Nonetheless, the methodology holds promise due to its potential to reduce laboratory effort to calibrate the resistivity results.

Moreno et al. (2015) used a model of water flow and solute transport to differentiate between the contribution of state variables (WC and salinity) to resistivity. Other studies discussed above have focused on plant inputs (Cassiani et al., 2015; Ursino et al., 2014), whereas their study was aimed at improving the quantification of non-plant related inputs to bulk resistance values. Both approaches are necessary in future modelling efforts. Plant physiological measurements were combined with ERT measurements by Brillante et al. (2016), in a study of grapevine. The work revealed that variability in the water uptake regimes was highly dependent on plant water stress as striking differences between regimes during night and day were found. Brillante (2016) fitted two models to predict soil water variation with the aid of field measurements of electrical resistivity. Instead of using absolute values of electrical resistivity for

model fitting, this study used their variations as predictors. They also used several machine-learning techniques to tune the model parameters in order to avoid over-fitting. For the current datasets, the gradient boosting machine method outperformed the others. Finally, the model results were compared to TDR measurements reaching to a satisfactory agreement (RMSE 22.6%).

2.4.4 Other applications

2.4.4.1 Resolving pedological parameters Morari et al. (2009) combined resistivity imaging, EMI and geostatistics and concluded that conductivity correlated positively with coarser textural soil components and negatively with finer components. Furthermore, this approach served as a basis for mapping subregions of the field within which crops are similarly affected by seasonal differences in weather and soil management. Celano et al. (2010) conducted a survey with the aim of establishing a correlation between pedological parameters, calculated through field sampling measurements, and electrical resistivity measurements. As resistivity measurements are sensitive to differences in salinity, ERT proved efficient in detecting salt accumulation in soil. Electrical monitoring was used to distinguish between different tillage systems in Basso et al. (2010). Soil properties such as bulk density or water storage are affected by tillage, therefore resistivity profiles showed significant differences between the soil practices. Future studies on this subject should consider correlating the variation in the electrical response with soil structure appraised by higher resolution imaging methods (e.g. X-ray CT). Kowalczyk et al. (2015) attempted to identify peat horizons through application of ERT, however, the heterogeneity of the soil made the inversion results inconclusive. The inversion generalized the resistivity values associated with the organic layers and treated them as parts of a sand layer, a result confirmed by a forward model based on geological

units determined by drilling. It would seem that, identifying soil peat horizons in this manner is currently below the ability of the ERT method alone due to the length scales involved.

2.4.4.2 Plant phenotyping Plant phenotyping is an emerging research area concerned with quantitative measurement of the structural and functional properties of plants. Lu et al. (2018) compared root zeta potential for 17 types of crops using streaming potential measurements whereby an electrical potential is generated when an electrolyte passes through a porous plug with charged surfaces. The study only found distinctive differences between legumes and non-legumes, due to a higher concentration of functional groups in the former. Combined ERT and EMI measurements were used to phenotype roots in the field by Whalley et al. (2017). The result of their study suggested that by comparing the shifts in patterns of soil moisture content, genotypes may be differentiated. Genotypic differences, more obvious in dry conditions, were observed in depth of water uptake and in the extent of surface drying. This result is very important for the economics of agricultural practices as the geophysical approach potentially saves time and effort spent on root excavation for direct measurements. The effect of soil physicochemical properties on the discrimination power of this method has yet to be investigated. Therefore, the first step is to test the phenotype discrimination methodology under different agropedoclimatic conditions and subsequently verify which factors enhance or diminish it.

2.5 Discussion and future outlook

2.5.1 Choice of geoelectrical method

The majority of geoelectrical methods are concerned with measurements of electrical impedance (Section 2.3). The main distinction between the nature and complexity of information resides in the information extracted from such measurements. Firstly, we can distinguish between single-frequency and multi-frequency acquisition strategies. Multi-frequency measurements offer additional information about polarization processes, but extracting electrical parameters, such as chargeability or relaxation time across a frequency spectrum is not straightforward and requires more acquisition time. However, methodology (Weigand and Kemna, 2017), instrumentation (Zimmermann et al., 2008) and sampling strategies (Weigand and Kemna, 2016), associated with spectral methods, are rapidly developing and are likely to replace the more extensively used single-frequency or DC methods, such as ERT, for root zone monitoring applications.

One of the overarching themes of this review is root detection. There is clear evidence for a strong correlation between the imaginary resistivity component and root parameters (Chloupek et al., 1972; Ellis et al., 2013; Weigand and Kemna, 2017), but several studies have also found a correlation between the real part and root parameters (Cermak et al., 2006; Amato et al., 2008; Rossi et al., 2011). However, electrical resistivity was only correlated to root biomass and failed to reflect other root physical parameters such as root length density. In addition, resistivity studies showed greatest success when investigating woody roots, and further studies indicated that the resistivity contrast generated by low-density herbaceous roots is indistinguishable from the effect of other root zone features such as WC or grain size (Rossi et al., 2011). Further-

more, methods that include measurements of polarization have the potential of resolving not only root physical parameters, but characteristics of root activity such as interactions with fungi colonies (Cseresnyés et al., 2013) and reaction to physiological stress (Weigand and Kemna, 2017) or even root health (Sabo et al., 2016a). In summary, measurements of imaginary impedance have proven more conclusive for root investigation and offer a broader range of applications. Figure 2.7 shows the increase in research articles featuring geoelectrical applications in the root zone, which highlights the rising interest in the use of such methods. It also shows that the use of classical ERT is in decline compared with other methods, whereas the use of ECM and SIP is growing. In addition, this analysis shows that the number of laboratory studies in this area has grown over time. This clearly reflects the increased effort dedicated to method development, especially for advance geoelectrical methods beyond ERT. These tend to require significantly more sophisticated instrumentation and greater care to obtain good quality measurements. So far they have therefore mostly been employed ex-situ, although field applications are likely to increase once the methodology development has reached a greater level of maturity.

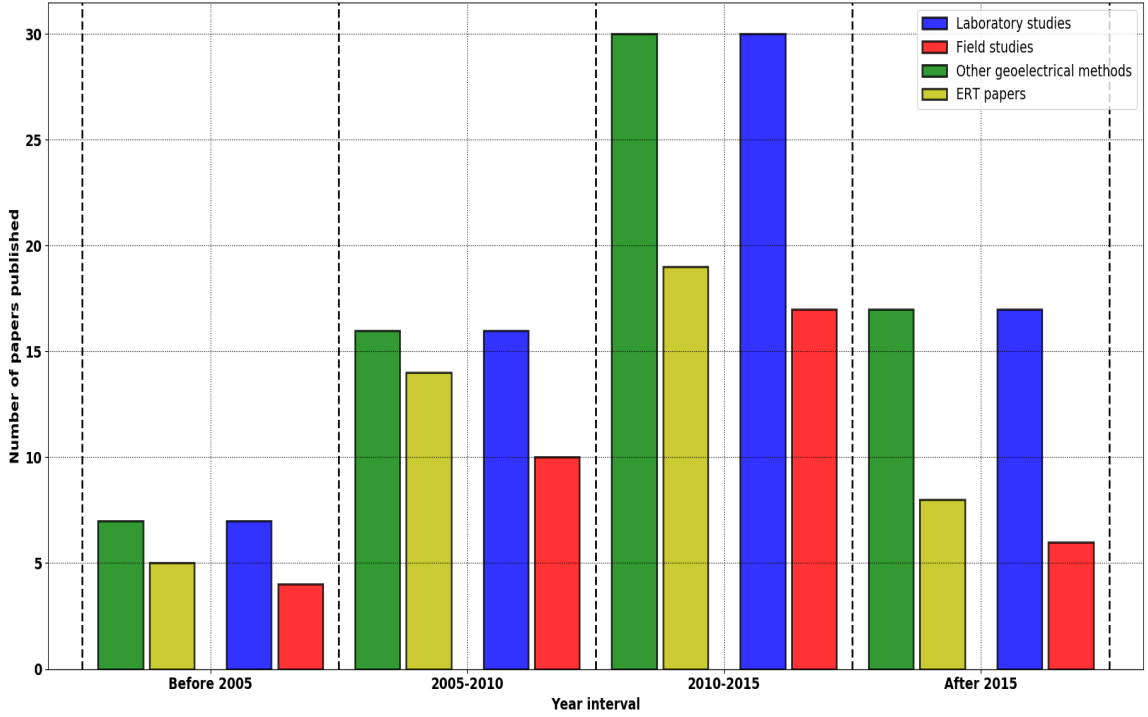


Figure 2.7: Bar chart indicating number of published articles which use Geoelectrical monitoring methods for the study of root zone processes.

2.5.2 Acquisition set-up and inversion algorithm

The dimensionality aspect of geoelectrical investigation is not to be treated lightly in the context of root zone monitoring. Previous research makes a clear distinction between the appraisal of a finer discretized model monitoring a singular root system, usually at lysimeter scale, and coarser models, usually at field scale. In addition, field surveys obtain a 3D properties distribution either by collating multiple 2D acquisition lines of superficial electrodes (Leucci, 2010) or by using a square array of acquisition with borehole electrodes (Cassiani et al., 2016). Using just one acquisition line, for 2D surveys, implies an easier set-up and quicker repetitive measurements. However, an agriculture field-site displays spatial heterogeneity, which this type of set-up fails to capture. A 3D survey by multiple superficial electrodes will provide the data

coverage required, but will imply an expense in resolution. In contrast, using borehole electrodes allows higher resolution (especially in depth) but limits the user to a confined field sub-volume of investigation (1-2 m³).

We mentioned previously (section 2.3) that the tomographic model mesh of the subsurface is discretized according to the specific volume of investigation. However, the inversion problem becomes increasingly delicate when one attempts to obtain a model of the root zone. Firstly, there is a question of scale which closely matches the acquisition options described above. A lower resolution survey (depending on electrode arrangement) will imply coarser mesh discretization. Secondly, there is a question of electrical property variability. The root, rootles soil and the volume surrounding their interface (i.e. the rhizosphere) can be considered as electrically distinct areas, which in consequence can be constrained differently. As we have demonstrated, knowledge about each of these areas exists individually. However, the challenge for future research is to collate this information into one electrical model and further refine inversion strategies around this parametrization. For example, providing one has information about the extent of the root system, this volume can be also meshed, disconnected and assigned a different smoothing factor from the rest of the surrounding soil.

2.5.3 Electrical response from woody versus herbaceous roots

The two categories of roots display different electrical responses. Essentially, the difference in size, not the root functionality, appears to account for the distinction. The larger woody root, with a higher density and surface area, showed higher correlations with electrical resistivity and had a bigger impact on its change than finer roots found in the same system (Rossi et al., 2011). In terms of polarization, other soil properties, such as WC, are important in

order to obtain a good response (Mary et al., 2016,2017). Furthermore, both types of roots show polarization, but not necessarily at the same frequencies. Weigand and Kemna (2017) reported a strong polarization at 70 Hz for herbaceous roots and Mary et al. (2017) reported 1 Hz to be suitable for woody roots. The distinct polarization frequencies could prove to be important for root classification if future research considers the analysis of larger scale root systems, which contain both kinds of roots.

2.5.4 Knowledge gaps in pedophysical relationships

It is a common observation in the literature that none of the previously developed pedophysical relationships (pedotransfer functions for geoelectrical data) is perfectly adapted to the specific site conditions (e.g. soil texture, porosity, organic matter content) under investigation (Laloy et al., 2011). Therefore, calibration is usually required in order to empirically determine new functional parameters corresponding to each individual site.

2.5.4.1 Formulating pedophysical relationships in the lab When considering a rootless soil calibration, most of the studies that have employed pedophysical calibration for field measurements have used soil samples repacked ex-situ. It is extremely difficult to recreate the chemical composition of the pore water (Furman et al., 2013) and a sample's natural pore structure under laboratory conditions. Working with disturbed samples disregards the effect of pore tortuosity, considered essential when evaluating conductivity pathways and consequently bulk resistivity measurements (Rhoades et al., 1989). Also, agricultural soils are quite frequently subjected to anthropic interactions, which generate spatial and temporal variations which can effect soil compaction. The latter is known to be a direct control on resistivity (Romero-Ruiz et al., 2018). In these circumstances a well suited approach is performing calibration mea-

surements on undisturbed soil samples or to be attempted *in-situ* (Srayeddin and Doussan, 2009; Michot et al., 2003).

We previously mentioned (section 2.2 and 3.1.1) the distinction some of the studies make between analysing electrical properties of the rootless soil, the root system or the root zone as a whole. We consider each has its own merit and corresponding relationships between root zone properties and electrical parameters important for future research. Currently, many studies referenced in this review (Srayedin and Doussan, 2009; Celano et al., 2011; Garré et al., 2013) are interested in the observation of root activity (e.g. suction), therefore being able to translate electrical measurements to WC balance of the target volume is crucial. In this case one would not be able to depict the outline of root system itself, but only delineate the impact on the surrounding soil. However, one can expand this methodology and determine root suction variability under different climatic, nutrient availability or soil textural conditions. This will contribute to our knowledge of plant health and yield potential. Also, plant phenotyping represents a promising potential application of geoelectrical research as suggested (Whalley et al., 2017). However, the methodology needs to be proven suitable in different environments before its effectiveness can be demonstrated. Furthermore, one may be interested in quantifying root development, therefore firstly it would require the derivation of a clear electrical response from the rootless soil. Any variation from the base electrical spectrum would imply root mass development or root activity. The rate of development obtained as such could determine a plant's medium adaptability or its interaction with other elements of the ecosystem.

2.5.4.2 On the variability of pedophysical relationships Garré et al. (2011) underlined the necessity for horizon-specific calibrations for an undisturbed soil column. Also, Furman et al. (2013) acknowledged climate seasonal

variations in climate cause not only changes in WC, but also salt accumulations, thus making concentration of solutes in the water-filled pore spaces variable with time. Ultimately, for an accurate description of soil properties it is desirable to include high spatial and seasonal temporal variability.

We have mentioned above the effect of roots on bulk resistivity measurements, which is caused by the electrically conductive pathways they form (created by the nutrient solution absorbed through the xylem) and EDLs both at the exterior and interior surfaces of the root. The literature offers examples of empirical relationships between root biomass and resistivity (Amato et al., 2008), therefore we recommend future studies should include this aspect in the formulation of pedotransfer functions. Also, root system development alters the soil structure and its chemical properties, invariably changing the electrical properties of the surrounding soil. Future research should therefore consider combining existing numerical simulations of root architecture and its impact on soil hydraulic properties (Postma et al., 2017) with geoelectrical numerical models in order to achieve a more realistic pedophysical calibration.

2.5.4.3 Computational approaches in pedophysical calibration A different way of approaching the translation is emerging from the field of data science, including 'big data' analytics and parameter prediction methods based on machine learning. Rather than attempting to develop a universal analytical transfer function, a more adequate result might be obtained by calculating an 'educated estimate' based on prior knowledge from existing data. Provided a sufficiently large input dataset exists, deep learning algorithms can be utilized to predict an effective representation of the desired output parameter. Examples of work in this direction have already appeared in the literature (Brillante, 2016). An emerging trend in data science is convolutional neural networks (Pound et al., 2017). These computational systems, inspired by natural neu-

ronal architectures, have the capability of developing a learned strategy that extracts the relevant characteristics from an existing series of inputs. When presented with a new input, the neural networks are able to identify in the new input the characteristics previously learned (based on the learned model) and subsequently classify or make a prediction from it. These kinds of algorithms are now widely used in image processing and pattern recognition. In soil science applications, a neural network could be used to predict moisture content, provided it was 'trained' with a large enough dataset containing other soil parameters including electrical data. Future opportunities will lie in the potential of such networks to transfer between domains. This implies that a network trained on a wide range of different experimental conditions could capture a more general model of the transformation which in turn could be tuned to new conditions by additional training with a comparatively small amount of data. Attempts to use such networks in soil and rock physics have already been reported in the literature (e.g. Pachevski and Timlin, 1996; Koekkoek and Bootink, 1999). Also, different machine learning methods are already being employed in an effort to enhance the fit between models of soil water balance and electrical resistivity data (Brillante, 2016).

2.5.5 Enhancing the geoelectrical characterization of the root zone

The tomographic imaging capability of geoelectrical methods offers unique quantitative information about the spatial variability of soil properties. Especially for field investigations it is desirable to be able to obtain large scale images of the subsurface. However, geophysical inversion is ill-posed and requires regularization, ideally combined with additional (a-priori) information in order to create an accurate model of the subsurface. The constraints are often unsatisfactory when inversion is applied to geoelectrical data alone. In

this section we discuss strategies to reduce the uncertainty in the geoelectrical images.

2.5.5.1 Use of complementary datasets In Section 2.3.1 and 2.3.2 we have discussed studies that simultaneously employed ERT together with other electromagnetic methods for synergetic monitoring and characterization of soil moisture. Complementary techniques include TDR (Beff et al., 2013, Boaga et al., 2013, Michot et al., 2003) GPR (Musgrave and Binley, 2011; Leucci, 2010) or EMI (Cassiani et al., 2012; Morari et al., 2009; Whalley et al., 2017).

The most commonly used method that provides complementary data is TDR. It measures the dielectric permittivity of the soil which is subsequently converted into SWC (Topp et al., 1980). TDR probes position usually follows the electrode arrangement used for geoelectrical surveying (Figure 2.2). This offers the advantage of directly comparing results without the need for correction for spatial distribution, scale or mesh discretization. Therefore, in the context of geoelectrical research, TDR data is mainly used for ground truth and can help isolate the contribution of SWC to the bulk resistivity response. Given the prevalence of TDR measurements in the literature, it could easily be assumed that TDR is sufficient for monitoring soil moisture variability. However, whilst TDR does provide good temporal resolution, is restricted to single point measurements, and therefore offers only limited spatial coverage.

In contrast to TDR, the output of GPR and EMI is an image of the subsurface, therefore they generally provide good spatial coverage. GPR offers a high spatial resolution and is primarily used to delineate zones with different lithology. Due to the physics of low frequency electrical flow, it is difficult to obtain sharp lithological boundaries (including soil horizons) from ERT images (e.g. Figure 2.5), but GPR data has the potential to enhance this (Musgrave and Binley, 2011). Due to the nature of the instrumentation, EMI provides a very fast and

effective way of determining the spatial distribution of soil electrical conductivity and resolving lateral contrasts on a large (field-) scale. However, EMI is faced with intrinsic challenges such as the lack of vertical resolution. When combined with ERT, it is possible to obtain comprehensive field-scale models of conductivity variation both laterally and vertically. Joint interpretation of this kind has proved successful for aquifer characterization (Linde et al., 2006) or estimating field scale soil hydraulic conductivity (Farzamian et al., 2015). Previous authors have highlighted the capabilities of a combination of EMI and ERT for root zone imaging and soil moisture characterization (al Hagrey, 2007).

Other complementary methods involve measuring soil parameters destructively. A number of studies presented in this review (Amato et al., 2008; Rossi et al., 2011; Celano et al., 2010; Zenone et al., 2008) quantified root length density (RLD) or root biomass (RMD) by collecting all the roots in the analysed sample and measuring their length and weight, before correlating this information to electrical results. This procedure is perhaps useful for proof of concept, but a fully non-invasive strategy is clearly more desirable for practical applications, particularly for monitoring processes in the root zone over time.

2.5.5.2 A-priori information about the root zone Soil structural details are an example of the kind of highly relevant additional information required and represent a good source of a-priori knowledge. Alternative methods of tomographic imaging from other fields of science are well developed, including X-ray CT, MRI or neutron imaging. These are able to provide details of soil structure at high resolution (down to 1 μm). There is significant future research potential in conducting joint experiments that include the synergetic application of geoelectrical methods and high-resolution structural imaging methods, both appraising the same soil volume. Early attempts were made by Olsen et al.

(1999) and Cassiani et al. (2009) using X-ray information to explain patterns in the electrical response, but conclusions were qualitative and a quantitative link is currently missing. Three-dimensional reconstruction of the pore architecture to a high resolution allows the calculation of pore network parameters (e.g. pore diameter, connectivity). On this basis, subvolumes of the pore space that account for fluid percolation in the soil sample can be identified (Koestel et al., 2018). This information can in turn be used to constrain geoelectrical inversion results, e.g. by specifying regions of the soil volume with an increased or decreased propensity to fluid movement. Those regions are likely to be associated with greater changes in electrical properties.

X-ray CT is also a very effective ground-truth method for root characterization as it permits reconstruction of the root system to a high spatial resolution by segmenting radiograms of the root zone (Mairhofer et al., 2016). This kind of information can be parametrized accordingly and included into coupled frameworks containing both 3D electrical and root architectural data. As previous laboratory polarization studies have looked at roots in hydroponic solutions (Cao et al., 2010; Weigand et al., 2017,2018) this strategy can serve to develop our understanding of root electrical properties in soils. The exact spatial position of every root segment can be used to modify the finite element mesh of the starting model for the geoelectrical inversion. We have highlighted studies that represent the root system as an electrical circuit analogue (Dalton et. al, ; Cao et al., 2011); in that context the root segment contribution to electrical properties can be quantified. Subsequently this contribution can be associated with the corresponding mesh element and its impact on the electrical inversion results assessed (Rao et al., 2018). Given that previous research has established that preferential infiltration can happen along main root channels (Werban et al., 2008), it is therefore possible to quantify the contribution of

individual root segments to water uptake using suitable parametrization in the geoelectrical model.

2.5.6 Enhancing root zone conceptualisation

Various authors have suggested conceptual models for the root zone, including models (complete list in Appendix B) that represents root materials as resistors (Cao et al. 2010; Ellis et al. 2013), models which account for water movement (Cassiani et al. 2016; Ursino et al. 2014) or a model that accounts for both, biomass and soil moisture (Cassiani et al., 2012). In this section we will discuss the current state of conceptualization of the root zone and propose future research opportunities from a geoelectrical perspective.

2.5.6.1 Root analogue electrical circuit models According to Ozierlafontaine and Bajazet (2005), the root zone system can be electrically divided into multiple components, namely the stem-root internal medium, the soil-root interface, the soil medium and the electrode contact with the plant/soil. Every component has a different manifestation with respect to conduction and polarization. Each requires careful electrical parametrization and their contribution to the overall electrical response needs to be appropriately quantified. For example, currently there is no clear distinction between the contributions from the root mass and the root-soil interface to capacitance measurements.

The Dalton model is considered an important benchmark for the way the root system is electrically represented, as multiple groups of Resistance-Capacitance (RC) pairs connected in parallel. However, inconsistencies in the Dalton model have been reported (Dietrich et al., 2012; Ellis et al., 2013), forcing a rethink in the way the soil-root system is electrically interpreted. One can regard the Dalton model as an oversimplified analogue, and in fact a more comprehensive model includes a combination of series and parallel RC groups (Cao et al.,

2010). Furthermore, for hydroponic systems, both Dietrich et al. (2012) and Cao et al. (2010) suggest that the root tissue above the solution surface is the main contributor to capacitance and resistance. The analogue circuit model architecture and relative contribution of individual components are key concepts that will guide the future quest for more effective models of the root zone.

2.5.6.2 Separating contributors to the electrical response

Recent studies have attempted to develop models which simulate the soil system water balance and use them as a substitute for collecting field data, highlighting the effectiveness of an accurate model (Cassiani et al., 2012). Frequently, soil electrical conductivity changes are solely attributed to variations in WC, but in fact multiple contributors can be responsible, including levels of salinity or organic content and distribution. Therefore, quantitative models require a clear separation between such contributors when computing electrical conductivity. It is also important that model boundaries take into account the open nature of the system being studied, as energy and mass are exchangeable with the medium surrounding the modelled system. Many models lack robustness from the poor definition of boundary fluxes (Garré et al., 2011). Therefore, better mathematical expressions of such exchanges are required, reflecting evapotranspiration, rain water influx, groundwater movement and others.

Future laboratory studies should firstly focus on the rootless electrical response to water content variation and only secondly introduce roots into the system once the medium is appropriately parametrized. Furthermore, the presence of roots will undoubtedly change their surrounding medium. How much the different resulting elements, such as: a modified soil structure, the suction power of root, mucilage formation or the presence of organic material itself contribute to such change remains an unknown and therefore must be explored.

2.5.6.3 Integrating plant hydrology models and geoelectrical mea-

surements The current state of computational technology allows the simulation and visualization of reasonably complex root zone processes in four dimensions. Elucidating the impact of root architecture on root zone hydraulics is of increasing interest especially for practical purposes, such as sustainable irrigation (Green et al., 2006). As different components of the root system have different hydraulic properties (Javaux et al., 2013), the ability to simulate and quantify this structural effect is essential for an accurate interpretation of monitoring root-water uptake. Access is already available to models that can simulate root-growth for different plant types (e.g. CRootBox; Schnepf et al. (2017)) and even models that couple root growth with water or nutrient uptake simulations (e.g. OpenSimRoot; Figure 2.8). However, as underlined by Draye et al. (2010), it is still unknown if the soil or the plant is the main driver of water flow, or indeed where the greatest barrier to water flow resides (e.g. root-soil interface, in the soil, in the root). As geoelectrical data provide a proxy for imaging changes in WC, there is potential in developing a coupled hydrological model of the root zone. From a plant research perspective, a useful review focused on plant biological models across scales is given by Hill et al. (2013), who discusses the interplay between root biology and surrounding soil system from cellular to crop level. The authors emphasize the need for monitoring quantitative changes in root biology (e.g. hormones, water status, nutrients), a need that could potentially be fulfilled by geoelectrical monitoring, as there is evidence that geoelectrical techniques are sensitive to root functional stress (Weigand and Kemna, 2017). Hill et al. (2013) also argue for bridging the gap between genetic and environmental regulation. In that context we believe that field scale geoelectrical surveys could provide an appropriate assessment of changes in water dynamics, root activity or even root growth.

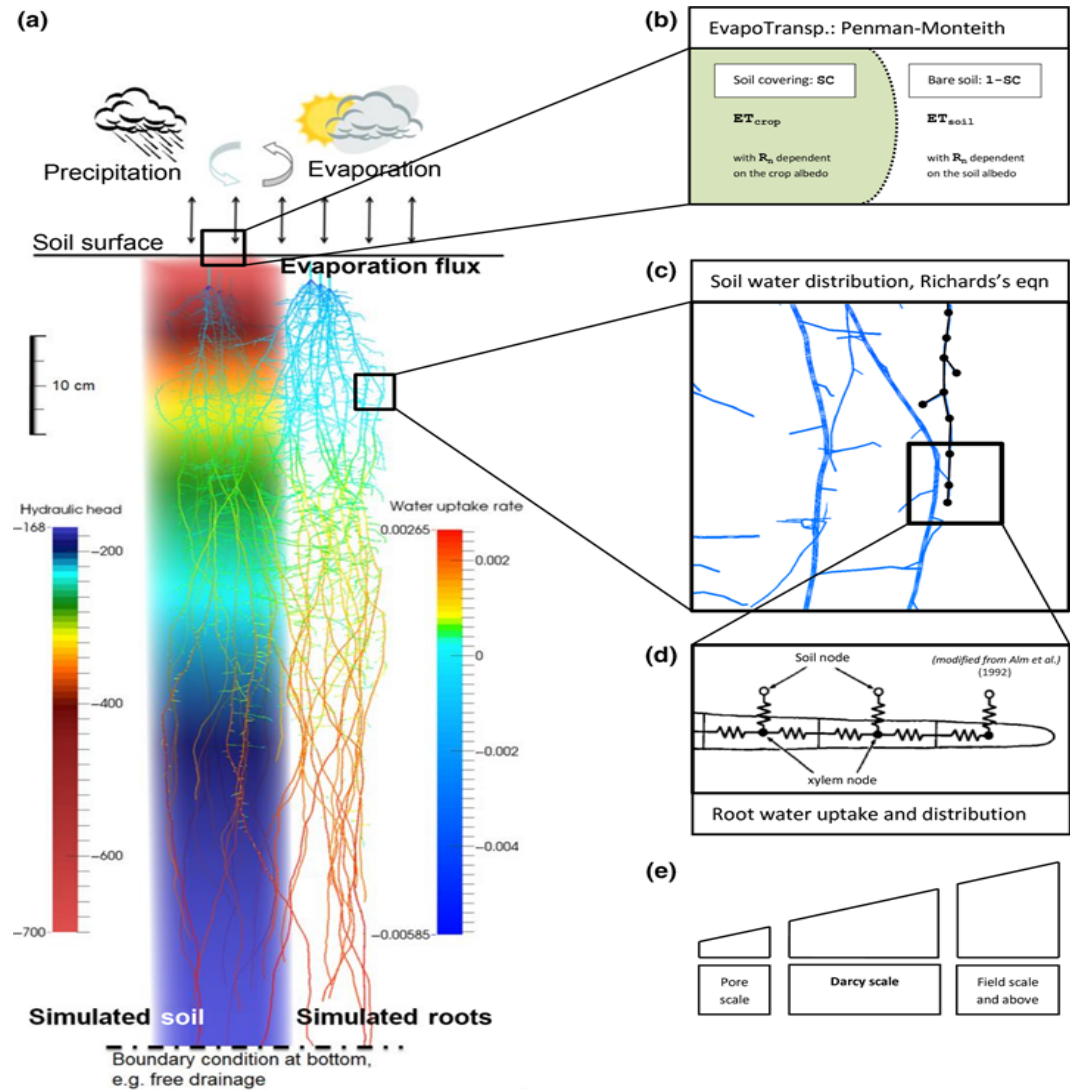


Figure 2.8: Schematic representation extracted from Postma et al. (2017) representing the model used that couples evapotranspiration, xylem transport and soil water dynamics. a) Soil pedon with the hydraulic head indicated in pseudo-color (left) and three barley root systems (right) taking up water from that column. b) Penman– Monteith equation was used for the simulation of transpiration and evaporation. c) Section of the simulated root network showing its edges and vertices d) Network model used for the simulation of water flow through the roots (Alm et al., 1992) e) Water transport in three dimensions in the soil was simulated by solving the Richards equation, which combines Darcy's law with mass conservation, using the finite element method.

In the light of this, there is significant future research potential in devel-

oping a coupled multidisciplinary framework for characterizing and monitoring root zone hydraulics (Figure 2.9). This framework comprises both a hydraulic and an electrical model of the root zone. It will undertake forward simulations of root zone hydraulics and translate the results to electrical properties via appropriate pedotransfer functions. The results will then be compared with simulated electrical measurements acquired on the same soil volume. In Stage 1 we establish the baseline soil medium and root network properties. This is followed by flow process modelling, expressing how does the properties determined in the previous stage affect root nutrient/water uptake (Stage 2), mapping prior obtained parameters on an appropriate mesh (Stage 3) and finally translating the model results into geoelectrical parameters (Stage 4). A disagreement between both sets of results (measured and modelled geoelectrical parameters) would imply a shortfall, either in the way flow processes are implemented in the model, or in the conversion between hydraulic and electrical root zone properties (Figure 2.9 stage 2-3). The simulations could be iteratively repeated until the discrepancy is minimized, hence providing an opportunity to determine the value of unknown parameters which lead to the initial misfit. This overall approach should allow us to simulate the electrical response in space and time holistically as a function of both soil and root properties. At present, tools are available to conduct numerical simulations of this kind at the individual plant scale, for example in laboratory containers under controlled conditions. Future research could follow a similar strategy for field scale simulations, although there are other external effects such as climate or vegetation growth (Cassiani et al., 2012), which need to be parametrized and integrated into the modelling framework.

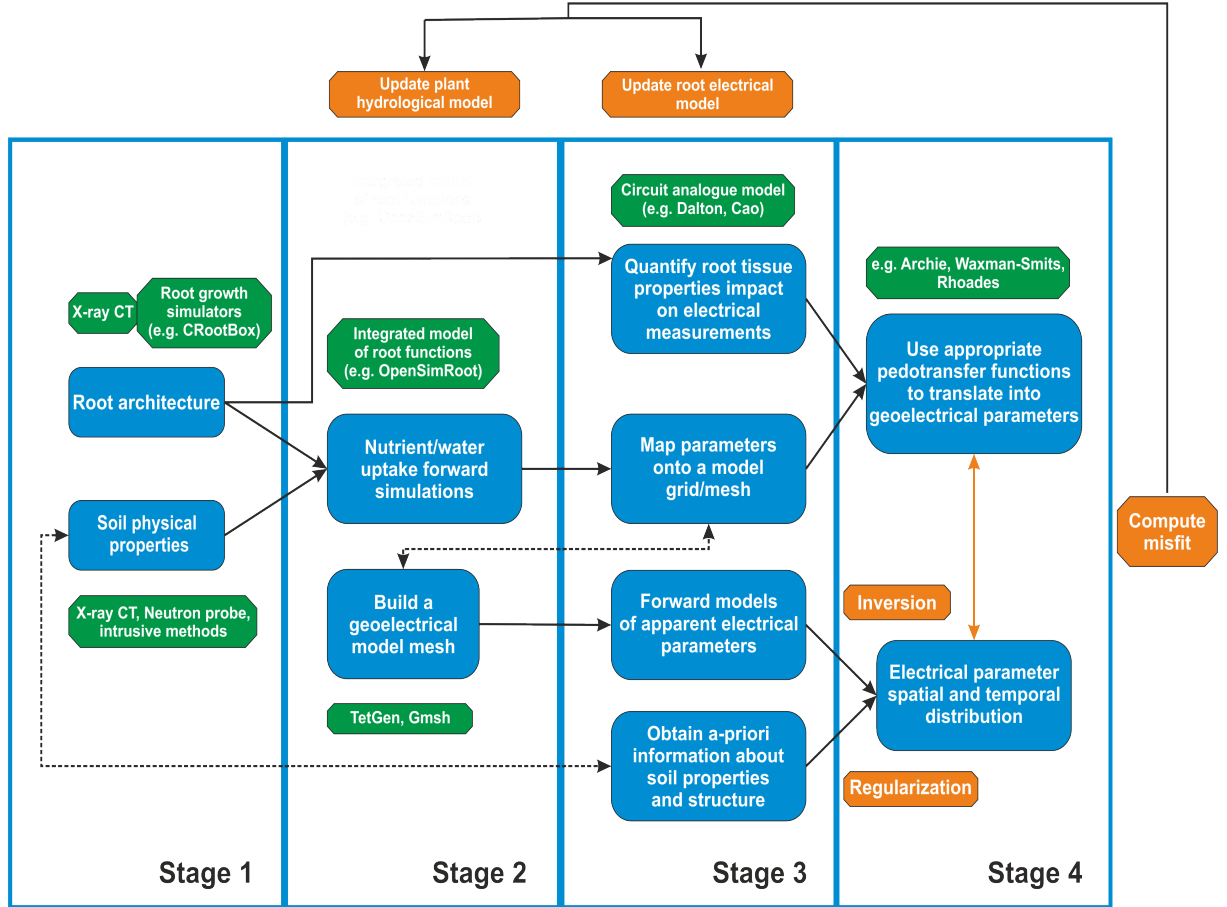


Figure 2.9: Stages of an interdisciplinary strategy to perfect root zone geoelectrical monitoring and corresponding conceptual models. In blue: Main steps of the strategy flowchart; In green: Existent auxiliary methods or models that can be used; In orange: Mathematical algorithms needed; Black arrow: Indicates the step succession; Dashed double arrow: Underlines the need of consistency between the two steps; Orange double arrow: Implies a comparison between the results.

2.6 Conclusions

This review sought to highlight the potential advantages and limitations that geoelectrical methodology can bring to research in the soil sciences and in particular to root zone studies. Geoelectrical methods offer minimally invasive data acquisition, are cost effective and have the ability to monitor key physical (soil water balance), chemical (soil water salinity) and biological (root growth) processes in the root zone both in space and time. A body of literature has

developed, which shows these methods to be very effective for the examination of root zone water dynamics and the detection and characterization of root architecture. It was presented and discussed the main characteristics of both established and emerging geoelectrical methodologies. Currently, ERT is one of the best established and most evolved techniques, however the information it delivers is limited to a single physical parameter and not without ambiguity. ERT is by far the most frequently used technique in the literature, but other methods (e.g. SIP, TDIP, EIT) provide more holistic measurements including electrical polarization. These have also proven their ability to determine soil properties (albeit often under more controlled laboratory conditions), and can provide superior sensitivity to root properties (e.g. mass, length), type (woody or herbaceous) and functions (e.g. evapotranspiration, nutrient absorption). Future root zone research must therefore carefully consider the choice of geoelectrical methodology in experimental design. Particularly for larger scale root zone field studies the availability of techniques and instrumentation is more limited.

An evaluation of previous research has highlighted the difficulty of determining robust pedophysical relationships (i.e. pedotransfer functions for geoelectrical data), which are required for meaningful property translation and experimental calibration. It is expected that future research to take into account their variability in space and time and to consider emerging trends in data science, including convolutional neural networks. Furthermore, due to the inherent limitations in the spatial resolution of geoelectrical methods, the value of synergistic studies with other soil assessment methods (e.g. TDR, EMI, GPR) is highlighted. Such a strategy is suitable for field scale characterizations of the root zone and offers the potential of including high resolution soil and root structural information into geoelectrical inversion models. Finally, it was

demonstrated the benefits of geoelectrical information in root zone conceptual modelling. This work calls for improvements to the analogue circuit representation of the root system components, underlining the need for separating the main contributors to the electrical property variations when constructing a model and propose a coupled multi-disciplinary characterization and monitoring framework incorporating simulations of plant growth-hydrological parameters and geoelectrical measurements.

3 General method description

In the following subsections, the two methods used in this research, X-ray CT and ERT, will be introduced in greater detail. The conditions and preliminary experimental work that facilitated a joint ERT-CT experiment will also be outlined. A combined methodology that benefits from the specific strengths and capabilities of both techniques is then presented.

3.1 ERT

The general principles of ERT have been outlined in subsections of the previous chapter (2.2, 2.3). In practice, the challenge arises with the way data is acquired, modelled and interpreted. In reference, this work is split into three distinct parts: sample selection, model design (forward modelling) and data processing (inversion modelling). Misinterpreting any of these could potentially heavily distort the representation of reality.

3.1.1 Sample selection

In order to obtain a value of soil electrical resistivity one requires a soil sample large enough to allow the passage of electrical current. For the electrical current to be injected and potential difference to be measured through electrodes, the samples need to physically accommodate an electrode galvanic contact (Furman et al., 2013). In addition, the quality of the electrical signal is dependent on the contact resistance between the electrodes and the sample, which desirably, was established empirically to be lower than 5 k Ω . Contact resistance is influenced by variables such as contact surface area, soil texture and soil moisture (Samouëlian et al., 2005). For these measurements cylindrical stainless steel electrodes of 2 mm diameter were used. In order to ensure a good

contact, the electrodes would protrude into the sample approximately 5 mm from the surface.

The size of X-ray CT samples is constrained by the size of the X-ray chamber. Therefore, in order to collocate measurements from the two tomographic methods, an ERT system had to be adapted to measure on laboratory size samples. Cylindrical samples have the most effective shape, allowing X-ray projections on the whole 360 ° range (du Plessis et al., 2017). Therefore, the objective here was to find a suitable ERT measurement sequence that allows the detection of conductive targets inside a soil (more resistive) cylindrical volume (Figure 3.1 A). The first column used measured 14 cm in diameter and 30 cm in height (Figure 3.1). The cylindrical core was surrounded by four rows of 20 equally spaced electrodes.

3.1.2 Forward model

Before conducting an ERT acquisition, it is highly recommended to carefully design and simulate the performance of the electrical model. The performance of the simulation represents the measurement's capability to render the real distribution of electrical properties. This is dictated by computational time, sensitivity and resolution attained. In this study, for ERT data, forward and inverse modelling it was decided to use E4D (code developed by Pacific Northwest National Laboratories - no specific version specified) (Johnson et al., 2010). The software has an integrated model mesh generator and allows predefinition of electrically distinct zones within a model. In this subsection it is explained how model performance is affected by its mesh structure, measurement sequence and error processing.

3.1.2.1 Model mesh As previously described, a computational mesh represents a spatial discretization of the geometrical model we are trying to reconstruct, starting from an apparent resistivity dataset. The model m containing n cells $[m_1, m_2, \dots, m_n]$ based on a finite-element mesh can be defined as:

$$m = \ln(\rho), \quad (3.1)$$

which effectively means the mesh cells are assigned corresponding to electrical resistivity values ρ . Data, $d = \ln(\rho)$, and parameters are transformed into logarithms in order to take into account the wide range of electrical resistivities found in the subsurface and to ensure positive values of resistivities and resistances.

The number of cells will be determined by how we parameterize the mesh. One has to make a decision upon the mesh structure, as too coarse a mesh may not be able to capture subtle variations in electrical resistivity and a mesh too fine would be computationally intensive. However, it is important to note the model resolution is actually determined by where the electrodes are and what measurements are made. The mesh needs to be fine enough to be compatible with these requirements, but adding in more cells will not necessarily capture finer detail. More important is how accurate the finite-element calculations are.

Figure 3.1 shows an example of a synthetic simulation. Figure 3.1 B shows the mesh used for the soil column monitoring experiments, which will be explored in more detailed in the following sections. A cylindrical mesh volume was chosen to match the geometry of the samples. This is made up of unstructured tetrahedra finer (denser and smaller in size) around the position of the electrodes, where the sensitivity of the measurements is expected to be higher (Figure 3.1).

3. GENERAL METHOD DESCRIPTION

The model comprises of a homogeneous medium (conductivity value= 0.01 S/m) and contains a cuboid target with a different conductivity (Figure 3.1 C). The conductivity contrast between target and background medium is 100:1. The target is well resolved with this model configuration. However, from this point forward, only the volume enclosed between the electrode rows will be considered due to lack of coverage outside that space.

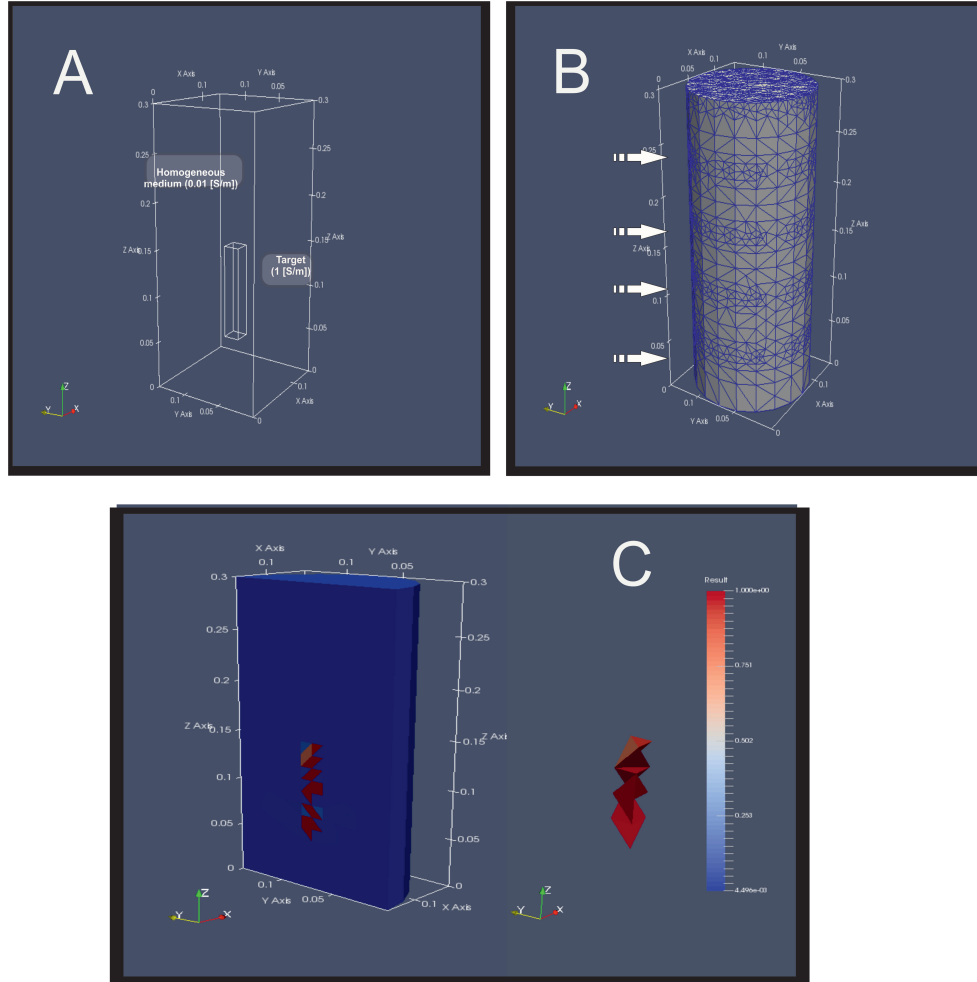


Figure 3.1: Synthetic Electrical Conductivity model. Cartesian grid values are in metres. A: Model outline, B: Model mesh, C: Vertical forward model result clip [S/m]. Color scale indicates the conductivity of the model.

3.1.2.2 Acquisition sequence As mentioned in chapter 2 a typical procedure is to use four electrodes for one measurement. Here, two are used for

current injection and two used for measuring potential in order to minimize contact resistance (Daily et al., 2005). For a given number of electrodes, the total possible number of electrical measurements, obtained by the combination of all electrode pairs, is often impractical (Everett, 2013). A lower number of measurements can ultimately result in an image of a comparative resolution (Wilkinson et al., 2006). An experiment which appraises dynamic fluid infiltration in soil will require a fast, near real-time, acquisition sequence, hence cutting down the measurement number was desired. Therefore, it was decided to test different measurement configurations, and for the column experiment design, it was found that 772 measurements comprised by a combination of vertically and laterally positioned electrode pairs provided the appropriate balance between model quality and speed of acquisition.

3.1.2.3 Sensitivity and Noise Different geometric factors account for different electrode arrangements. Figure 3.2 shows some of the most frequently used types and their corresponding sensitivity. Another aspect that has to be taken into consideration is signal to noise ratio, which is inversely proportional to the geometric factor. This can however be enhanced by always taking repeated and reciprocal measurements (obtained by swapping the current-potential pairs). Their values are an important indicator for noise evaluation. An underestimate can cause unrealistic features in resulting images called artefacts. On the other hand, an overestimate of noise causes smoothing and a decrease in image resolution (LaBrecque et al., 1996).

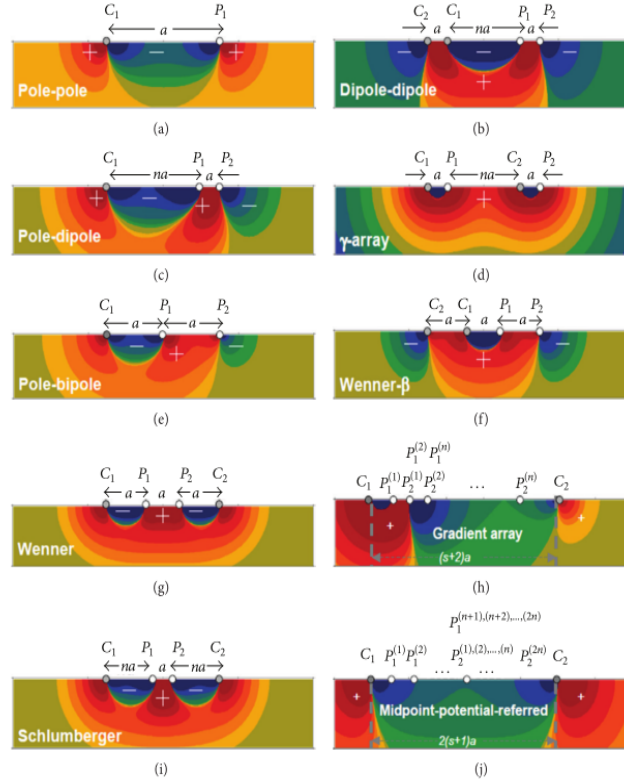


Figure 3.2: Sensitivity diagrams of electrode configurations (Warm colors indicate higher sensitivity). C_1 , C_2 are the current electrodes and P_1 , P_2 the potential electrodes. Extracted from Dahlin and Zhou (2004).

3.1.3 Error processing

The apparent resistivity value subsequently used for modelling was the average of normal ρ_n and reciprocal ρ_r measurements ρ_m and its associated error, referred to as the reciprocal error E_r , which is defined as:

$$|E_r| = 100 \times \left(\frac{|\rho_r - \rho_n|}{\rho_r + \rho_m} \right), \quad (3.2)$$

Firstly, in order to only retain measurements with a corresponding small measurement error, it was empirically established to discard all measurements with a reciprocal error greater than 5%. Secondly, in the attempt to have more robust error estimates, following an approach described in (Mwakanyamale et al.,

2012), the transfer resistance data was distributed in logarithmically equally sized bins. Subsequently, a linear error model was fitted to the reciprocal error average corresponding to each bin:

$$|E_r| = a + b \times R, \quad (3.3)$$

where a and b are the error model parameters and R is the measured transfer resistance. Figure 3.3 provides an example of this model fitting exercise using data from one of the ERT acquisitions. The error model estimates were subsequently used for data inversion.

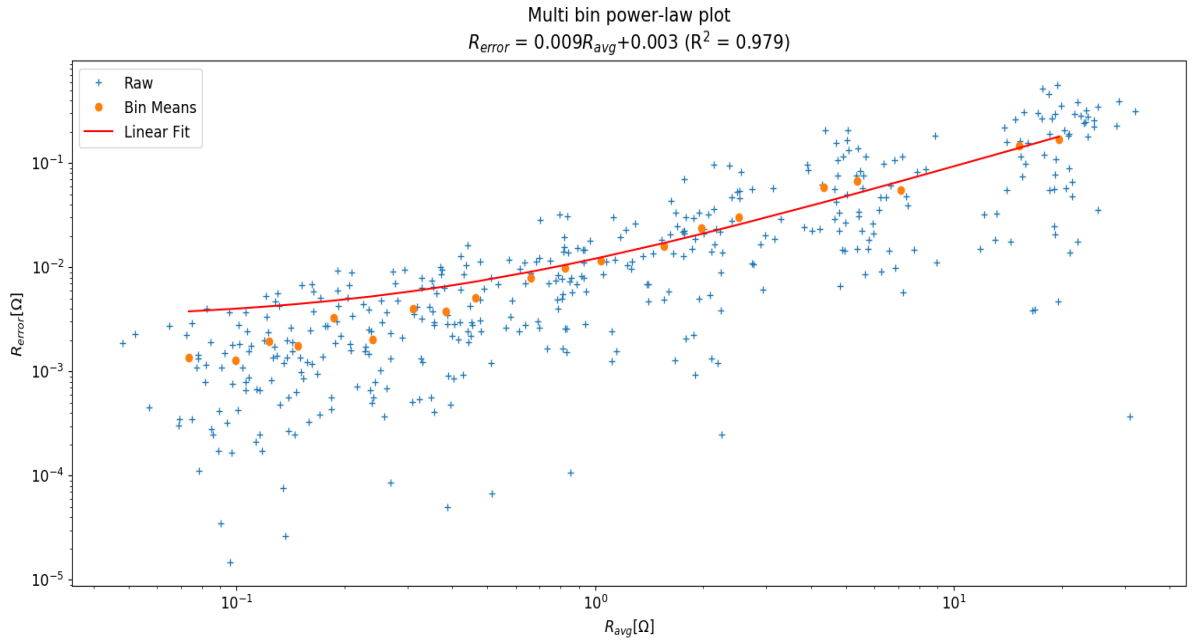


Figure 3.3: Error model fit to the apparent resistance reciprocal error and its corresponding weight parameters. Data corresponds to an ERT acquisition on the test column.

3.1.4 Inversion model

In order to obtain a model of electrical resistivity distribution, typically, an inversion algorithm is used, by which a starting resistivity model is iteratively

adjusted in order to achieve the best fit with the measured apparent resistivity values.

3.1.4.1 Static inversion An Occam's type (after William of Occam's razor) least squares inversion is described below, also embedded in E4D. It produces an image of n voxels of electrical resistivities (ρ_i with $i=1,2,...n$) given a set of t four electrode resistance (R_j with $j=1,2,...t$) by minimizing the objective function Ψ :

$$\Psi = ||W_\epsilon[d - f(m)]||_2^2 + \lambda ||W_s[m - m_0]||_2^2, \quad (3.4)$$

where d is the data vector, $m_j = \ln(\rho_j)$ are the parameters of the inversion, $f(m)$ is the forward model for parameters m , W_ϵ is a smoothing operator, λ is the regularization parameter that determines the amount of smoothing imposed on m and W_s is an error weighting matrix. The first term of equation 3.4 is a measure of the error weighted data misfit. The second term expresses the model misfit and contains an additional constraint imposed on the model, needed to overcome the ill-posed nature of the inversion problem. Finally, the role of λ parameter is to balance the two terms.

3.1.4.2 Time-lapse inversion In order to capture the dynamics of soil hydraulic processes, ERT was used to monitor changes in the electrical properties over time, which in turn reflected changes in soil properties, such as: saturation, temperature, pore fluid salinity and soil texture. In practice, the time-lapse acquisition process consists of repeated acquisition sequences using the same electrode configurations.

Time-lapse inversion can be approached in multiple ways. Firstly, one can invert individual datasets separately and then compare the model results. This strategy has the advantage that there is no need to use the same data points

for every inversion, but if the model results have different resolutions or cover different areas they can be difficult to compare. Secondly, one can invert the data differences instead. LaBrecque and Yang (2000) demonstrated that the data-differences inversion method allows reducing the effect of systematic error present in the data, which cancels out by subtraction. In contrast to the first strategy, here data points between time-steps need to be matched. At the error processing stage a number of data points is often discarded with distinct locations between time steps, hence the subsequent matching stage will result in discarding an even larger amount of data points. Therefore, in some cases the inversion process might conclude in an unrepresentative model result due to data scarcity. Lastly, one can use a 4D inversion algorithm where every datapoint has a fourth dimension (time) (Kim et al., 2009). Therefore, this allows the simultaneous inversion of the entire monitoring data sets to obtain a 4-D model using just one inversion process. However, the algorithm does not directly constrain the direction of changes in time (Loke et al., 2019). For this reason, in this work were used, depending on data availability, the first and second inversion strategies to represent changes in electrical resistivity through time.

As mentioned before, electrical resistivity measurements are sensitive to changes in soil moisture content and soil solution concentration. Because of this, several previous studies have used saline solutions as tracers, due to their contrasting low resistivity to the surrounding soil medium, for monitoring soil hydraulic properties using ERT (Slater et al. (2002); Koestel et al. (2008)). Therefore, soil cores used throughout this work were subjected to the infiltration of a saline solution.

The first experimental design implied the use of a KI solution as a saline tracer. Following Koestel et al. (2008), aggregates (> 5 mm) of a sandy loam soil were

used to repack a column (14 cm diameter) up to a height of 20 cm at a bulk density of 1.4 kg/m^3 . The electrode configurations and column design used for synthetic modelling (in 3.1.2) were tested here. Through the column's top surface a plastic tube (diameter 4 cm) was inserted down to 6 cm from the top of the column. In the tube, a potassium iodine (KI) solution of 1M concentration sat at a constant head of 5 N/m^2 throughout the monitoring experiment. This preliminary experiment lasted 690 minutes acquiring 30 complete datasets (normal and reciprocal) sat 23 minutes apart. Results corresponding to different time-steps of the infiltration are presented in Figure 3.4. Model cells with low values of resistivity determined by the tracer were observed. These were purposely highlighted in order to show the tracer's infiltration path. The surface of the column's model was also purposely made more transparent in order to enhance the visibility of the regions affected by the tracer. In addition, large resistivity values can be noticed on the surface of the model indicative of the position of the infiltration tube.

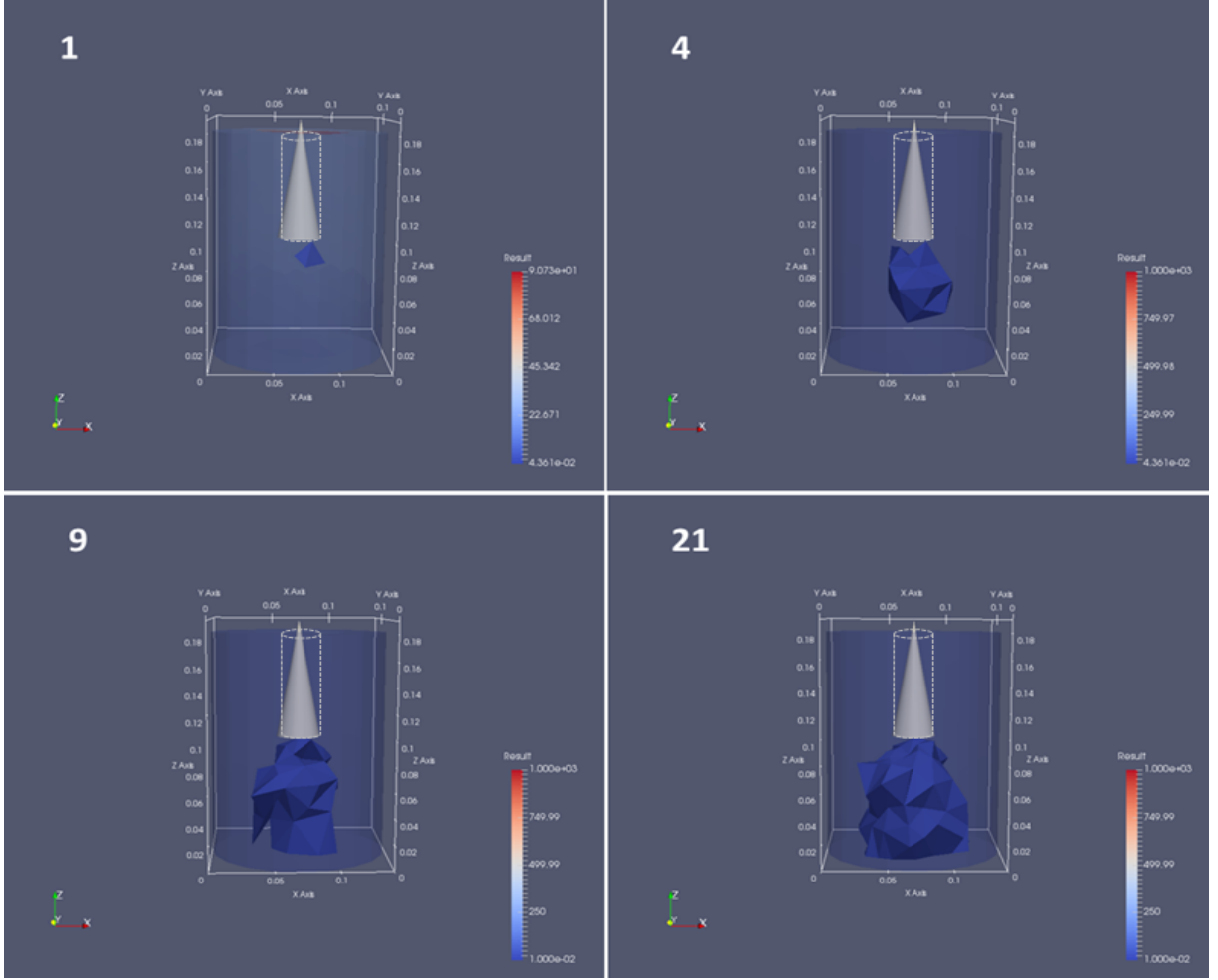


Figure 3.4: ERT inversion models of Electrical Resistivity (Result - $[\Omega.m]$) in 4 stages of KI solution infiltration. The white number indicates the time-step number, recorded 23 minutes apart. The infiltration tube is outlined by the white dotted line and the grey cone.

3.2 X-ray Computed Tomography (CT)

3.2.1 Measurement principles

X-ray CT allows visualization of the interior structure of a target object due to the attenuation properties of electromagnetic waves. The innovation of this non-invasive and non-destructive method is attributed to Sir Godfrey Hounsfield (Hounsfield, 1973). X-rays are produced in a tube containing an anode and a cathode when a voltage is applied across the electrodes. The

resulting X-ray beam is attenuated as it passes a target medium. Such attenuation is described by the Beer-Lambert equation (Wildenschild et al., 2002):

$$I = I_0 \times \exp(-\mu \times D), \quad (3.5)$$

where D is the thickness, μ is the attenuation coefficient, and I_0 and I are the intensities before and after passing through the sample. Subsequently, a detector measures the beam's change in energy intensity. Denison et al. (1997) relates the attenuation coefficient to material bulk density (D) by:

$$\mu = D \times \frac{a + bZ^{3.8}}{E^{3.2}}, \quad (3.6)$$

where E is the energy of the beam and Z is the effective atomic number.

In medical CT scanners the source-detector pair rotates, whereas in industrial scanners the source-detector pair is fixed and the sample rotates, allowing projections from different angles. The 2D slices of the target material appear as an array of pixels, which is more commonly known as a digital image. Every pixel is classified in the greyscale according to its corresponding Hounsfield Unit (HU) (Duliu, 1999). The HU value is calibrated in such a way that 0 HU corresponds to water and 1000 HU corresponds to air:

$$HU = \frac{(\mu_{subject} - \mu_{water})}{(\mu_{water} - \mu_{air})}k, \quad (3.7)$$

where k is 1000 and μ_{air} is 0. Therefore, following this normalization, the brightest features are also the ones with the highest density. Finally, by collating multiple slices, 3D structures can be digitally reconstructed as volumes of pixels expressed in greyscale (GS) values.

3.2.2 Data Acquisition

3.2.2.1 Scanner and experiment settings A GE v—Tome—x M scanner, part of the Hounsfield Facility at the University of Nottingham, was used in this research. It is an industrial scanner with the following general capabilities: 5-150 μm spatial resolution, $400 \times 300 \times 300 \text{ mm}^3$ sample size, up to 240 kV energy and a flat panel detector.

The quality of the images resulting from the scan is highly dependent on the initial set-up conditions. Distance between the sample and the gun-detector pair, sample thickness, sample components, power, exposure time, number of projections are a few of the most important variables that can systematically change the image resolution.

3.2.2.2 Sources of error In X-ray CT imagery there are several common artefacts that we need to take into consideration, namely: ring artefacts, caused by inhomogeneities in the detector, beam hardening artefacts, caused by the preferential absorption of low X-ray energies, and star artefacts, caused by the presence of very dense materials (Taina et al., 2008). Fortunately, beam and ring artefacts can be minimized by using filters in the path of the X-ray beam. Sample mounting also needs to be carefully considered. The basic principle is that the sample needs to be sat in a stable position, which will not allow movement during the scanning rotation. Such movement will result in image blurring. Also, it is a common practice to use low density materials (e.g. polystyrene, glass, PVC) in order to hold or stabilize the sample.

3.2.3 Data processing

3.2.3.1 Appropriate image acquisition An optimal resolution is usually 1000 times smaller than the width of the sample. This fact is based on the

standard practice of using only the central 1000 of the 2000 available pixels to minimize possible artifacts from the edges (du Plessis et al., 2017). To obtain the highest possible scan quality, the image acquisition time needs to be maximized and the detector range used at full range. In contrast, if the acquisition time is too low, the resulting contrast will be poor. In addition, at every step multiple images can be acquired and averaged in the attempt to reduce noise. Also, in situations where movement during rotation is likely, it is advisable to ignore the first image acquired (skip function) until the sample stabilizes (du Plessis et al., 2017). X-ray voltage is also another parameter which must be carefully taken into consideration. The redundant material discrimination is usually obtained by using lower voltages, unless the material is too dense, in which case this would cause artefacts.

3.2.3.2 Image processing Once the scan is complete, the resulting sequence of 2D images can be reconstructed into a digitized version of the sample 3D volume. Depending on the level of detail, these can be reconstructed over 8 (2^8 distinct pixel values - shades of grey), 16 (2^{16}) or 32-bit (2^{32}) ranges. Most scanners have an inbuilt system that performs such reconstructions. At this stage, the user can crop unnecessary parts of the image to use less memory, apply beam hardening corrections or correct for image blurs caused by sample movement. It is important to note that if it is required to compare different subvolumes of the same sample independently scanned they need to be reconstructed over the same range of pixel values.

Once the volume has been successfully reconstructed we need to discriminate its constituents. As soil is usually a highly heterogeneous material (e.g. water, roots, minerals, soil aggregates), this step is always challenging and brings a high level of uncertainty when one attempts to quantify the proportion of such constituents. This can be achieved by using a segmentation technique.

The most common practice is to use a global threshold value based on the histogram distribution of pixel values. Figure 3.5 shows an example distribution. One may notice that in one case (right) it is easier to discriminate between two distinct phases whereas in the other overlapping GS values make localising the boundary between phases increasingly difficult.

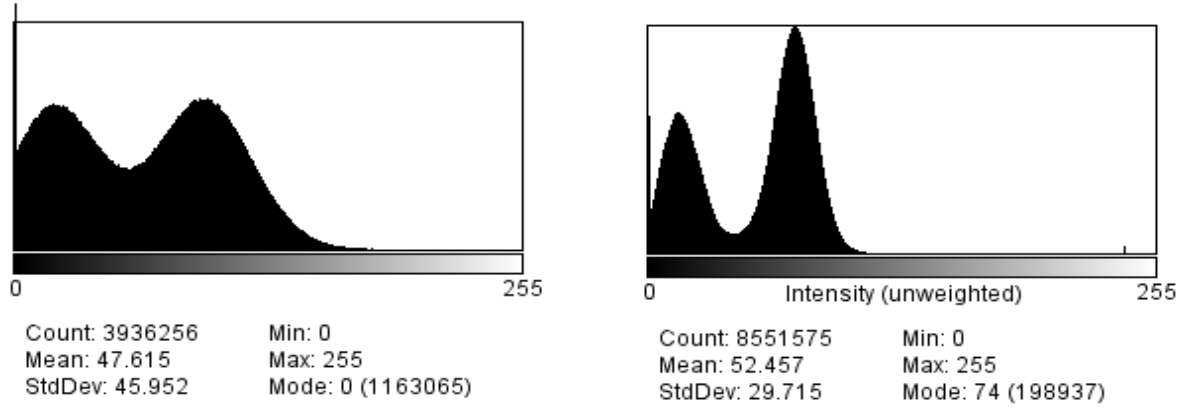


Figure 3.5: Examples of two histograms corresponding to the same dry soil sample, but under different scanning conditions.

In early stages of this project, image quality and phase contrast were tested in order to resolve different features for the chosen sample type and diameter. Firstly, a test was attempted in order to see if the segmentation of the outline of water saturated features from CT scans is possible. Therefore, a cylindrical volume of kiln-dried sand (grain size >0.5 mm) was partly saturated. The sample holder had the same diameter as the synthetic ERT column modelled (section 3.1.4.2.) but not the same height. The difference in height will account only for extra scanning time without a cost in resolution. In figure 3.6 A the scan reconstruction is presented, which shows the drier left half and the wetter right half. Further processing shows the segmentation of the wetter half and classification of its connected components (distinct enclosed subregions of the resulting image obtained using an algorithm as presented in Burger et al. (2006)) into distinct

3. GENERAL METHOD DESCRIPTION

areas of the volume. In addition, segmentation of the outline of such areas is also shown, based on which, an export of their Cartesian coordinates is viable. This result shows that is possible to extract spatial information from the X-ray scans which represents the distribution of moisture throughout the soil volume.

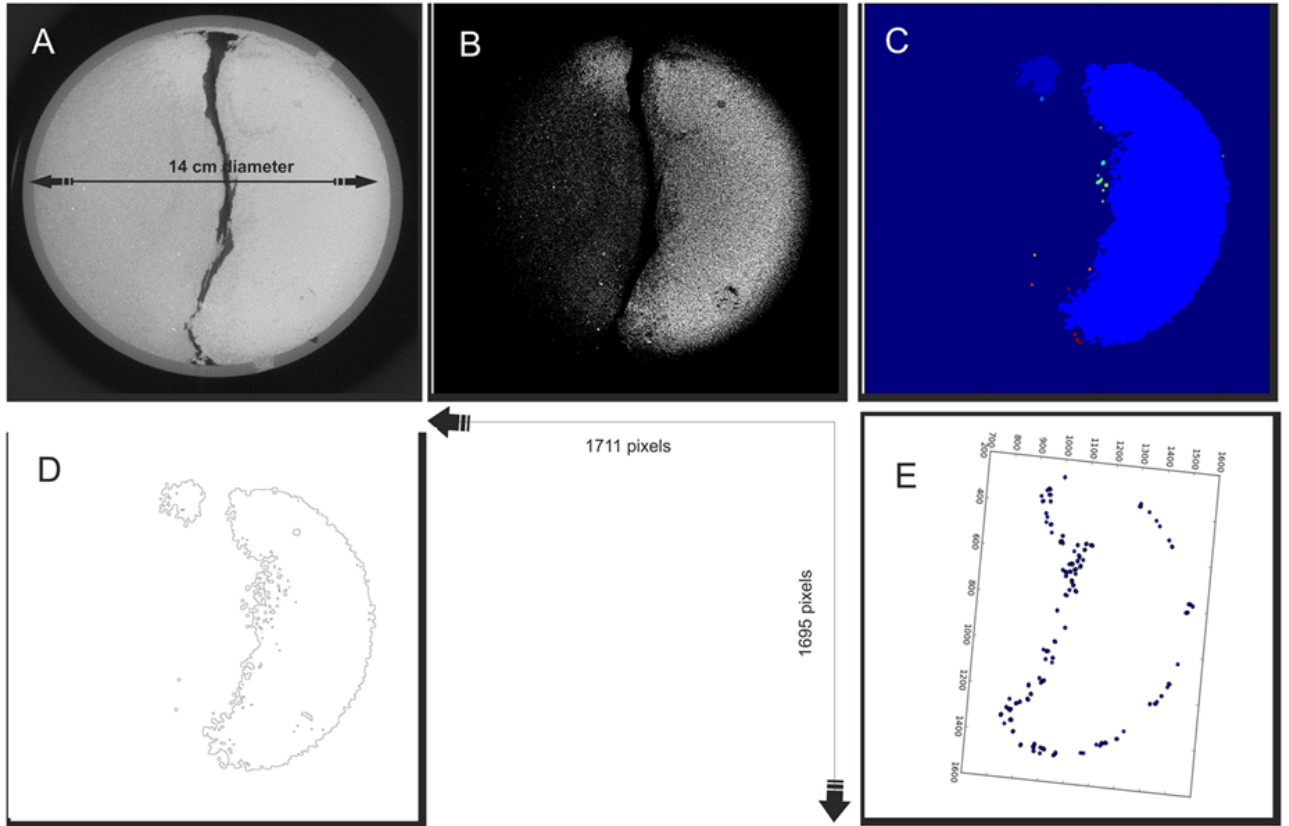


Figure 3.6: Scan of kiln sand and further image processing. A: Original scan result, B: Segmented wet sand, C: Classified Connected components, D: Outline of the connected components, E: XY position of the main feature boundary points.

In order to confirm that at the current operating resolution water is identifiable in soil macropores, a partly saturated repacked sandy loam soil, sieved at 5-10 mm aggregates, was scanned. As before, the same sample diameter was maintained. A section of the reconstructed scanned volume is shown in Figure 3.7. The resolution achieved was 96 μm , which allowed water to be segmented,

which was subsequently false colored for visualization purposes.

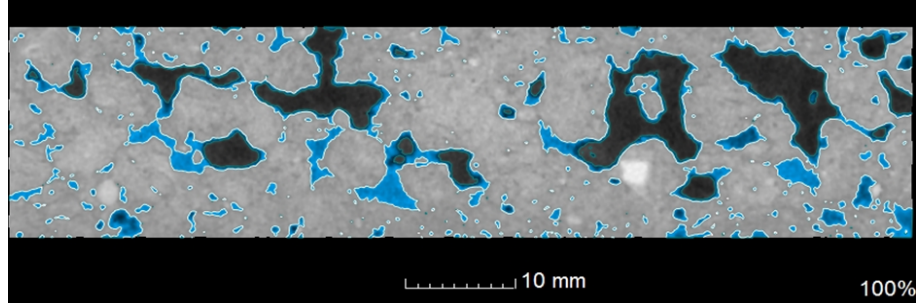


Figure 3.7: Reconstructed 3D scanned soil volume. Blue depicts the water-filled macropores. Black depicts air-filled macropores.

3.2.3.3 Soil structural parameters Given the strong contrast in X-ray attenuation of soil pores and associated solids, their discrimination in CT imagery is relatively straightforward, a fact that aids in the quantification of pore networks (Taina et al., 2008). However, if one requires an accurate estimate of pore structural parameters, small changes in the boundary between the air-filled pore space and soil solid phase are crucial. In order to improve such distinction a range of filters can be used. From these, Sharpen (accentuates boundaries by replacing each pixel with the weighted average of its 3×3 neighbors) with the weighting factor:

$$\begin{matrix} -1, & -1, & -1 \end{matrix}$$

$$\begin{matrix} -1, & 12, & -1 \end{matrix}$$

$$\begin{matrix} -1, & -1, & -1 \end{matrix}$$

and Median (replaces each pixel with the median values of its 3×3 neighbors) were used in this order for this work. In this study, the filters were applied prior to image segmentation using ImageJ, an image processing package of codes (Schindelin et al., 2012).

Once the pore network has been segmented, a soil pore channel can be geometrically represented. Therefore, its spatial characteristics, such as: diameter, perimeter, length, area and volume, can be estimated. This assessment can be

done for individual images and consequently over the whole volume. Further analysis can be done determining pore classification (e.g. size), their spatial distribution or connectivity.

3.3 An experimental design for a joint ERT-CT experiment

Both methods described above appraise soil properties non-invasively by imaging a sample's interior. However, it was mentioned there are specific conditions corresponding to each method under which a sample can be imaged. For example, the size of the samples used is limited by the size of the X-ray scanning chamber. Also, the sample dimensions will influence the instrumentation required (e.g. number of electrodes) and/or the results (e.g. scan resolution). Therefore, the optimum conditions were sought in which both methods' capabilities are maximised.

3.3.1 Resolving a saline tracer using X-ray CT

This work mainly focuses on soil hydraulic properties and how are they impacted by soil structure. Anderson et al. (2003) conducted a solute breakthrough experiment where porosity and saturated hydraulic conductivity were estimated using X-ray CT. The tracer used was a solution of KI due to its high atomic number. Similarly, Koestel and Larsbo (2014) observed the solute transport through a soil column using X-ray CT and a KI solution as a tracer. As shown before in 3.1.4.2., a KI solution was also deemed to be a successful tracer in soils for ERT monitoring purposes. Therefore, a KI tracer was chosen for future experimentation involving X-ray CT scanning.

One of the first experimental objectives was to check under which experimental conditions (e.g. sample size, pore solution concentration) the X-ray CT

scanner is able to image the presence of KI in the soil pores. The first test involved two vessels filled with sandy loam aggregates, one saturated with water and the other saturated with a 20 g/l KI solution. The scan results shown in Figure 3.8 indicate a distinct absorption of soil aggregates, water and a KI solution present in the pore system. Water segmentation is successful, as water differentiates in GS from the surrounding medium. However, when KI solution segmentation is attempted, the water saturated soil shows a similar GS range and is also captured by the segmentation.

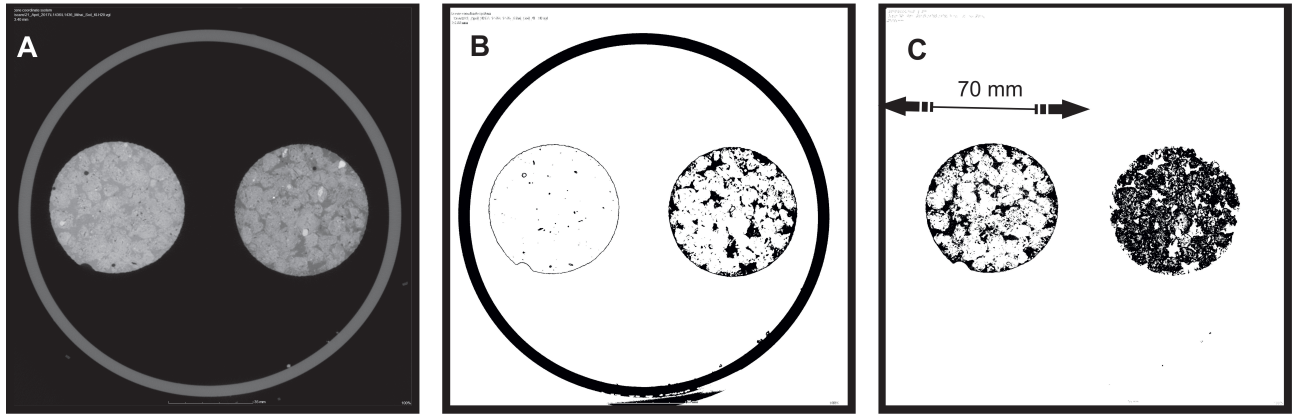


Figure 3.8: Scan of sandy loam soil saturated with water and KI. A: the original scan, B: the segmentation results after applying a threshold for water absorption and C: the segmentation results after applying a threshold for KI absorption.

Using the appropriate KI concentration for future experiments also needed to be addressed. Referring back to previous literature, Figure 3.9, extracted from Grayling (2015), shows the difference between KI solutions at different concentrations, representative of different peaks on the greyscale spectrum. Table 3.1 contains a number of studies purposely reviewed, which quote a range of concentration values between 0.1 and 1 M (16.6 and 166 g/l). In Grayling (2015) it is stipulated that using values greater than 100 g/l would

not improve the image processing stage, to differentiate between KI solution and surrounding soil due to the overlap of their corresponding GS values.

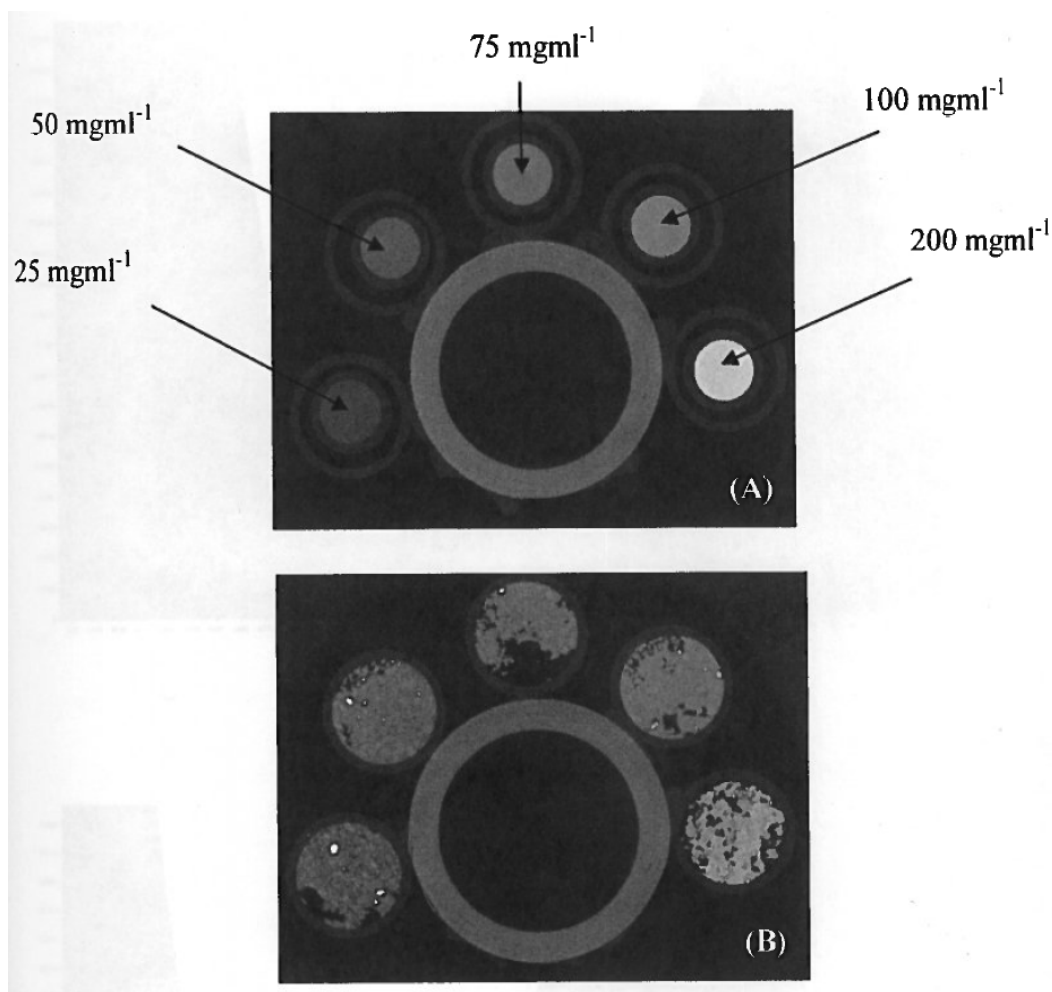


Figure 3.9: Grayscale image of KI in pure form (A) at 25, 50, 75, 100, 200 mg/ml and in soil (B). Extracted from Grayling (2015).

3. GENERAL METHOD DESCRIPTION

Name	Sample shape	Sample size	Soil/Rock type	Moisture Content	KI concentration	Scan specifications	Resolution	Other specifications
Koestel and Larsbo (2014)	cylindrical	68.2 mm diam; 38 mm height	silty clay	80 ml water	20 g/l	170 kV, 350 μ A, 131 μ s exposure	48 μ m	55% porosity
Luo and Lin (2009)	cylindrical	76 mm diam; 265 mm height	silt loam	satiated	60 g/l	Industrial CT unit OMNI-X 225 kV(instrument capacity) microfocus	86.7 μ m	Housed 4 days in a polyvinyl chloride pipe and satiated from the bottom by raising the water
Agbogun et al. (2013)	cylindrical	11 mm diam, 18 mm length	dolomite stone	saturated	0.6 M	90 kV, 100 μ A	18.5 μ m	To minimize osmotic movements the sample was presaturated in a 0.6 M KNO ₃ solution

3. GENERAL METHOD DESCRIPTION

Anderson et al. (1992)	Cylindrical	76.2 mm diam	Silt loam	saturated	1%	SOMATOM DRH CT scanner, 125 kV ,410 mA/s, 720 projections	0.5 / 0.5 / 2 mm	Soil cores prepared for different aggregate size : 0.25-0.5 mm/ 0.5-1 mm/ 1-2 mm; Cores slowly saturated with solutions of CaCl ₂ and MgCl ₂
Heijs et al. (1996)	Cylindrical	12.3 cm diam, 25 cm length	Clay soil	Orginal dry state	HKI solution = 2930	Siemens Somaton +	0.27 mm	15 mm of contrast agent was sprinkled with an intensity of 20 mm/h
Cavé et al. (2009)	Cylindrical	11 mm diam, 15-20 mm length	Argille limestone	Saturated in syn- thetic pore water	0.6, 0.8 and 1 M solutions	Skyscan 1072 microCT, 60kV, 164 µA, Aluminum filter	18.7x18.7 µm	Samples were oven dried but then submerged in synthetic pore water (mimic the pore water)

Anderson et al. (2003)	cylindrical	68 mm long, 76 mm inner diam	Silt loam	Saturated	7.5 g/l KI and 50 mg/l 2chlorophe- nol	Siemens Somatom DRH	Slice thickness is 8mm, Pixel size is 2x2 mm	Samples were saturated in a solution of water and CaCl ₂ and MgCl ₂ 1.4 g/cm ³ density, 0.470 porosity, Tracer was applied 3.5 mL/min
Latrille and Néel (2013)	cylindrical	5 cm internal diameter, 82 cm height	Quartz sand	Saturated with KCl solution	0.11 mol/l	Dichromatic X-ray spectrometer 20-40 KeV, 50-75 KeV	-	Sand was washed with pure water and equili- brated 10-3 M KCl solution

Table 3.1: Studies using KI as a tracer in CT scanning and their corresponding experimental conditions

Finally, tracer detection in a soil column was attempted. The same cylindrical core was used as for the ERT testing (size of 14 cm (diameter) $\times$ 20 (height) cm). The column was packed with disturbed sandy loam soil aggregates, sieved as before to an aggregate size of (>5 mm). The core was first slowly saturated with DI water from the bottom up. At the column's surface, two veils with DI water and pure KI solution were placed as reference. Afterwards, just before the scan, a KI solution was applied through a plastic tube perturbing the top

surface of the column. The concentration of the KI solution was 60 g/l and was decided based on consulting previous literature. Figure 3.10 shows two of the resulting column scan reconstructions. No differences between the saturated soil matrix before and after the KI injection were observed.

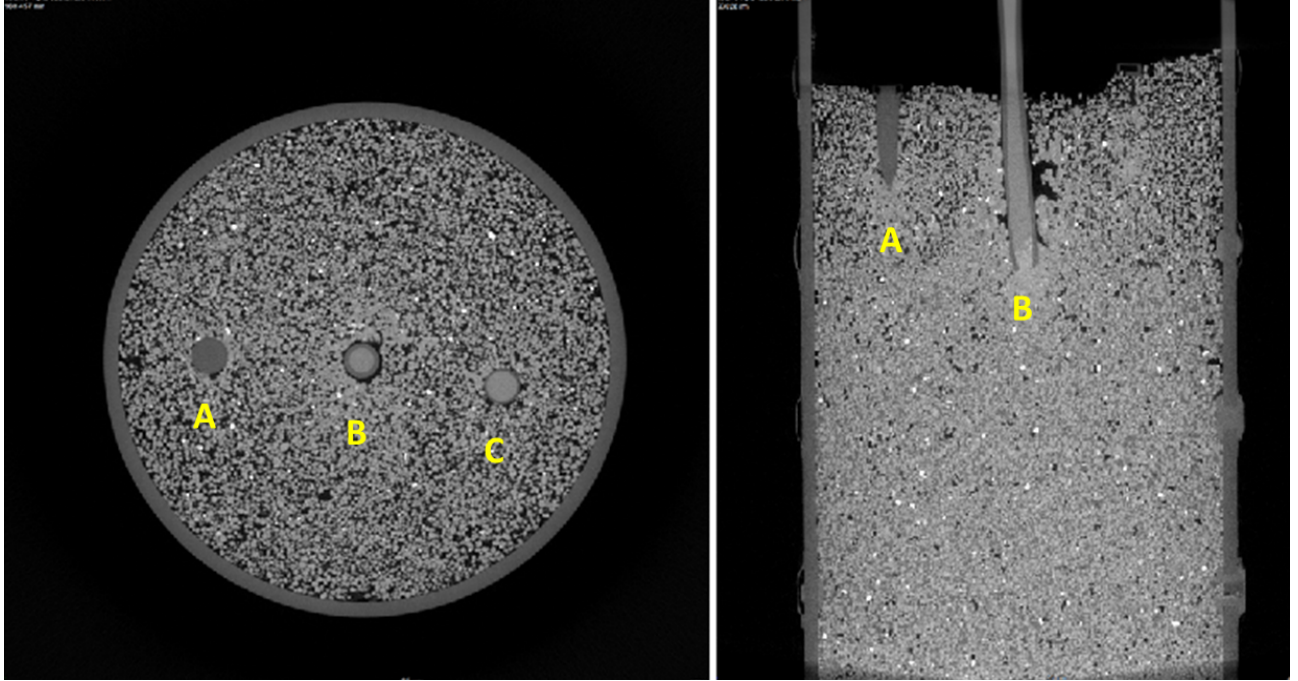


Figure 3.10: Scan views of a partly water saturated soil column (Left - top view; Right - lateral view) undergoing KI infiltration. Top view: Veils containing pure water (A), KI solution (C) and infiltration tube containing KI (B). Right view: Veil containing pure water (A) and infiltration tube containing KI (B).

3.3.2 Preliminary conclusions

KI is a proven X-ray CT tracer in soils as shown by previous research (Table 3.1), however, in this study, attempts to obtain similar results were unsuccessful. One potential explanation is that a larger KI solution head was required in order to obtain significant differences in the resulting scans. The small quantities used were easily dispersing. Also, this might have been beyond the capabilities of the scanner and sample characteristics available as previous research used smaller diameter samples. Therefore, for future research it was decided to

reduce the sample diameter from 14 cm to 6.8 cm. In addition, as the macro-pore network was easily distinguishable, it was decided to use X-ray CT only to resolve macro-structural parameters. On the other hand, ERT time-lapse forward modelling (Figure 3.1) and inversion results (Figure 3.4) were successful and were ultimately able to image and monitor the infiltration of a saline solution. Therefore, the same experimental set-up will be kept and adapted to cores of a smaller diameter. The contrast between tracer and background resistivity will also be maintained and the same ERT acquisition sequence will be used. In addition, infiltration from the top of the sample caused an uneven tracer distribution. As a comprehensive understanding on how all the channels of the pore network contribute to solution transport is sought, one that avoids preferential flow, the solution will be infiltrated from the bottom up.

3.4 Outline of experimental work

This preliminary experimental work was intended to set the scene for a column experiment that benefits from the strengths of both tomographic methods. However, some of the initial failures determined an objective re-evaluation. The aim of this work remains to explore the impact of soil structure on solute hydrodynamics in soil and how this reflects on the quality of agricultural soils. Therefore, this link was assessed across three scales in the attempt to: at small scale - derive an effective parameter relationship (electrical resistivity and X-ray absorption), at medium (column) scale - quantitatively link pore architectural distribution and solution percolation and at large (field) scale - determine if differences in soil structural parameters can explain the variability in field geoelectrical properties.

4 A PEDOPHYSICAL RELATIONSHIP BETWEEN X-RAY COMPUTED TOMOGRAPHY AND ELECTRICAL RESISTIVITY TOMOGRAPHY DATA

The work in this chapter was published in the scientific journal Journal of Environmental and Engineering Geophysics (JEEG):

Cimpoiaşu M.O., Kuras O., Pridmore T. and Mooney S.J. (2020). A Pedophysical Relationship between X-ray Computed Tomography and Electrical Resistivity Data. Journal of Environmental and Engineering Geophysics, 25: 181-187. <https://doi.org/10.2113/JEEG19-079>

Author contributions:

All authors conceptualized the aims of this work and the experimental steps. Cimpoiasu M.O. carried the sampling, laboratory experiments, data analysis and wrote the initial manuscript. Kuras O. supervised the laboratory experiment involving the relationship between electrical resistivity and soil moisture content. Mooney S.J. supervised the X-ray CT scanning and image processing. Pridmore T. supervised the design of computational strategies for image analysis. Kuras O., Mooney S.J. and Pridmore T. further edited the initial manuscript and improved its language and conciseness.

4.1 Abstract

Quantitatively linking observations from independent non-invasive soil assessment methods enhances the ability to understand root zone processes. Elec-

trical Resistivity Tomography (ERT) and X-ray Computed Tomography (CT) are two advanced non-invasive technologies routinely employed in soil science. ERT allows 4D process monitoring (e.g. solute transport) and is sensitive to changes in moisture content (MC) and soil texture. X-ray CT is a higher resolution method used to appraise soil structure. The variation of electrical resistivity and X-ray absorption with gravimetric moisture content (GMC) were measured for two distinct soil types. Experimental results were compared with existing pedophysical relationships that express these dependencies. Based on the good fit between measurements and model predictions, a new pedophysical relationship that links directly the two soil properties was formulated. This will allow a direct translation between ERT and X-ray data for the study of root-zone parameters under well-defined experimental circumstances.

4.2 Introduction

A very important aspect of root zone processes is understanding the behaviour of water in soils. Consequently, linking soil hydraulic properties, such as water retention curve and hydraulic conductivity, with soil structure is essential for understanding processes that control soil functions (van Genuchten and Pachepsky, 2011), such as water storage or food production. In recent years, the scientific community has sought to develop numerous non-invasive methods that preserve soil structural integrity. Two categories of methods: static, offering higher spatial resolution, such as Neutron Radiography (Shokri et al., 2008) or X-ray CT (Tracy et al., 2015), and dynamic ones offering higher temporal resolution, such as Electrical Resistivity Tomography (Cassiani et al., 2016) or Time-Domain Reflectometry (Nyberg, 1996) can be distinguished. The methods in the latter category enable time-lapse monitoring and give greater flexibility, as they can be employed both in the lab (Garré et al., 2011) and in the

field (Boaga et al., 2013). Instead, the static methods attain greater spatial resolution (pore-scale - $\mu\text{m} - \text{mm}$) and a very high contrast sensitivity between different soil matrix components, such as minerals, water and air-filled pore spaces (Wildenschild et al., 2002). Past research suggests a strong correlation between visually-derived soil structural information and other soil intrinsic properties. Mueller et al. (2009) showed that physical properties and qualities, such as dry bulk density or soil strength, correlate significantly with visually observed structure, such as aggregate shape and size. Paradelo et al. (2016) correlated CT-derived parameters with water transport in soils and suggested the potential of the method to estimate air, water and solutes fluxes at the field scale. Lewis and Sjoström (2010) emphasized the importance of having appropriate pedophysical calibrations for a fluid infiltration experiment on a soil monolith. For ERT monitoring experiments, prior calibration is needed in order to translate electrical resistivity (ER) into values of MC. Such calibrations can be done by regression analysis comparing resistivity results with MC measurements made independently (Srayeddin and Doussan, 2009) or by using a pedophysical relationship (Beff et al., 2013). This study focuses on two methods: ERT has been frequently employed for monitoring water content in the root zone (Samouëlian et al., 2005), whilst X-ray CT has proven to be very successful for assessing soil structure (Peyton et al., 1992) and reconstructing root architecture (Mooney et al., 2012). A quantitative link is established between X-ray absorption, the parameter representative for the structural information contained in the CT scans, and bulk electrical resistivity, which is an electrical property of soils and the measurable parameter for ERT. In order to test the validity of this methodology for different soil textures we sampled two soil types, clay loam and silt clay loam. Subsequently, ER and average X-ray absorption are measured of both soils as a function of MC. By fitting known

pedophysical models, which express the dependence of either physical parameters on MC, to the laboratory measurements, soil-specific calibration curves corresponding to the two different textures are obtained. Encouraged by the good fit between measurements and models, we derive a quantitative link between X-ray absorption and ER of the soil by rearranging the pedophysical expressions. Finally, an alternative strategy for the quantitative interpretation of electrical measurements is proposed, based on water content estimates obtained from X-ray CT scans.

4.3 Theoretical background

4.3.1 Basic principles of ERT and X-ray CT

X-ray CT allows visualization of the interior structure of a target object due to the attenuation properties of electro- magnetic waves. X-rays are produced in a tube containing an anode and a cathode when a voltage is applied across the electrodes. The Beer-Lambert equation describes the X-ray beam attenuation as it passes through a target medium (Wildenschild et al., 2002):

$$I = I_0 \times e^{(-\mu \times D)}, \quad (4.1)$$

where D is the thickness, μ is the attenuation coefficient, and I_0 and I are the intensities before and after passing through the sample. In medical CT scanners the source-detector pair rotates whereas in industrial scanners the source-detector pair is fixed and the sample rotates, allowing projections from different angles. From these measurements, 3D structures can be digitally reconstructed as volumes of pixels expressed in grayscale (GS) values, which represent the X-ray attenuation coefficient of the volume element. ERT is a near-surface geophysical method that uses electrical resistance measurements in

order to reconstruct an image of the bulk electrical resistivity of the subsurface. Small electrical currents are injected into the ground and the resulting electrical potential difference is recorded. Resistivity (or its inverse conductivity - σ) is obtained using Ohm's law:

$$\rho = K \times \frac{\delta V}{I}, \quad (4.2)$$

where I is the injected current, δV is the electrical potential difference and K is the formation factor which depends on the geometric arrangement of electrodes.

4.3.2 Known pedophysical models

Archie (1942) formulated one of the first petrophysical relationships to describe the dependency of ER on MC in porous rocks. Building on Archie's relation, the WS model includes surface conductivity effects, which become important when an increased content of clay particles is present (Waxman and Smits, 1968). In this study a modified formulation of WS (Chambers et al., 2014) was used:

$$\rho(GMC) = F \times \left(\frac{(1 - \phi) \times D_g \times GMC}{\phi \times D_w} \right)^{-n} \times (\sigma_w + B_{ws} \times \left[\frac{(1 - \phi) \times D_g \times c}{100\phi} \right] \left[\frac{\phi \times D_w}{(1 - \phi) \times D_g \times GMC} \right]^{-1}), \quad (4.3)$$

where $F = \phi^{-m}$ is the formation factor, ϕ is porosity, c is the cation exchange capacity, B_{ws} is the average ion mobility, σ_w is the water conductivity, D_g, D_w are the grain and water densities. In this model, m and n are empirical parameters. As its application has extended to soil studies it will be referred here as a pedophysical relationship. As described by Bailly et al. (2003), Beer-Lambert's law can be used to describe the contribution of various parameters to the overall absorption process. Baker et al. (2007) used this to formulate

GMC in terms of dry and wet conditions:

$$GMC = \frac{\ln(\frac{I_{dry}}{I_{wet}})}{\mu_{water} \times x_{dry} \times \rho_{dry}}, \quad (4.4)$$

, where μ_{water} is water attenuation coefficient, x_{dry} is the dry thickness, ρ_{dry} is the dry density and I_{dry}, I_{wet} are the dry and wet X-ray intensities respectively. For simplicity, Equations (4.3) and (4.4) will be further referred as BR and XA relationships respectively.

4.4 Methodology

A range of steps were undertaken to prepare the soil samples for X-ray CT and resistivity measurements. Following the acquisition of both datasets, data processing is discussed and the formulation of a combined pedophysical relationship. It is also suggested an alternative method of obtaining a BR calibration based on CT estimates.

4.4.1 Soil sample preparation

Two soil types: clay loam (Clay:Silt:Sand (%) 65:23:12) - soil type 1 (S1) and silty clay loam (Clay:Silt:Sand (%) 52:39:9) - soil type 2 (S2), were sampled from University of Nottingham's Bunny Farm, Nottinghamshire, UK (Fieldsite 1: N 52.85593 W -1.12520 and Fieldsite 2: N 52.85743 W -1.12723). In the subsequent discussion measurement set 1 corresponds to S1 and measurement set 2 to S2. The samples were fragmented and sieved to < 5 mm aggregates. Afterwards, samples were dried for 72 hours at 35°C, a temperature low enough to avoid the destruction of clay particles. The whole soil mass was then split into seven batches of three samples each for S1 and eight batches of three samples each for S2. To each batch different amounts of water were added

by uniformly spraying the soil aggregates. Water addition was quantified by weighing the soil (GMC values in Figure 4.2 XA and BR). Finally, the soil was compacted into rectangular plastic receptacles (dimensions 2.5x2.5x7 cm).

4.4.2 Electrical and CT measurements

To facilitate resistivity measurements, stainless steel plate electrodes were placed at either end of each receptacle and two thin steel rod electrodes were inserted into the middle section. The electrode positioning resembles a Wenner geometry (Burger et al., 2006). The sample was left for 24 hours for moisture redistribution and equilibration. Afterwards, electrical resistance measurements were made with a Terrameter 4000 device, and using Equation (4.2), ER of the samples was estimated. To facilitate CT scanning, the electrodes were removed with minimal soil disruption. On the following day the samples were transported to the University of Nottingham's Hounsfield Facility where they were scanned with a v|Tome|x M X-ray scanner (Scan settings: 140 kV , 160 μ A, 8 minutes scan time and 30 μ m resolution). Cross-sectional scan images were reconstructed using Volume Graphics 2.1 software over an 8 bit value range, implying each of the pixels had Gray Scale (GS) values in the interval 0(Black) - 255(White).

4.4.3 CT image processing

Each sample was reconstructed lengthwise and widthwise as two sets of 1400 and 500 cross-sectional 'slice' images respectively (Figure 4.1 I). From the whole image, a representative area was selected, which was kept constant in every cross-sectional image. The selection, visualized in Figure 4.1 II, does not take into account the edges of the soil volume, which are more likely to have been subjected to interactions with the exterior medium. For every image, over the

4. A PEDOPHYSICAL RELATIONSHIP BETWEEN X-RAY COMPUTED TOMOGRAPHY AND ELECTRICAL RESISTIVITY TOMOGRAPHY DATA

indicated area, an average GS value was computed, without taking into account the pixels with very low (< 10 GS corresponding to air filled pore/fissure space) or very high (> 100 corresponding to high density minerals) GS values present in the sample, as this work is strictly interested in the soil material response to variations in MC. For both orientations, a GS value distribution along the sample was computed from which the average and standard deviation have been derived.

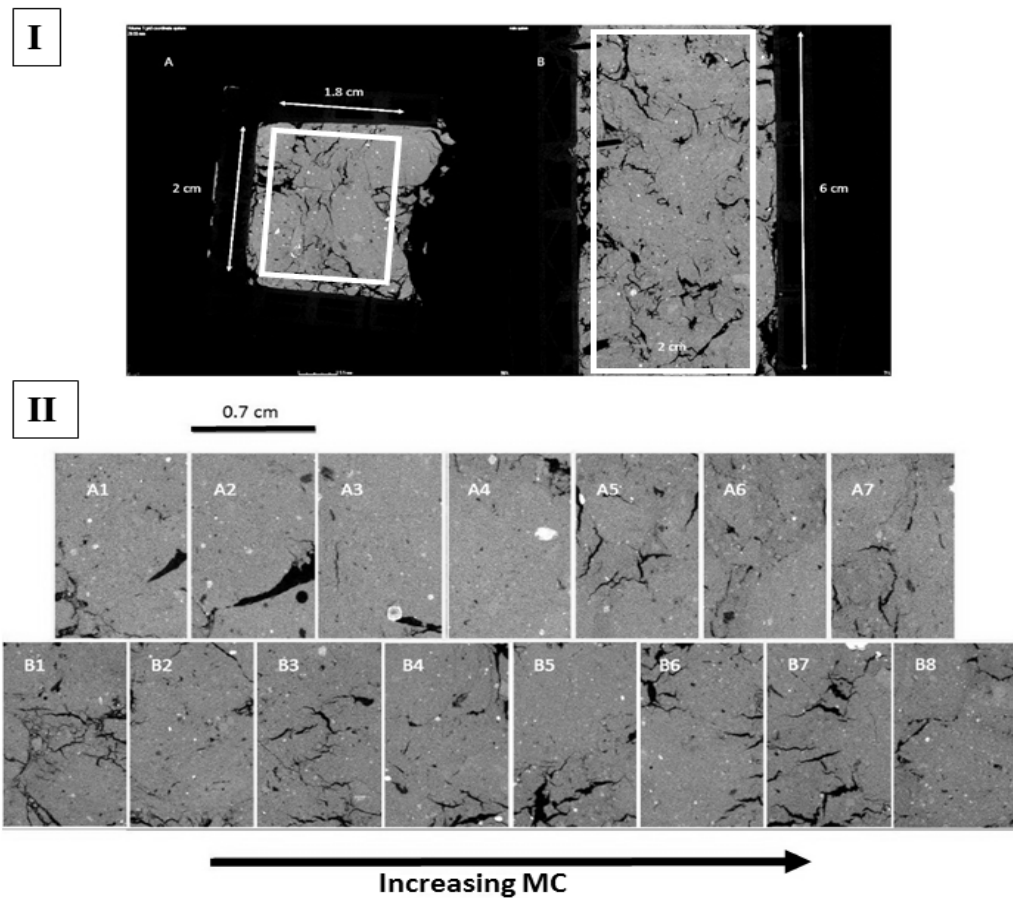


Figure 4.1: Image showing two cross-sections (I- Widthwise and B- Lengthwise) of a CT reconstructed soil volume. White rectangles indicate the selection area used for image processing. II: Selected area cropped from scan images corresponding to every soil batch. 'A' group corresponds to soil type 1 and 'B' group to soil type 2.

4.4.4 Formulating a pedophysical link

Given the BR and XA relationships, an expression of ER as a function of X-ray absorption can be computed by re-arranging the two equations. Hence:

$$\rho^{-1} = \left(\frac{\ln\left(\frac{I_{dry}}{I_{wet}}\right)}{\rho_{dry} \times x_{dry} \times \mu_{water}} \right)^{n-1} \times \left(\frac{\ln\left(\frac{I_{dry}}{I_{wet}}\right)}{\rho_{dry} \times x_{dry} \times \mu_{water}} \times \frac{\sigma_w}{\phi^{-m}} + B_{ws} \times D_g \frac{(1 - \phi) \times c}{\phi^{-m+1}} \right), \quad (4.5)$$

Except for m and n, all other soil and fluid properties in the combined expression above have been measured independently in the laboratory (Table 4.1).

4. A PEDOPHYSICAL RELATIONSHIP BETWEEN X-RAY COMPUTED TOMOGRAPHY AND ELECTRICAL RESISTIVITY TOMOGRAPHY DATA

WS		S1	S2
	$\phi(\%)$	35	30
	$c(\text{meq}/100\text{g})$	27.2	37
	$B_{ws}(\text{Scm}^3\text{m}^{-1}\text{meq}^{-1})$	2	2
	m	2.84	0.87
	n	2.51	1.22
	$D_g(\text{g}/\text{cm}^3)$	2.65	2.65
	$D_w(\text{g}/\text{cm}^3)$	1	1
	$\sigma_w(\text{S}/\text{m})$	0.05	0.05
BR lab fit	Pearson r	0.958	0.89
	RMSError	5.89	2.84
BR CT fit	Pearson r	0.97	0.93
	RMSError	4.43	2.22
XA	$I_{dry}(\text{GS})$	46.04	42.5
	$\rho_{dry}(\text{kg}/\text{m}^3)$	3800	3794
	$x_{dry}(\text{m})$	0.02	0.02
	$\mu_{water}(\text{m}^2/\text{kg})$	0.01186	0.01186
XA fit	Pearson r	0.93	0.96
	RMSError	1.1	1.9
Combined relationship fit	Pearson r	0.87	0.93
	RMSError	5.96	2.41

Table 4.1: Laboratory determined parameters used to compute WS and XA relationships

4.4.5 Enhancing BR predictions based on CT estimates

As described previously, calibration curves for interpreting ERT monitoring experiments are obtained by taking bulk electrical resistivity measurements on samples of a known MC, estimated by weighing each sample. The water is added manually and its distribution is assumed to be uniform, therefore the estimates are subject to error. An alternative option arises from the methodology described above. The soil MC was estimated by fitting the XA model

to the average GS measurements. These values were, in turn, used to estimate ER on the basis of a BR relationship (Figure 4.2 BR).

4.5 Results and Discussion

4.5.1 MC variability

Visual inspection of the image selections in Figure 4.1 II, show how GS decreases with increasing MC. This is also later confirmed by the average GS per sample estimates (Figure 4.2 XA). Figure 4.2 shows a significant variance within the triplicate samples of the same batch. In order to determine the source of this variance, an average percentage of air-filled pores from the CT scans was derived. It is important to note that these estimates were recorded after the samples were packed so they will differ from the soil's undisturbed values of air-filled porosity. For S1 we recorded values between 9.3 and 0.8 % with larger air-filled porosity values corresponding to the first three batches with lower MC. In consequence, they had the highest variance within the batch between the three replicates. For S2 it was recorded a similar range of values between 12.7 and 2.88 %. As for S1, the highest values and variance were observed within the first three batches. For S1, greater variation was noticed within the batches corresponding to the upper half of the GMC distribution. This implies that, when more moisture is present in the system, the variations in GS are higher. This can be explained by the way water redistributes once it enters the soil matrix. Capillary pressure and movement of free water determine different regions of higher and lower MC (Free, 1911). Therefore, an increased capillary activity may cause such variability. The percentage of air-filled pores per sample batches showed a higher variance corresponding to the driest three batches for both soil types. This implies a GMC threshold between 0.128 g.g^{-1} and 0.15 g.g^{-1} , over which, for this particular sample size and ge-

4. A PEDOPHYSICAL RELATIONSHIP BETWEEN X-RAY COMPUTED TOMOGRAPHY AND ELECTRICAL RESISTIVITY TOMOGRAPHY DATA

ometry, a higher percentage of water-filled pores reduces the heterogeneity of water distribution.

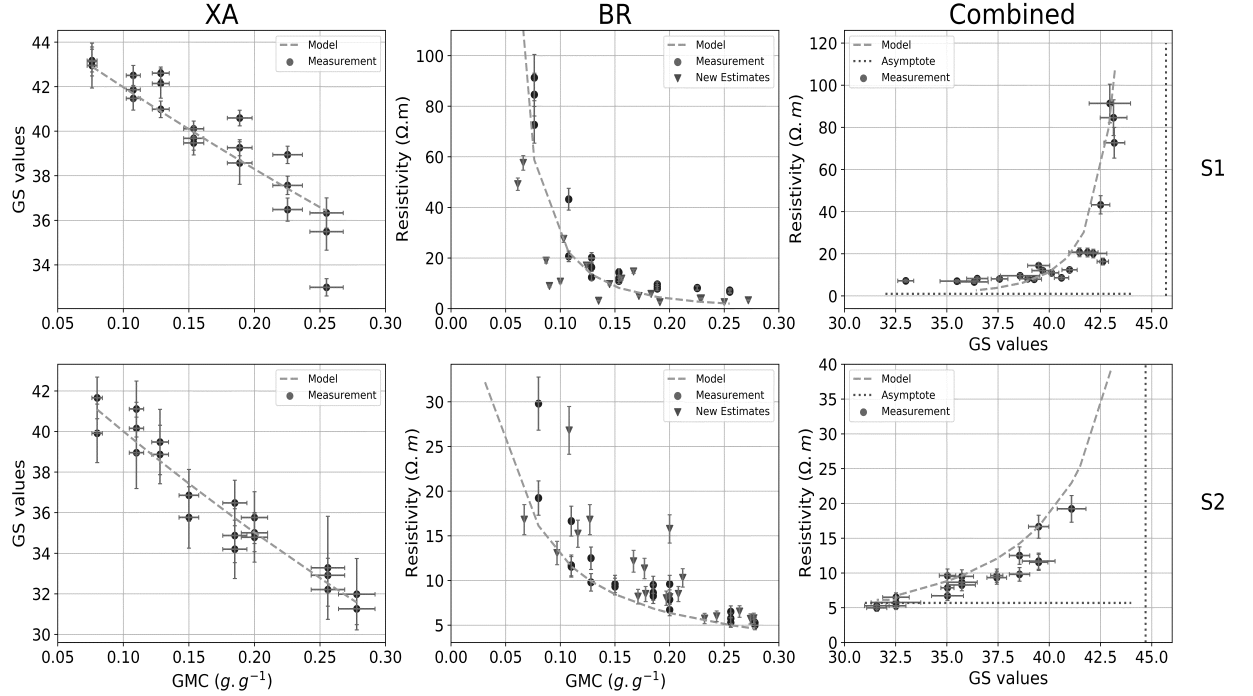


Figure 4.2: XA: Average GS measurements (circle) fitted by XA estimates (dashed line). Error bars indicate the GS standard deviation within the sample; BR: Resistivity measurements (circle) fitted by BR estimates based on laboratory measurements (dashed line) of MC and based on X-ray CT estimates (down triangle) of MC; Combined: Lab-derived measurements fitted by the new pedophysical relation, Equation (4.5), estimates (dashed line). BR and Combined plots have an assumed 10% error for resistivity estimates.

4.5.2 Implications of the pedophysical fit

For both soil types the conceptual models show a good fit with measured datasets (Figure 4.2 XA and BR and Table 4.1), implying the experimental data validates the model predictions. However, it is useful to remember the pedophysical relations are case specific and correspond only to samples with the intrinsic physical properties listed in this study (Table 4.1). Therefore, soil texture is an essential variable, which it can also be understood by observing

the different shapes of the BR curves corresponding to the two soil types. For the BR model, the S1 exhibited higher resistivity values than S2 for low and medium GMC (Figure 4.2 BR). This effect may well be due to the difference in sample air-filled pore space, as an increase implies an increase in electrical resistivity. However, these measurements do not support such statement as the average percentage of air-filled pores is similar between the soil types. In the high GMC region, where the majority of the pore-space has been occupied with water, the models produce similar values, hence air-filled pore-space contribution to bulk values of resistance decreased. The electrical response is also correlated with the soil clay content as it is directly linked to an electric charge deficit (Waxman and Smits, 1968). Calculated cation exchange capacity (Table 4.1) supports the difference between S1 and S2 implying a clay content effect on resistance values recorded. From the XA model, a more abrupt change in X-ray attenuation is observed on the curve corresponding to S1 (Figure. 4.2 XA). Also, S1 exhibits a higher dry GS value (intercept). Given the same X-ray energy, the differences in absorption magnitude are also correlated to the sample's porosity and texture. With increasing MC, a higher porosity implies a lower rate of saturation hence a higher absorption increase rate.

4.5.3 Improving BR calibration

An alternative way of estimating water content for ERT experiment calibrations was proposed. In Figure 4.2 (BR) and Table 4.1 (BR lab and CT fit), the new estimates represent BR values based on CT estimates of MC. These show a better fit with resistivity lab measurements than BR values (Model) based on MC weighing for both soil types. It can also be observed that the new estimates correct the resistivity underestimation for S1 in the high GMC region, but underestimate the measured resistivity values in the low GMC region. The

conventional methodology is very laborious and time-consuming with daily additions of extra water to subject samples which have to reach hydraulic equilibrium before electrical measurements. The CT strategy suggested allows simultaneous preparation of multiple samples. Therefore, total experimental time is reduced to a few hours. Also, MC is derived for each individual sample and not for each individual batch. It can be stated that from a theoretical point of view, a calibration based on CT measurements is more advantageous and improves the calibration estimates. However, it is acknowledged that the use of X-ray CT is not always cost effective.

4.5.4 CT-ER relationship

In Equation (4.5), an expression for bulk ER as a function of X-ray intensity was formulated. As seen in Figure 4.2-Combined and based on the Pearson r and RMS Error values (Table 4.1) the model fits well the corresponding datasets. We observed an underestimation of electrical resistance in the low GS region of the S1, which was a consequence of BR inaccuracy. For S2, this behaviour was not observed, but BR also accurately predicted the resistivity in the high GMC region. We extended the models beyond the dataset boundaries and towards both ends the estimations asymptotically tend to a constant. For low values of GS the value implies reaching soil water saturation and for the high values implies reaching a dry state, zero GMC.

4.6 Conclusions

A methodology that facilitates the joint appraisal of datasets obtained through two well established non-invasive soil observation methods: X-ray CT and ERT was presented. Laboratory measurements of resistivity and average X-ray absorption were obtained for two soil types at different GMC. Subsequently, the

results were fitted to representative MC pedophysical relations - Equations (4.3) and (4.4). The good fit between the model and measured datasets enabled us to: 1. rearrange the pedophysical equations in order to formulate a quantitative link between CT images and ER and 2. obtain an improved BR soil resistivity calibration based on X-ray CT estimates of MC. These results indicate the possibility of inferring electrical properties from CT images of soil and can be used as a benchmark calibration reference for future joint studies which employ the two methods. Further research should use such a relationship for a more comprehensive investigation of soil hydraulic properties by directly correlating MC distribution due to soil structure to changes in electrical resistance due to water infiltration flux or evapotranspiration. Furthermore, these new insights allow the development of improved geoelectrical calibrations that will enhance the ability to non-invasively monitor vadose zone processes, vital for agriculture management or civil engineering.

5 HYDRODYNAMIC CHARACTERIZATION OF SOIL COMPACTION THROUGH AN INTEGRATED ERT AND X-RAY CT AP- PROACH

5.1 Abstract

Modern agricultural practices can impact significant stress on soil, which ultimately has degrading effects, such as compaction. There is an urgent need for fast, non-invasive methods to characterize and monitor compaction and its impact on hydraulic processes. Electrical resistivity tomography (ERT) is a well-established method used for the assessment of soil hydraulic properties due to its high temporal resolution and sensitivity to changes in moisture content and salinity. X-ray Computed Tomography (CT) is a method employed for high spatial resolution imaging soil structure. The combined capabilities of both techniques were used in this study to look at soils under three different levels of compaction. Columns of soil (6.8 cm diameter, 12.5 cm height) were X-ray scanned and electrically monitored following the application of a saline solution to the soil surface. The scans revealed a greater porosity for soils with a lower bulk density, for which, ERT models also showed an inhibited solution percolation rate. Furthermore, a quantitative link between the two methods was obtained, by which voxels of high density in pore space had higher temporal variations in electrical resistivity. Thus, it was established a spatial link between pore structure and distribution of solution during percolation. This demonstrates the potential of the combined capabilities of the two tomographic methods to characterize soil hydrodynamic properties, supporting

efforts to understanding the impact of human activity soil-water management.

5.2 Introduction

With an increasing agricultural demand world-wide and pressure from an expanding population and a changing climate, fast, robust and non-invasive methods of soil assessment are required. Due to intensive use of heavy machinery soil structure degradation or compaction has become a serious problem (Hamza and Anderson, 2005). Classic invasive soil sampling methods often require significant manual labour, alteration of soil's natural properties e.g. structure and have difficulties in measurement repeatability (Furman et al., 2013). Other practices that make use of minimally-invasive sensors, such as time domain reflectometry (TDR), have a good temporal resolution, but lack in site spatial coverage (Furman et al., 2013). Electrical resistivity tomography (ERT) is a non-invasive, quick and relatively easy to use method of monitoring changes in soil bulk electrical resistivity, a proxy for changes in soil properties such as: pore fluid content, soil texture, pore structure, saturation, pore fluid salinity etc. (Samouëlian et al., 2005). Its substantial coverage allows it to be applied to large scale field studies (Michot et al., 2001) and on smaller scale laboratory investigations of root zone properties (Garré et al., 2011). ERT produces tomograms of the subsurface by fitting measured electrical resistance data to a predicted model of the subsurface resistivity distribution. Furthermore, (Romero-Ruiz et al., 2018) identifies electrical resistivity methods as valuable for the study of soil compaction due to the amount of information regarding soil properties it can reveal. However, its methodology suffers from inherent problems such as model solution non-uniqueness or instability. Therefore, the amount of information it provides can be both an advantage and a liability. A good way of enhancing the method's robustness is by providing

a-priori information to constrain the final result (Loke et al., 2013). X-ray Computed Tomography (CT) is also a well-established non-invasive method that has proven successful in soil science for assessing soil structure at very high resolutions (10 μm) (Tracy et al., 2015). It lacks high temporal resolution, as the acquisition time of a complete 3D scan sequence depending of the level of detail required can take several hours, although most modern systems are usually able to scan much quicker (e.g. minutes rather than hours). However, through recent advancements in computer vision, CT technology allows the visualisation and a quantitative assessment of pore architecture, which in turn can be used to estimate soil hydraulic properties (Anderson et al. (2003), Grayling et al. (2018)).

This study aimed to formulate an improved characterization of the effect compaction has on the hydrodynamic behaviour of soils using a combined imaging approach utilizing the specific strengths of the two tomographic methods mentioned above. Firstly, X-ray CT scanning was performed on columns of soil (6.8 cm diameter, 12.5 cm height) to resolve the parametric differences in pore structure due to soil compaction. Secondly, ERT was used to monitor the infiltration of a saline solution through the same soil columns. By this approach soil solution percolation rates were associated with soil structural parameters affected by compaction. Furthermore, it was demonstrated how datasets from the two tomographic methods can be quantitatively correlated in order to expose the 3D spatial distribution link between levels of pore structure density (from CT) and changes in electrical resistivity.

5.3 Methodology

5.3.1 Soil sampling

18 undisturbed soil columns (6.8 cm diameter, 12.5 cm height) were collected from random locations in an experimental field at the University of Nottingham experimental farm at Bunny, Nottinghamshire, UK (52°51'21"N 1°07'31"W). The sampling locations were decided by dividing the plot into 50 equal sized areal subdivisions out of which 18 were randomly selected. The soil was a clay textured (clay 40%, silt 25%, sand 35%) orthic luvisol from the Worchester series. Plastic cylinders were gently inserted into the topsoil to 20 cm depth and were extracted by careful removal of the surrounding material. On return to the laboratory the samples were assessed for their bulk density and then attributed to three equal sized groups (G1-3) that corresponded to G1 - 1.3-1.4 kg/m³; G2 - 1.4-1.5 kg/m³ and G3 - 1.5-1.65 kg/m³.

5.3.2 Saline solution infiltration

For the solute infiltration experimental stage, from each group (G1-3), one column with a bulk density closest to the group's average (for G1 - 1.39, G2 - 1.44, G3 - 1.54 kg/m³) was chosen. The underlying assumption was that samples with similar bulk densities show similar X-ray and laboratory derived porosity and hydraulic conductivity estimates (Anderson et al., 2003). The infiltration mainly followed the procedure detailed in Olsen et al. (1999). Prior to the start of infiltration, the soil column was modified in order to accommodate electrical measurements. 24 stainless steel electrodes were therefore fitted around the circumference of the plastic sleeve in three equally spaced rows of eight (Figure 5.1). Firstly, using a peristaltic pump, the samples were slowly saturated with deionised (DI) water from the bottom up. Secondly, a 0.01 M KCl (1.3

5. HYDRODYNAMIC CHARACTERIZATION OF SOIL COMPACTION THROUGH AN INTEGRATED ERT AND X-RAY CT APPROACH

mS/cm) solution was infiltrated until a steady-state was reached (decided upon the evolution of effluent's conductivity). Finally, a much more conductive 0.05 M KCl (5.3 mS/cm) solution was infiltrated, which acted as a tracer. As the pore solution reached the top of the sample, the effluent was collected and its electrical conductivity measured with a Decagon 5TE sensor and recorded with a EM50 Data Logger.

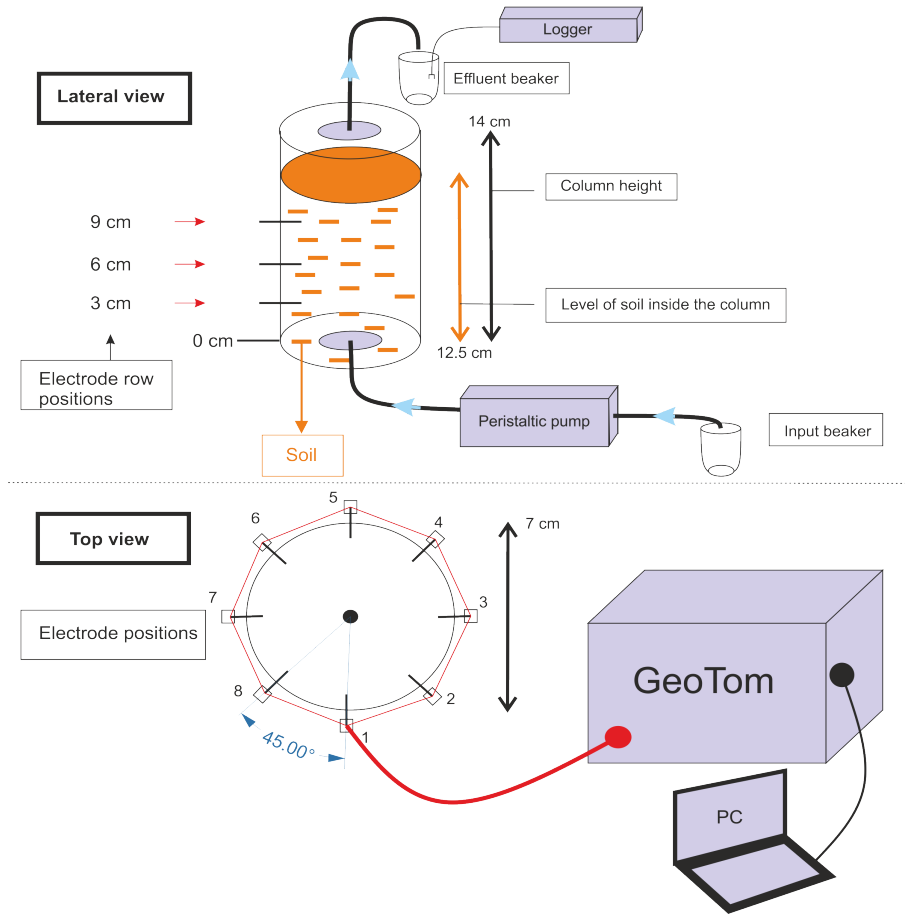


Figure 5.1: Schematic of the laboratory soil column experiment. Lateral view: KCl solution infiltration setting. Top view: Electrode arrangement for ERT monitoring.

During the infiltration, resistivity measurements were continuously collected, following a Dipole-Dipole electrode configuration for each measurement, using a GEOLOG2000 GeoTom MK-RES/IP/SP. One complete sequence pair, normal (ρ_n) and reciprocal (ρ_r) (current and potential electrodes are switched)

LaBrecque et al. (1996), contained 772 measurements and took approximately 15 minutes.

5.3.3 X-ray scanning and image processing

All of the nine sample cores were scanned with a v|Tome|x M X-ray scanner (Scan settings: 140 kV, 160 μ A, 8 minutes scan time and 40 μ m resolution) at the Hounsfield Facility, University of Nottingham, Sutton Bonington, UK.

The obtained radiograms were digitally reconstructed using Datos|x and processed using the VGStudioMax 2.2 software, over an 8-bit value range. From the 3D representation of the soil core, volume stacks of cross-sectional images were imported on multiple Cartesian directions. Further image processing was realized using the open source program ImageJ (Schindelin et al., 2012). A representative sub-volume of 3.8x3.8x6 cm³ (Figure 5.2) was selected in order to exclude areas adjacent to the sample edges, which might have been subjected to physical disturbance during extraction. This sub-volume was then subjected to one pass of both process filters: Sharpen and Median, in order to improve image quality before segmentation. Afterwards, an Otsu threshold was applied in order to binarize the images and segment the air-filled pore space represented by low grayscale values indicative of low absorption (Figure 5.2 D). The segmented images were finally collated into a binarized 3D soil volume. By further calculating the proportion of white pixels from the whole volume an estimate for total air-filled porosity and pore size was obtained. It is acknowledged that at this resolution only macroporosity could be estimated. Also, by using BoneJ (Doubé et al., 2010), a plugin for ImageJ, an estimate for the pore connectivity density (*ConD* - number of trabeculae per unit volume) was obtained following:

$$ConD = \frac{1 - \Delta X}{A \times h} \quad (5.1)$$

where X is the sample's Euler characteristic (a number that describes a topological space's shape or structure), ΔX is the sample's contribution to the Euler characteristic, A is the area of the image and h is the height of the image stack. Finally, in order to establish if there was a statistical significant difference between result groups an Analysis of Variance (ANOVA) test was computed using Python 3.6.

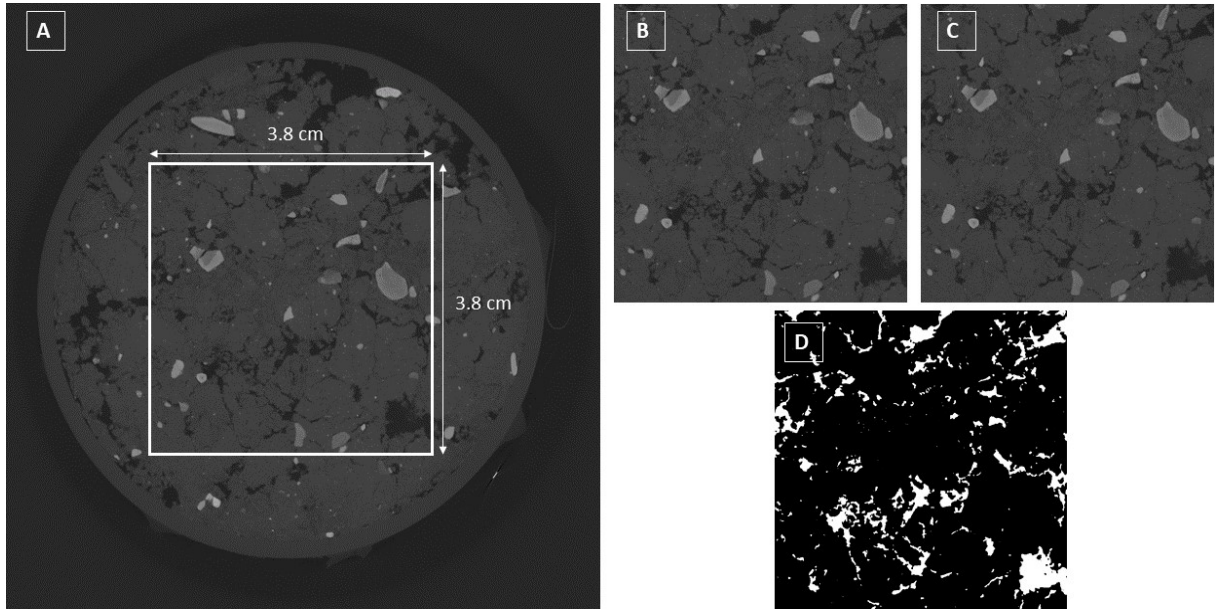


Figure 5.2: Soil volume image processing steps. A: Top view cross-section and representative selected area. B: Selected area cropped. C: Sharpen and Median filters applied. D: Threshold applied to segment empty pore space.

5.3.4 Pedophysical model

Soil bulk electrical resistivity is a complex parameter that depends on many physicochemical properties. Archie (1942) was one of the first formulated pedophysical relations to describe electrical resistivity as a function of rock's porosity and fluid content ($f(\phi, \theta)$). Building on Archie's relation, the WS model includes surface conductivity effects, which become important when an

increased content of clay particles is present (Waxman and Smits, 1968):

$$\rho^{-1} = f(\phi, \theta) = \phi^m \frac{\theta^n}{\phi} [\sigma_f + B \cdot Qv \cdot \frac{\phi}{\theta}], \quad (5.2)$$

where ϕ is porosity, θ is pore fluid content, σ_f is pore fluid conductivity, B is an empirical equivalent counterion mobility factor at 25 °C, Qv is the excess of surface charge of the solid phase per unit of pore volume and m and n are dimensionless empirical parameters. Assuming the samples are fully saturated, this relationship was used to translate between porosity and corresponding electrical resistivity. Ultimately, in order to express resistivity change, the ratio between two resistivity values (ρ_i and ρ_j) corresponding to i the initial/first time-step of the infiltration and j a subsequent time-step was computed:

$$\frac{\rho_j - \rho_i}{\rho_i} = \frac{f(\sigma_{f_j}) - f(\sigma_{f_i})}{f(\sigma_{f_i})}, \quad (5.3)$$

With no other external factors acting on the samples, the underlying assumption was that the change in pore solution salinity will be the main contributor to the change in bulk soil electrical resistivity. Nonetheless, in an attempt to decrease the uncertainty posed by the inversion solution, X-ray CT pore structural parameters were used as a source of a-priori information to enhance the inversion model interpretation.

5.3.5 Quantitatively link ERT and X-ray models

The ERT and X-ray model results essentially represent the distribution of electrical resistivity and X-ray absorption respectively over the same cylindrical volume. It is appreciated that there is a significant gap in resolution between the two tomographic methods. This volume was therefore divided into 128 equally sized voxels ($4 \times 4 \times 8$) and for every voxel (Figure 5.3), the average

5. HYDRODYNAMIC CHARACTERIZATION OF SOIL COMPACTION THROUGH AN INTEGRATED ERT AND X-RAY CT APPROACH

model cell change in electrical resistivity was estimated. Concurrently, for the corresponding voxel with the same position and dimension in the X-ray 3D pixel model the average air-filled porosity was computed. Finally, the voxel resistivity changes were binned into 5% intervals (starting at 10-15%) and the average resistivity change in each bin was calculated.

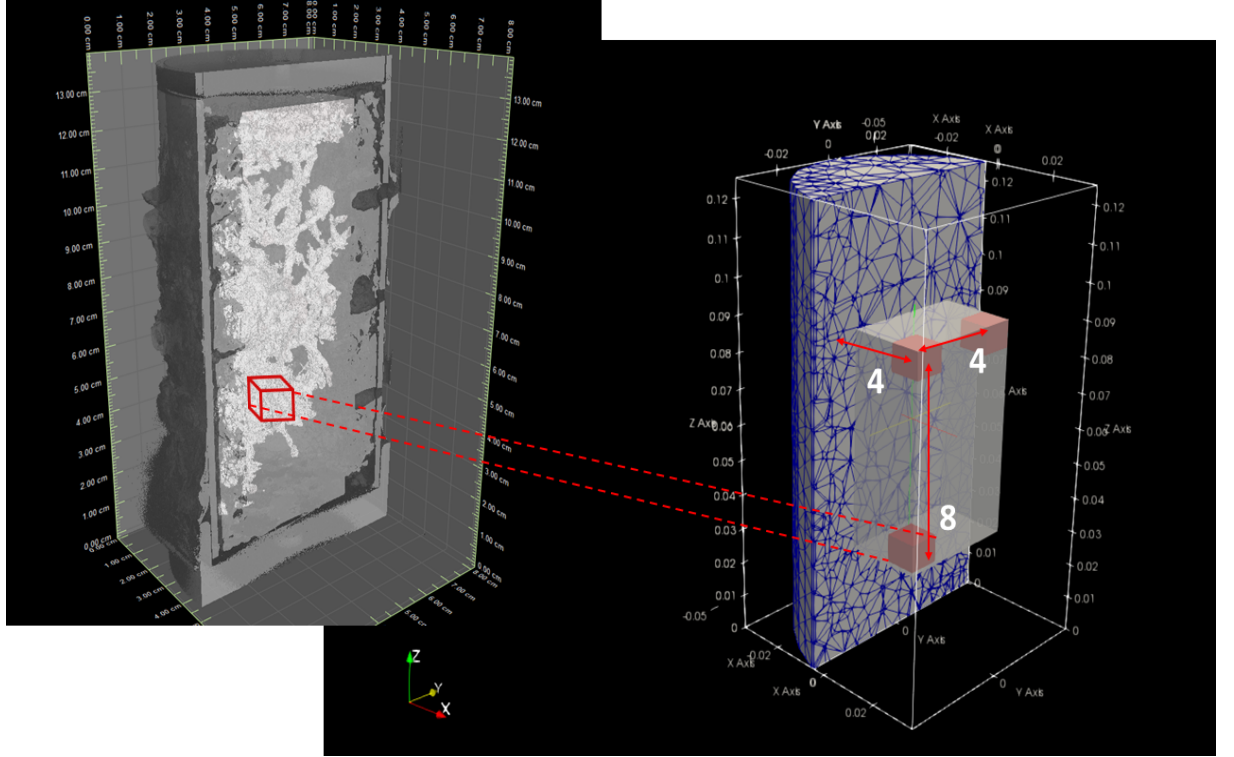


Figure 5.3: Cross-sectional vertical clip of the Left: X-ray CT 3D model of binarized soil. The white structure represents the air-filled pore space on which the surrounding soil in light gray was superimposed Right: model mesh used for resistivity inversion. The red cubes represent the voxel selection used to draw a quantitative correlation between the two datasets. The opaque grey box encloses the sample subvolume subjected to quantitative analysis.

5.3.6 Inserting X-ray CT derived pore architecture information in the geoelectrical mesh

It was broadly explained above that the process of segmenting non-percolating pore channels was undertaken by processing the 3D X-ray CT representation of a soil volume. Building on this, the procedure of pore channel reconstruction

within the geoelectrical mesh is presented. From each image cross-section of the non-percolating porosity (Figure 5.4 A), the current 2-Dimensional horizontal slice (Figure 5.4 B I) through a selected pore channel was isolated (Figure 5.4 B and C). Its outline was then extracted using ImageJ and the spatial coordinates of every point on the outline was computed. In order to automatize and make this process more efficient, instead of redefining every outline point within the geoelectrical mesh the best fit ellipse was determined (Figure 5.4 B III) (to the point distribution) and its features were integrated as a new surface element within the mesh. Finally, in order to create a 3D pore channel feature, adjacent vertical planes were defined between successive ellipse cross-sections. After all elements were imported and an enclosed 3D feature was obtained, a new zone could be redefined with its own properties and boundary constraints. The resistivity datasets were then inverted according to the newly defined geoelectrical model, which now includes the zone previously described.

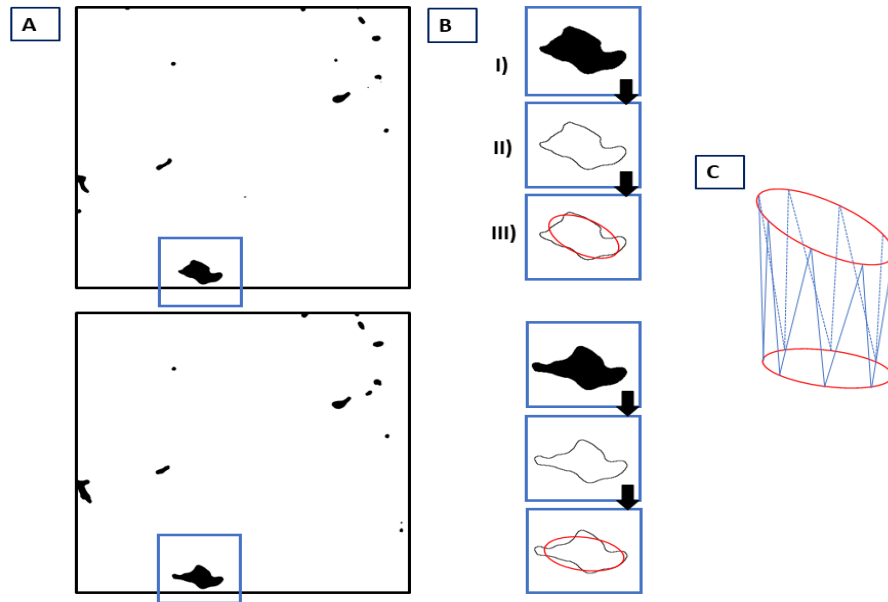


Figure 5.4: A: Two successive cross-sections of the non-percolating pore space (pores are indicated by black features) B: Pore feature ellipse fitting processing steps - I. Full pore II. Pore outline III. Ellipse fit to the pore outline. C: Reconstruction of the pore channel outline within the geoelectrical model mesh.

5.4 Results and Discussion

5.4.1 ERT monitoring

Several models of bulk soil electrical resistivity corresponding to different stages of the infiltration were obtained. As the saline solution infiltrates the column, in Figure 5.5 just a few representative time-steps illustrate the temporal changes in electrical resistivity. As electrodes were only placed at 3 cm, 6 cm and 9 cm height on the sample's exterior, just the subvolume enclosed between them is shown. As time progresses an increasing number of model cells display a lower resistivity (indicated by blue rather than red colours). As the 5M KCL saline solution reached these regions of the soil volume, the pore solution will become more conductive, hence decreasing the bulk electrical resistance of the volume cell. Although this result is to be expected given the experimental settings, this work aimed to estimate the change in electrical resistivity distribution across the whole volume more accurately. Therefore, the way pore structure and pore size distribution impacted the changes observed was investigated further.

5. HYDRODYNAMIC CHARACTERIZATION OF SOIL COMPACTION THROUGH AN INTEGRATED ERT AND X-RAY CT APPROACH

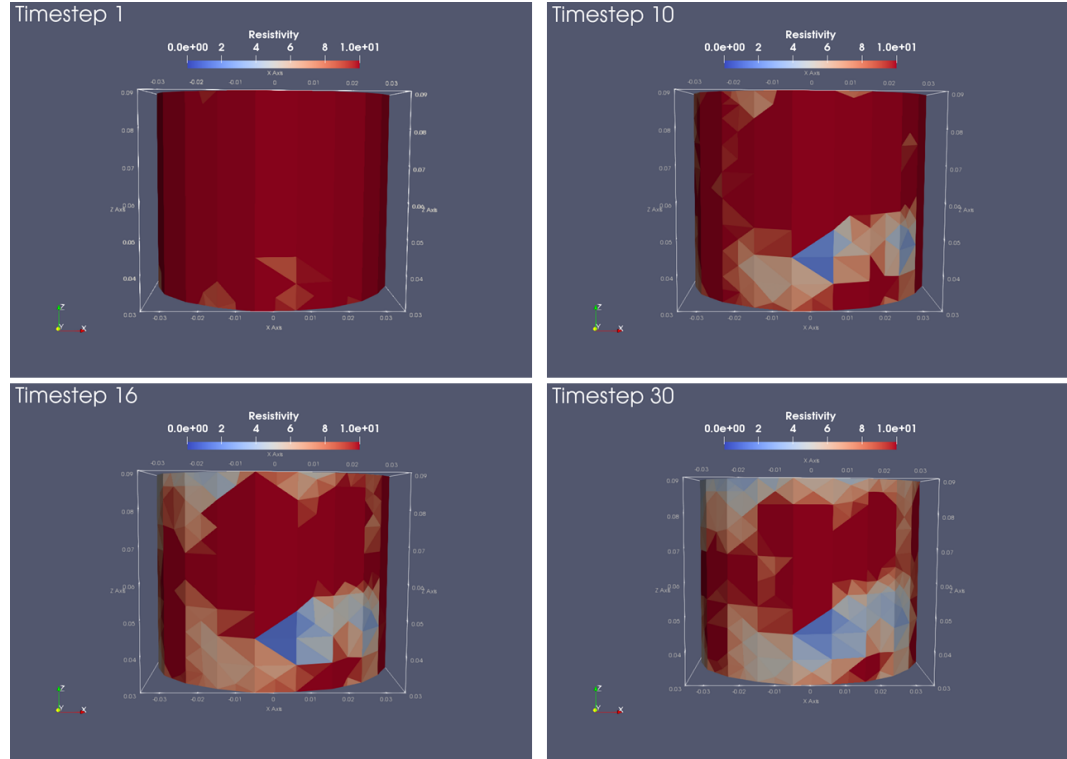


Figure 5.5: Clip of the G1 Column Resistivity model in 4 stages of the high molarity solution infiltration. Dimensions are expressed in cm.

First, the sample's bulk changes in resistivity were quantified. For every time-step, the percentage of model cells that changed their corresponding resistivity over time by more than 10% of the initial value was calculated. In Figure 5.6-A, the columns percentage electrical resistivity change in time are compared. As in Figure 5.5, with time, more cell values are expected to change, hence the percentage will increase. Here, it is noticeable that the rate of such increase is different between the three groups. This can be explained by pore networks with different sizes and connectivities (Olsen et al., 1999). Also, the percentage of modified cell values reaches a stable state given enough time after the start of infiltration. This implies reaching saturation with the new saline solution. Therefore, the different stable maximum percentage values suggest samples with different porosities, as a larger pore volume would allow the percolating saline solution to reach more cells. Analyzing the effluent's

conductivity progression with time (Figure 5.6-B) we notice that the denser the soil the faster the effluent approaches the tracer conductivity. A less developed porosity leads to a smaller available pore fluid volume. Therefore, under the same constant rate of tracer injection, the concentration and therefore the conductivity of the pore fluid changes in a shorter time and at a higher rate.

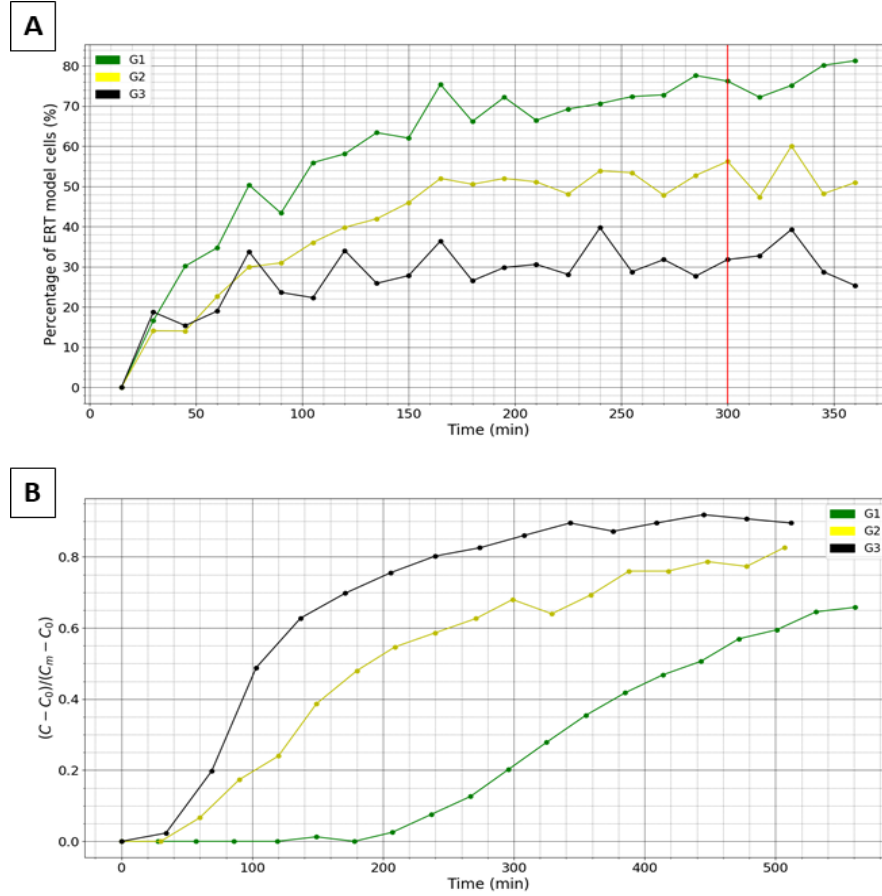


Figure 5.6: A. Percentage of ERT model cells which changed their resistivity by at least 10 % with respect to the first time-step. Red vertical line denotes time-step 20. B. Effluent breakthrough of solute recorded presented as reduced concentrations. C is measured conductivity, C_i initial conductivity and C_m the 5M KCl tracer conductivity.

5.4.2 X-ray CT resolved parameters

The samples with higher bulk densities had a significantly lower porosity and pore connectivity density (Figure 5.7). However, in terms of pore size distri-

bution, there was not a significant difference between the three groups.

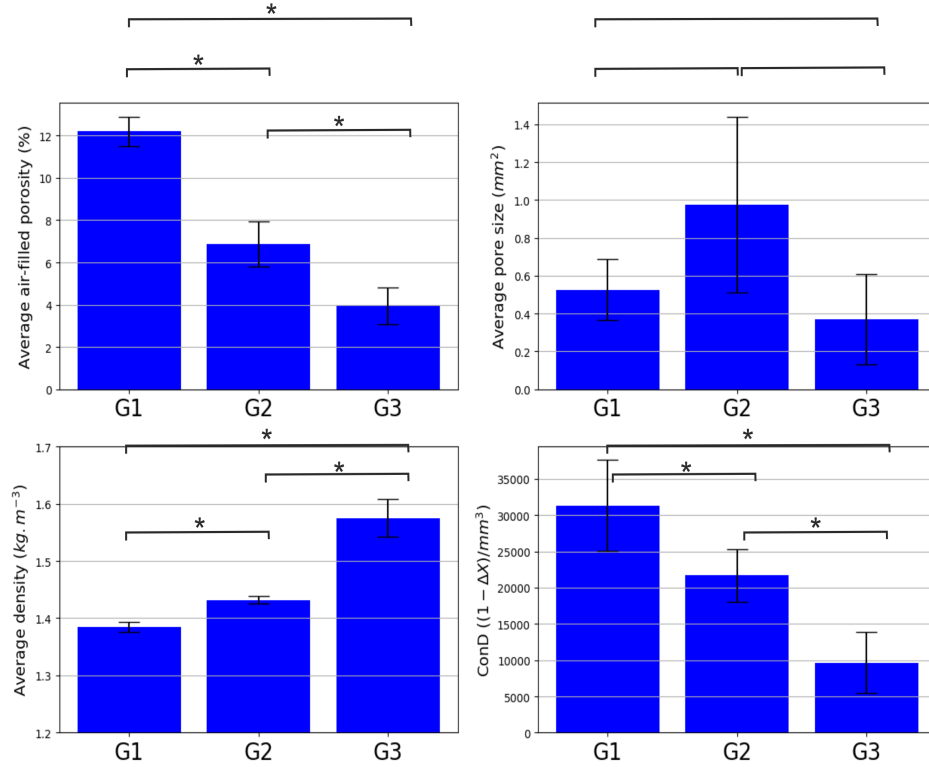


Figure 5.7: Air-filled pore structural parameters as resolved after the soil columns X-ray image processing. In the connectivity density unit formula ΔX denotes the sample's contribution to the Euler number of the sample. * indicates statistical significance ($p < 0.05$)

With reference to the ERT results, it was observed that the samples with a higher porosity also had a higher percentage of resistivity model cells change over time by the percolating solution. This underlines the fact ERT was effective in delineating the differences in soil bulk density at this scale. Also, the difference in resistivity rate of change between columns can now be viewed from the perspective of the different pore networks, as columns with higher rates of change also shown higher values of pore connectivities.

5.4.3 Enhancing time-lapse geoelectrical models of soil moisture dynamics with a-priori X-ray CT derived information

After obtaining the time-lapse inversion resistivity models corresponding to every time step of the infiltration, the resistivity change between the time-steps was computed. Figure 5.8 only shows the resistivity change between the TS 1 and TS 20 as it is believed the resistivity contrast was easy to visualise. This was indicated by the evolution of the effluent's conductivity measurements which showed an approximately four-fold increase in conductivity at the time of the 20th TS with respect to the first. Also, the model is truncated around the region of the mesh where the pore channel zone was introduced. In Figure 5.8 A, it is noticed that along the non-percolating pore channel the changes in resistivity are lower than its surroundings. This validates the initial assumption that a non-percolating region, due to the absence of a conductive fluid flow, will appear as a more resistive electric pathway through the soil medium. However, due to the constraints applied to the newly defined zone, a much better representation of the non-percolating channel was obtained (Figure 5.8 B). The resistivity distribution is more homogeneous, but also the shape and the extent of the pore feature are better represented. Nonetheless, it is acknowledged that in this work it is only presented a localized small scale example of what can be achieved by using this methodology. Further research is encouraged to develop a computational framework that uses the entire pore channel network as a-priori information for the inversion model. Also, future studies might determine more robust boundary constraints that can be applied to different areas of the pore channel, both percolating and non-percolating.

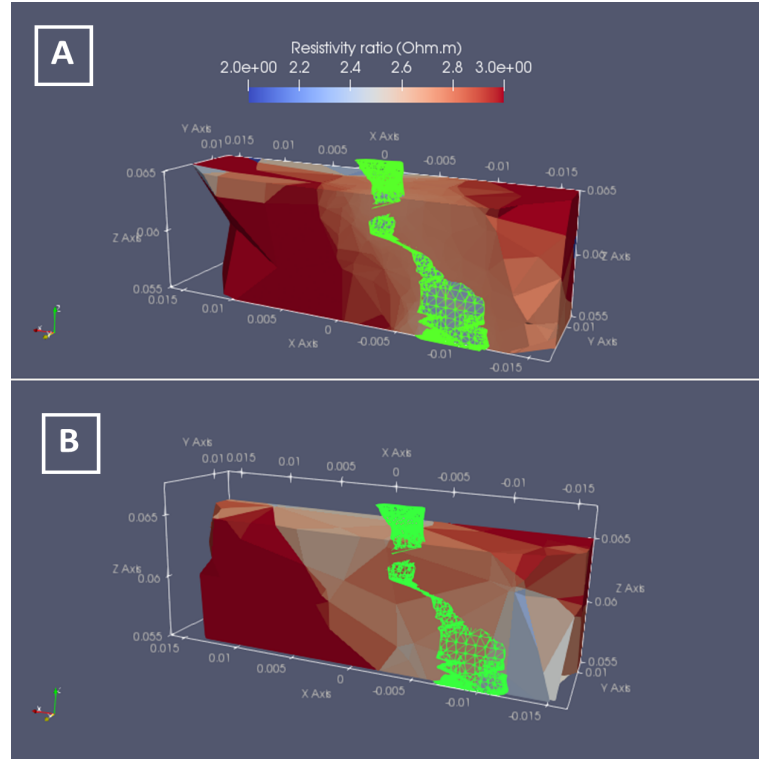


Figure 5.8: Extract from a resistivity change inversion model result corresponding to the soil column A: before and B: after including the non-percolating feature zone (green wireframe overlapping the model) in the geoelectrical mesh. The result shows the resistivity change between time step 20 (5 hrs after start) and time-step 1 (15 min after start). Dimensions in cm.

This result indicates that, by including a-priori pore architectural information into the geoelectrical model, a more accurate temporal and spatial representation of the resistivity variation is captured. Through this method, at laboratory scale, non-invasive monitoring of macropore fluid flow in soils can therefore be enhanced. Furthermore, it could potentially be applied to enhance the parametrization of soil hydraulic models which aim to quantify RWU and contribute towards an electrical monitoring strategy of plant physiological processes.

5.4.4 Correlation between porespace and change in electrical resistivity

5.4.4.1 Qualitative assessment As mentioned previously, there was a correlation between the pore structural parameters and electrical resistivity change during the infiltration. It was further aimed to explore the distribution of such changes across the 3D soil volume in greater detail. The change in resistivity between TS 1 and 20 was calculated and expressed as a percentage. The segmented pore space is compared with the distribution of electrical model cells which had a change in resistivity greater than 10% between TS 1 and 20 (Figure 5.9). It is shown in Figure 5.9 that in regions where pores were not present or their density is small, and hence solution cannot percolate, a significant change in resistivity was not detected. Such regions are highlighted by the red outlines in Figure 5.9. Also, the available air-filled pore space across the sample decreases with increasing bulk density. A qualitative correlation between the two outputs is observable even for the columns with the highest bulk density, which implies that, providing pore connectivity, the contribution of pore solution salinity is significant to the overall bulk electrical resistivity even when the porespace is sensibly reduced (values of porosity corresponding to G3 are approximately a third of those corresponding to G1).

5. HYDRODYNAMIC CHARACTERIZATION OF SOIL COMPACTION THROUGH AN INTEGRATED ERT AND X-RAY CT APPROACH

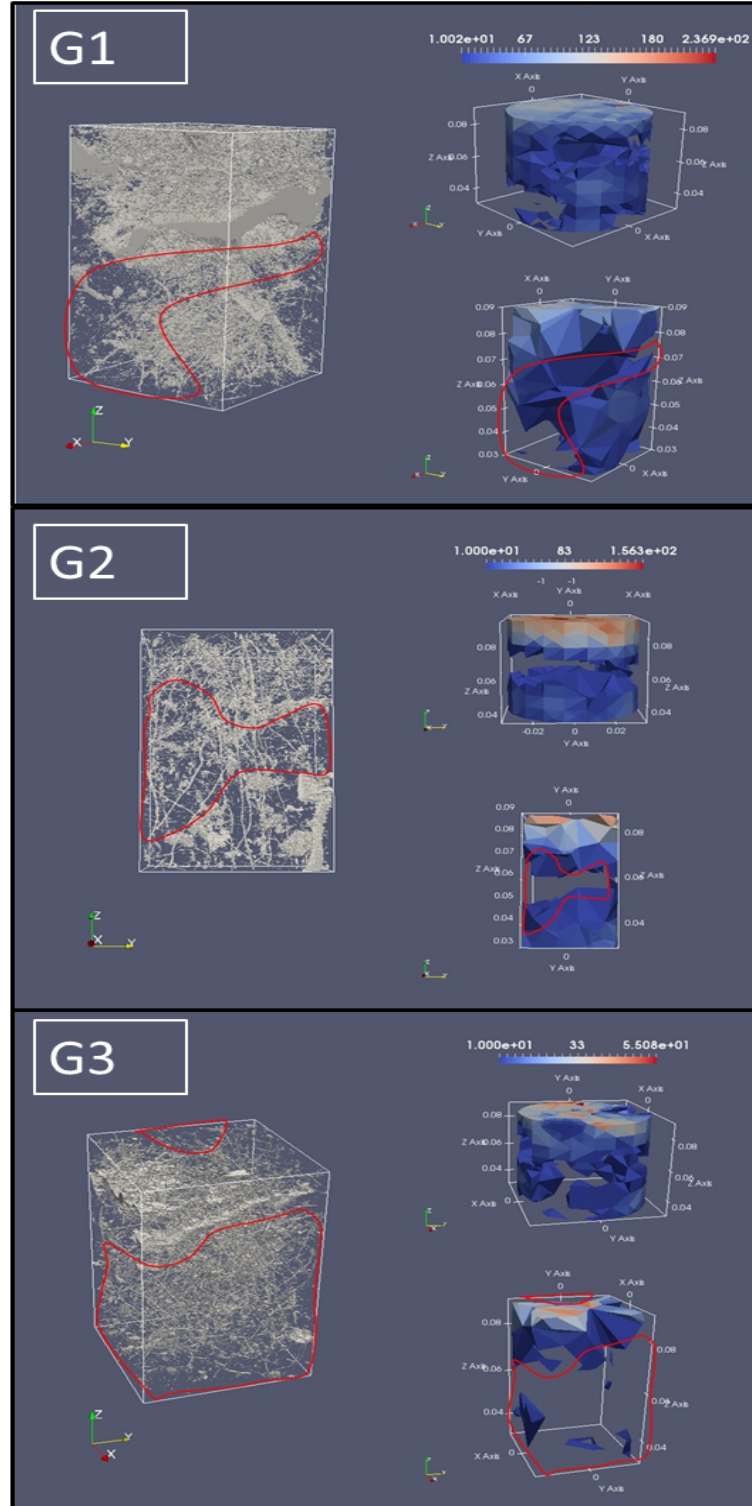


Figure 5.9: Left: Cropped segmented air-filled pore space. Red outline points towards the areas of interest, areas of underdeveloped porosity. Right: Resistivity model cells which exhibited a change greater than 10% over the top: whole column, bottom: same region cropped for X-ray analysis. Dimensions are expressed in cm.

5.4.4.2 Quantitative assessment A quantitative correlation between the two output models is required in order to be able to assess the impact that pore network structure has on the hydrodynamic behaviour of soil. Estimated average resistivity changes for every sub-volume voxel are verified against the existing pedophysical theory (Figure 5.10). The expected (model) resistivity change values were obtained using Equation 5.2 and X-ray CT estimated values of porosity. These are shown against the average pore space for the same voxels (Figure 5.10) in order to underline spatial correlation. The WS estimated values correlated very well with the voxel average measurements, in fact also underlined by the Pearson correlation coefficient (0.94) between the two datasets. The value of the average porosity standard error was larger for greater values of resistivity change. Due to a larger available pore space, hence more available pore solution, the homogenization process between the resident and the infiltrating solution takes longer. Also, macropore channels of similar volumes do not necessarily share the same connectivity, which imposes different susceptibilities to preferential flow (Jarvis et al., 2017). This in turn determines different homogenization rates and consequently different pore solution conductivities. Therefore, it can be postulated that for this sample with its intrinsic physical properties, areas of porosity larger than 10% are indistinguishable using time-lapse ERT. At the other end of the spectrum a slight disagreement was observed between measurements and the WS curve (for 10-15, 15-20 % change bins). The theoretical model estimates predict that lower porosities, than the ones measured, should account for the changes in electrical resistivity observed. However, in reality, pores are not perfectly interconnected, thus a certain proportion of the porespace does not participate to the solution percolation in soils (Koestel et al., 2018). Therefore, an air-filled pore disconnected from the main flow path will contribute to the increase of total porosity, but

will fail to contribute to changes in electrical resistivity.

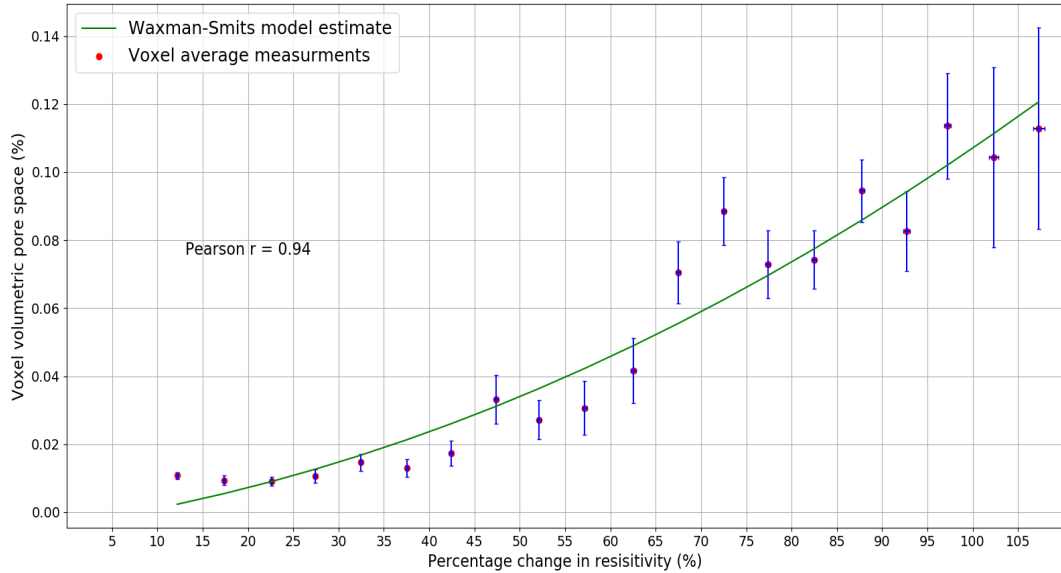


Figure 5.10: Relationship between the change in resistivity and soil air-filled porosity. Blue error bars represent the standard error of the mean.

Even though the assumption was that changes in pore solution salinity will drive the resistivity changes, there was more certainty in the electrical model results when enhanced by complementary datasets (Everett, 2013), such as the soil columns' corresponding pore network. The X-ray scans offered the spatial distribution of porosity across an individual sample. The variability in electrical resistivity can now be explained based on the porosity variability across the sample. Furthermore, one may assume that if the porosity does not explain the resistivity variability there must be other pedophysical factors responsible (e.g. organic material, increased salinity, clay aggregates) (Samouëlian et al., 2005), hence establishing a way to quantify their effect. As the resolution used in this study only allows the quantification of macropores, the good fit between estimates and measurements suggests that macroporosity alone accounts for the detectable changes in electrical resistivity, hence for the changes in pore

solution concentration. Also, from the visualization of the air-filled pore network, even though it gives an appreciation of the soil hydraulic capability (e.g. water holding capacity, infiltration speed) (Tracy et al., 2015), details about the 3D pore solution percolation in near real time cannot be inferred. Therefore, information from the two methods is complementary and enables a more comprehensive understanding of the soil hydrodynamic character.

5.5 Limitations and future perspectives

Aforementioned results showed how the models of soil electrical resistivity changed over time with the passage of the infiltrating solution. ERT monitors solute flow in near-real time, so during a TS acquisition solute continued to move inside the column, which determined temporal smearing of electrical resistivity values (Slater et al., 2002). This can be accounted for if the datasets corresponding to different TS are inverted together in a time lapse inversion (Koestel et al. (2008); Kemna et al. (2002)) and not individually.

Soil hydraulic properties and structure are investigated here under different levels of compaction. However, only one soil type (orthic luvisol) is considered in this research. The physicochemical properties of a different type of soil found under a different climate could change the soil's resilience and hydrodynamic response to compaction. Therefore, in order to expand our understanding, following a similar methodology, more soil types need to be investigated. Furthermore, microporosity could not be assessed here due to limitations in resolution. This could be provided by future advancements in instrument resolution and sensitivity. This would offer further insight on pore connectivity and is required for an accurate assessment of the soil's water holding capacity.

5.6 Conclusions

This study presented a methodology which combines the strengths of two tomographic methods, X-ray CT and ERT, in order to expose the hydraulic characteristics of a soil under different degrees of compaction. To that extent, soil columns at three levels of increasing bulk density determined by field compaction were investigated. X-ray CT facilitated visualization of the soil pore architecture, obtained after approximately 0.5 hours of scan time and 1-2 hours (per column) of data reconstruction, processing and quantification of structural parameters (e.g. total porosity, average pore size, pore connectivity). ERT facilitated 4D models representative of a 9 hours high molarity (5M) KCl tracer solution infiltration through the soil matrix from the bottom of the columns up.

By quantitatively linking observations from the two tomographic methods it was obtained a direct relationship between soil structure (from X-ray CT) and solution percolation (from ERT) distribution with time. Even though the soil columns had the same texture and the tracer had the same entry infiltration rate, the lower compacted columns revealed different percolation rates through faster spatial changes in electrical resistivity. Taken separately, X-ray CT could not describe or monitor the infiltration, as ERT could not depict the fluid pathways due to its inversion model non-uniqueness limitation. However, together, the X-ray pore structural parameters exposed a decreasingly pore connectivity with compaction, which explained the inhibited infiltration rates resolved through ERT bulk resistivity estimates. X-ray derived pore channel spatial information was used to enhance the inversion results producing a more accurate representation of the solute flow path. Furthermore, the spatial distribution of electrical resistivity change was quantitatively correlated with areas of large air-filled pore space density, indicating the accurate position of percolation

channels. These results underline the potential this methodology has to monitor and characterize vadoze zone hydrodynamic processes. Further research could consider time-lapse inversion of electrical data to avoid temporal smearing and use a similar methodology to investigate what is the hydrodynamical response of other soil types to compaction.

6 ASSESMENT OF THE LONG-TERM IM- PACT OF ZT AGRICULTURE ON SOIL HYDRODYNAMICS

6.1 Abstract

Conventionally, tillage has been a heavily used practice in agriculture for centuries. However, eliminating tillage or practicing zero-tillage (ZT) is considered to have a positive effect on the soil's health and productivity. It is not presently clear what are the long-term effects of ZT on the soil's structure and hydraulic properties. ERT is a well-established method used to monitor changes in soil electrical resistivity, a proxy for changes in soil moisture content and saline concentration. X-ray CT is a method well-suited for imaging soil structure at high resolutions ($< 100 \mu\text{m}$). In this study the two tomographic methods were used in conjunction to study columns of soil extracted from fields under ZT for 2, 7 and 12 years. ERT was used to monitor the infiltration of a saline solution through the soil columns and revealed that with duration of ZT the solution's lateral distribution inside the columns increased. Modeling such flow revealed a higher dispersivity and a lower pore solution velocity with ZT age. By imaging the pore structure of the same columns, X-ray CT revealed an initial decrease in porosity for the 7 year ZT, followed by an increase for the 12 year ZT. However, images suggest a more cohesive pore structure for the 7 and 12-year ZT soils, supporting ERT observations of a more expansive flow. Thus, this study indicated a resurgence in macroporosity in soils under ZT for more than 7 years, but further research is necessary to circumstantiate such observation, potentially explained by a rejuvenation in bioactivity.

6.2 Introduction

Tillage is one of the oldest practice in agriculture. It is also the most widely researched management practice affecting soil hydraulic properties and processes (Strudley et al., 2008). Most studies of tillage practices include comparisons of conventional tillage (e.g ploughing) with conservation tillage (non-invasive) approaches. Changing from conventional tillage (ConT) to ZT practices has previously been thought to negatively impact the soil properties by some researchers (Strudley et al., 2008). However, more recent evidence suggests that the opposite may be true (Mangalassery et al., 2014). ZT essentially implies that the soil structure is not disturbed in the preparation of a seedbed and seeds are directly drilled in the undisturbed ground. This practice leads to a greater amount of crop residue on the soil surface (Larney et al., 1994), which in some cases can enhance crop productivity and sustainability (Bhaduri and Purakayastha, 2014). Nonetheless, the underlying physicochemical mechanisms across different time-scales remain poorly understood and especially the impacts of ZT on soil structure over time.

6.2.1 The impact of ZT practives on soil structure and hydraulic properties

Tillage primarily implies a disruption of the natural cohesion of soil aggregates, therefore an alteration of soil structure. Conservation agriculture practices are based on disturbing soil as little as possible, which initially increases bulk density (Gomez et al., 1999) and reduces macroporosity (Alegre et al., 1991). In turn, such changes affect the hydraulic properties of the soil. Marsili et al. (1998) reported a reduction in saturated hydraulic conductivity due to increased compaction. This influences the rate at which soil exchanges water with adjacent mediums (e.g. atmosphere, groundwater system) which conse-

quently affects the overall quantity of water retained in the soil. Soils under ZT have therefore a reduced water infiltration rate which determines more available soil water (Mahboubi et al., 1993) and a greater water storage capacity (Lipiec et al., 2006), especially following conversion, though it is likely these properties will change over time as the soil develops a natural, faunal-driven structure. Even though there is evidence of differences from ConT, it is not yet clear at what rate and with what magnitude these changes impact the soil over years of continuous ZT.

6.2.2 ZT and flow parameters

Solute transport in soils can be described using the Convective-Dispersive Equation (CDE). The solutions of such models enable us to quantify the hydrodynamic behaviour through the estimation of flow parameters (van Genuchten and Wierenga, 1986). This was applied in controlled infiltration lab experiments on soil columns (Olsen et al., 1999). More specifically, this work will refer to parameters such as dispersivity, defined as the spreading of solution due to local variations in infiltration velocity, pore water velocity and the ratio of mobile to immobile water content. The values of such parameters are relevant as they dictate the nature of the flow. For example, the degree of preferential flow can be indicated by greater values of dispersivity (Luo and Lin, 2009) or by high values of immobile water (Bedmar et al., 2008).

Some soil physical properties have been shown to be correlated with dispersivity, such as particle size distribution and macropore parameters (Zhang et al., 2015). Paradelo et al. (2016) observed a strong correlation between CT-derived macroporosity and preferential flow. For lower macroporosities, the degree of saturation of the macropores is higher, with pore channels acting as preferential flow paths. In consequence, as ZT leads to a reduced macroporosity, an

increased preferential flow, and hence an increased dispersivity are expected.

6.2.3 ERT and tillage

The electrical resistivity of the soil is a parameter which is a function of porosity, saturation and solution salinity (Archie, 1942). Therefore, altering the distribution of aggregates and air/solute filled pore space through tillage will undoubtedly change the bulk electrical resistivity of the soil. However, when it comes to tomography, the resolution and scale of such structural changes becomes relevant. Romero-Ruiz et al. (2018) underlined the potential of field ERT to capture differences in compaction. Samouëlian et al. (2003) used ERT successfully to identify cracks (at the cm scale) in soils. In Chapter 5, a column scale study was presented where compaction is also successfully appraised by ERT. Therefore, there is potential for this method to monitor soil structural changes generated by agricultural management. Consequently, there are previous studies (Rossi et al., 2013; Séger et al., 2009) that quote correlations between ERT data and the effects of tillage practices. Rossi et al. (2013) reports greater values of electrical resistivity in tilled plots. However, detection of pores would have required a greater resolution (< 0.25 m electrode spacing). Operating at a higher resolution (i.e. 0.1 m electrode spacing), Séger et al. (2009) managed to detect the position of structural alterations caused by tillage, but not their exact geometrical size and form. In conclusion, using ERT at column scale, with centimetric scale resolution, one is able to observe differences between soils under different stages of ZT and use this in conjunction with X-ray CT resolved macroporosity to better characterize the hydrodynamics of ZT soil systems.

The combination of time-lapse ERT monitoring of solute flow and X-ray CT resolved soil macroporosity at column scale resulted in a more robust inter-

pretation of how the pore network size and architecture affects solute hydrodynamics (Chapter 5). Therefore, the aim was to apply such methodology here on columns of soil under ZT for different durations (2, 7, 12 years), in order to assess the long term effect of ZT on the hydraulic properties of soils. It is hypothesized that soil available porosity will decrease over time due to continuous machinery compaction, but potentially increase due to undisturbed bioactivity. Furthermore, effluent data is modelled in order to resolve specific flow parameters, which will add to our understanding of how solute transport is affected by such changes in soil structure.

6.2.4 Literature analysis

There is an extensive literature available on ZT practices and their impact on soil properties. Therefore, firstly, a quantification of such impact is attempted in order to subsequently correlate previous findings with current experimental observations. More specifically, the focus chosen here is on research that compares conventional tillage (ConT) with ZT impact on two types of soil parameters, namely structural parameters, such as: total porosity (Φ), macroporosity ($\text{Ma}\Phi$), microporosity ($\text{Mi}\Phi$), bulk density (D), water conducting pores (WCP), and hydraulic parameters, such as: hydraulic conductivity (K), water storage (WS), infiltration (I). In total, 85 articles were assessed. For each individual parameter it was recorded how many studies reported higher values during ZT practices, higher values during ConT or no significant change.

An analysis of the literature (list of articles in Appendix C) is presented in Figure 6.1. Here it is shown, for every aforementioned parameter, the proportion of the studies reviewed, which indicate a larger value for soils under ZT, ConT or which quote no change between the two (NC). Even though the outcome of this analysis only compares ZT and ConT soils without any insight

about the duration of ZT, it provides the basis of how ZT is expected to impact soil properties. Further experimental investigations will reflect upon the literature's conclusions and compel whether the long-term ZT soil exhibits any different characteristics.

A result was deemed conclusive if there were enough research studies to support it and the majority ($> 50\%$) indicated that result. The results were inconclusive for K, with 47% of studies quoting larger values in ZT soil versus 33% in ConT and 20% NC. Although references to changes in $Mi\Phi$ were found, there are no sufficient studies to support a trend. On the other hand, there were identified clear differences for the other parameters, hence for WS and D, ZT induced higher values. In contrast, for Φ , $Ma\Phi$ and I, ConT was found responsible for an increase. Therefore, the majority of studies indicate that upon ConT the soil becomes less dense and develops a volumetrically larger pore network, due to the intensive alteration of its natural integrity. In turn, this determines a greater water flow and a lower water storage. Similarly, Soracco et al. (2012) observed that the absence of tillage affects soil water movement mainly through the reduction in water-conducting macropores.

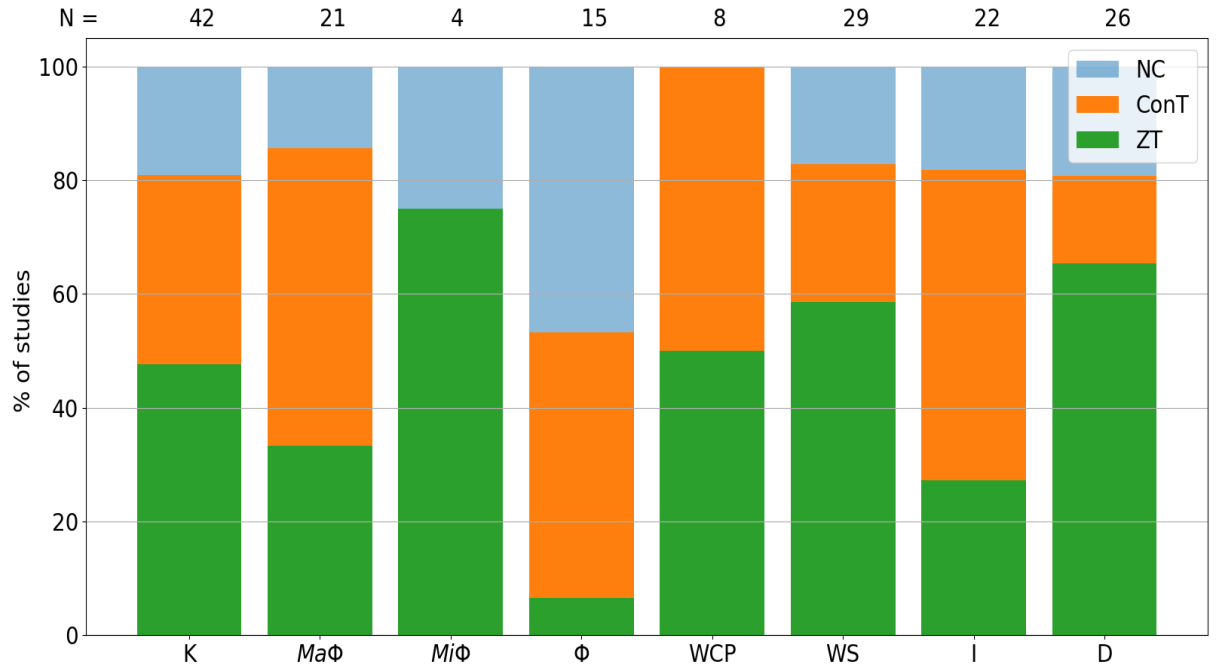


Figure 6.1: Data distribution of nine soil variables according to previous studies comparing ZT and ConT. N represents the total number of studies referring to every specific parameter. Color legend: 'Green' indicates the proportion of studies which quote an increase for soil under ZT, 'Orange' indicates the proportion of studies which quote an increase for soils under ConT and 'Blue' indicates the proportion of studies which quote No Change (NC).

6.3 Methodology

6.3.1 Soil sampling

Triplicate undisturbed soil columns (68 mm diameter, 120 mm height) were collected from a farm near Melton Mowbray, Leicestershire, UK. The soil was a silty clay loam texture and the samples were taken from fields under ZT for 2, 7 and 12 years old. The cores were extracted from the soil surface to approximately 25 cm depth.

6.3.2 Infiltration monitoring

The ZT soil columns were subjected to the same methodological steps as presented in Chapter 5. The columns were therefore saturated with DI water, followed by a two step slow injection of two saline tracers of increasing salinities. The same ERT monitoring array, detailed in Chapter 5, was used with the same measurement sequence.

6.3.3 X-ray scanning and image processing

Similarly to the procedure applied previously in Chapter 5, all sample cores were scanned with a v|Tome|x M X-ray scanner (Scan settings: 140 kV, 160 μ A, 8 minutes scan time and 40 μ m resolution) at the Hounsfield facility, University of Nottingham, Sutton Bonington, UK.

The obtained radiograms were digitally reconstructed using Datos|x and processed using the Volume Graphics 2.2 software, over an 8-bit value range. From the 3D representation of the soil core volume, stacks of cross-sectional images were imported on multiple Cartesian directions. Further image processing was realized using the open source program ImageJ (Schindelin et al., 2012). A representative sub-volume of 3.8x3.8x6 cm³ was selected in order to exclude areas adjacent to the sample edges, which might have been subjected to physical disturbance during extraction. This sub-volume was then subjected to one pass of both process filters: Sharpen and Median, in order to improve image quality before segmentation. Afterwards, an Otsu threshold (Otsu, 1979) was applied in order to binarize the images and segment the air-filled pore space represented by low grayscale values indicative of low absorption.

Finally, in order to establish if there was a statistical significant difference between result groups, an Analysis of Variance (ANOVA) test was computed using Python 3.6.

6.3.4 Effluent conductivity modelling

Inferences from non-invasive tomographic investigations, of both CT and ERT, are subjected to multiple sources of uncertainty (as described in Chapter 3). Therefore, analysis of the effluent concentration data provides the means to ground-truth electrical measurements and facilitate correlations between complementary datasets.

As previously, the effluent was periodically collected from the top of the soil column and its electrical conductivity recorded. According to Javaux and Vanclooster (2003) solute breakthrough curves (BTC) are typically measured from the column's effluent. They provide integrated and flux-averaged information on the processes governing solute transport in the column. In order to obtain local-scale solute transport parameters, such as dispersivity (λ) and pore solution velocity (v), several studies (Koestel et al. (2007), Olsen et al. (1999)) have shown how analytical or numerical solutions of transport models can be inversely fitted to such effluent breakthrough measurements. One of the most widely used models is the convection-dispersion equation (CDE):

$$\frac{dC}{dt} + v\frac{dC}{dx} - \lambda v\frac{d^2C}{dx^2} = 0, \quad (6.1)$$

where C is the KCl solution concentration and x and t are variables accounting for space and time. As underlined in the previously presented infiltration methodology (Chapter 5.3.2), the soil column was initially saturated with a lower molarity KCl solution of concentration C_i and conductivity σ_i , followed by the injection of a higher molarity tracer solution of concentration C_t and conductivity σ_t . In order to relate solution concentration to the recorded electrical conductivity of the effluent, a couple of assumptions were made: 1. The ratio between relative changes concentration $(C - C_i)/(C_t - C_i)$ and solute elec-

trical conductivity $(\sigma - \sigma_i)/(\sigma_t - \sigma_i)$ was constant over time and 2. The latter ratio was constant for the entire soil column and obtained from the effluent BTC (Koestel et al., 2008).

The second model considered here was a modification of CDE in equation 6.1 which splits the total moisture content θ into two domains, one mobile θ_m and one immobile θ_{im} fractions, with $\theta = \theta_{im} + \theta_m$ (van Genuchten and Wierenga, 1986):

$$\theta_m \frac{\partial C_m}{\partial t} + \theta_{im} \frac{\partial C_{im}}{\partial t} - \theta_m D_m \frac{\partial^2 C_m}{\partial x^2} - q \frac{\partial C_m}{\partial x} = 0, \quad (6.2)$$

where C_m and C_{im} are the mobile and immobile concentrations respectively, D_m is the mobile domain dispersion coefficient and q the Darcy flux. The solute exchange coefficient α can be expressed as the following Jaynes et al. (1995):

$$\theta_{im} \frac{\partial C_{im}}{\partial t} = \alpha(C_{im} - C_m), \quad (6.3)$$

Assuming that the initial tracer concentration in the soil is 0, the tracer concentration in the mobile water phase is equal to the input concentration, and the measured soil solution concentration is equal to $\theta_{im}C_{im} + \theta_mC_m$, the variables in equation 6.2 can be separated and solved to obtain the following mobile-immobile (MIM) model:

$$\ln(1 - \frac{C}{C_i}) = \frac{-\alpha}{\theta_{im}}t + \ln(\frac{\theta_{im}}{\theta}), \quad (6.4)$$

Therefore, according to Jaynes et al. (1995), plotting $\ln(1 - \frac{C}{C_i})$ vs. time, t , for all of the tracers should result in a straight line with a negative slope. The intercept ($t = 0$) gives us the natural log of the ratio of immobile water to total soil water content.

6.3.5 Percolation porosity

Percolation theory is a mathematical description of the behaviour of connected clusters in a graph. Such concepts can also be applied in soil science as a pore network can be considered as an interconnected graph. Percolating pore models of conducting porous media envisage that flow takes place through a percolating network of pores consisting of multiple connected pathways (Hunt et al., 2014). An effective (conducting) porosity in soil, ϕ_{eff} , accounting for the connectivity of the pore space, was defined by Katz and Thompson (1987) as:

$$\phi_{eff} = \phi_p[d_{opt}/d_c] \quad (6.5)$$

where d_c is the critical pore diameter, defined as the smallest pore neck encountered along the path of least resistance through the sample, ϕ_p is the accessible percolating porosity with thicknesses larger than d_{opt} , a value corresponding to the optimal path for hydraulic conductance.

Such concepts are implemented in an ImageJ plugin called SoilJ (Koestel et al., 2018). For a given binary set of scans representing pore volume, it allows the computation of parameters such as d_c , surface connected pore volume and percolation ratio (proportion of the interconnected pore volume, which in turn connects to the surface where the infiltrating liquid exits the sample).

6.4 Results and discussion

6.4.1 X-ray CT analysis of pore structure

Images resulting after X-ray scanning reveal the undisturbed structure of ZT soils. It can be observed in Figure 6.2. that the porosity significantly decreased for samples under ZT for a longer period of time (7 and 12 yr).

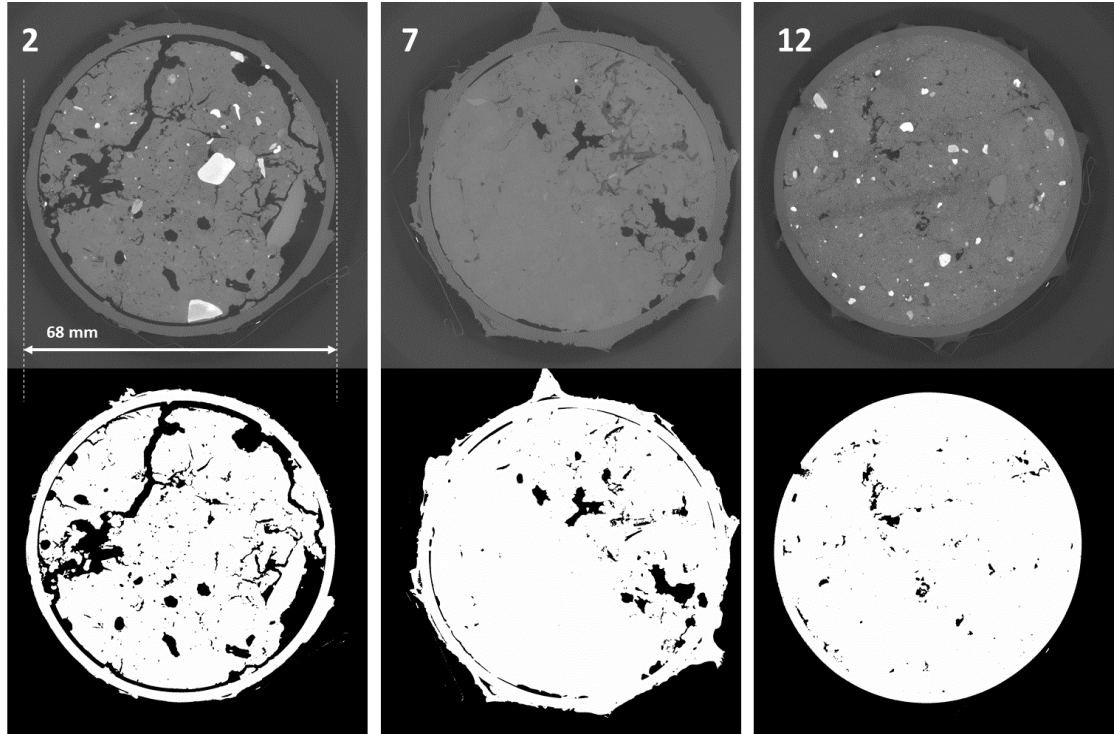


Figure 6.2: Top: 2D cross-sectional images (10 cm depth) of three soil samples at different ZT durations. Bottom: Binary correspondent of the same images after the segmentation of air-filled pore space (as detailed in section 6.2.4).

CT image analysis resolved parameters such as Average pore size and Total porosity (Figure 6.3). Based on the literature review, soils under ZT are expected to show a decrease in total porosity. An initial decrease was estimated for the 7 yr samples, but was followed by an increase. On the other hand, the size of the macropores decreased with age, which implies compaction due to machinery in the absence of tillage, but the total porosity estimates refute this assumption. One hypothesis is that the absence of tillage allows time for undisrupted bioactivity (e.g. roots, worms, microbes), which becomes the main source of macropore formation, therefore the soil pore space will contain more macropores, but with a smaller average size.

6. ASSESMENT OF THE LONG-TERM IMPACT OF ZT AGRICULTURE ON SOIL HYDRODYNAMICS

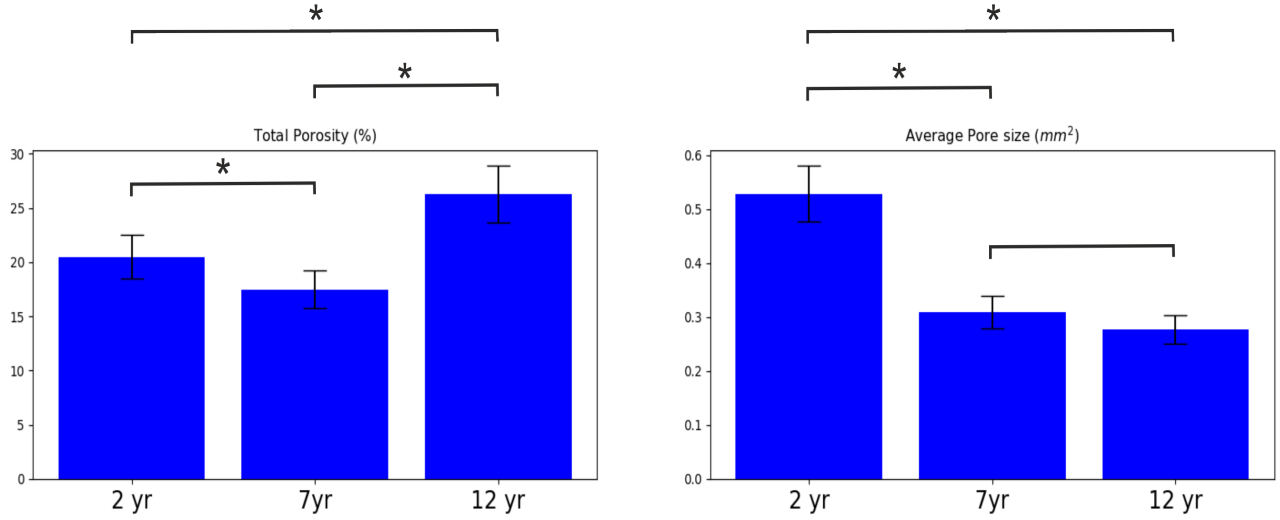


Figure 6.3: CT resolved structural parameters corresponding to different ZT ages. * indicates statistical significance ($p < 0.05$)

Percolation analysis enabled the estimation of another set of structural parameters corresponding to the soil core samples (Figure 6.4). Critical pore diameter values followed the same trend as average pore size estimations with values of around 4 mm for 2 year ZT which approximately halved for 7 and 12 year ZT. Surface connected porosity values mirrored total porosity with averages of 19, 15.7 and 25.1 (%) for 2, 7 and 12 year ZT duration respectively.

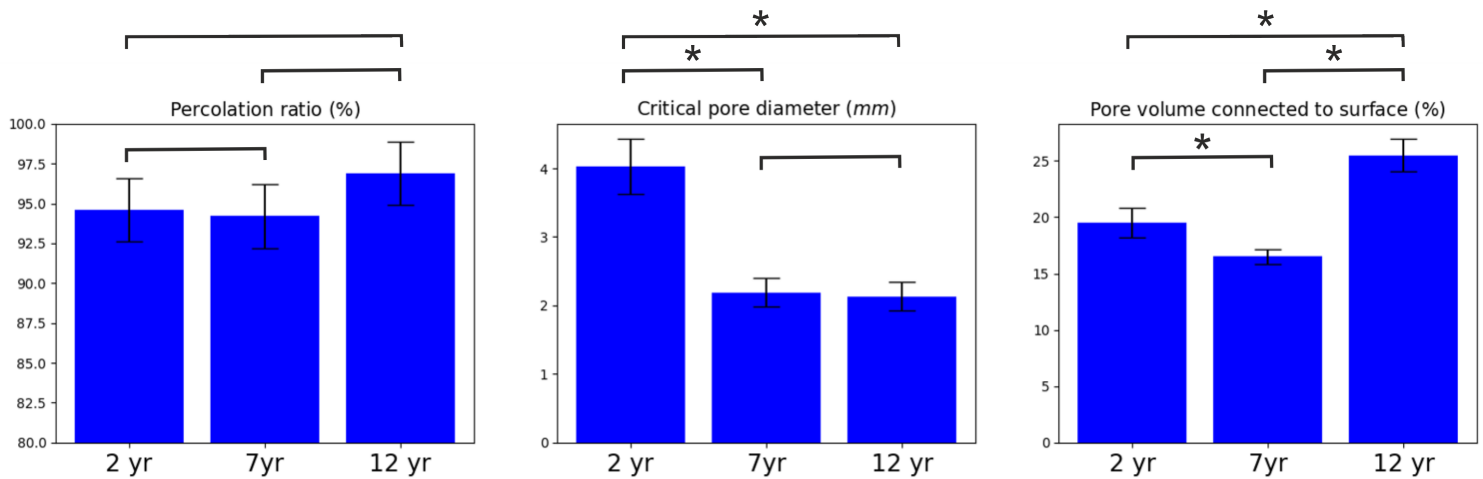


Figure 6.4: Percolation pore volume structural parameters corresponding to every ZT age. * indicates statistical significance ($p < 0.05$)

6. ASSESMENT OF THE LONG-TERM IMPACT OF ZT AGRICULTURE ON SOIL HYDRODYNAMICS

The total pore volume can be separated into a non-percolating and a percolating network. Cropped subvolumes of the whole pore network used for X-ray CT analysis show that several areas do not support percolation and are isolated from the main interconnected flow network (Figure 6.5). In addition, the 3D pore reconstruction shows a more cohesive structure for the soils under 7 and 12 year ZT. However, percolation ratio (Figure 6.4) was not significantly different among samples, just under 90 (%) for 2 yr and 7 yr ZT and marginally higher, 95 (%) for 12 yr ZT.

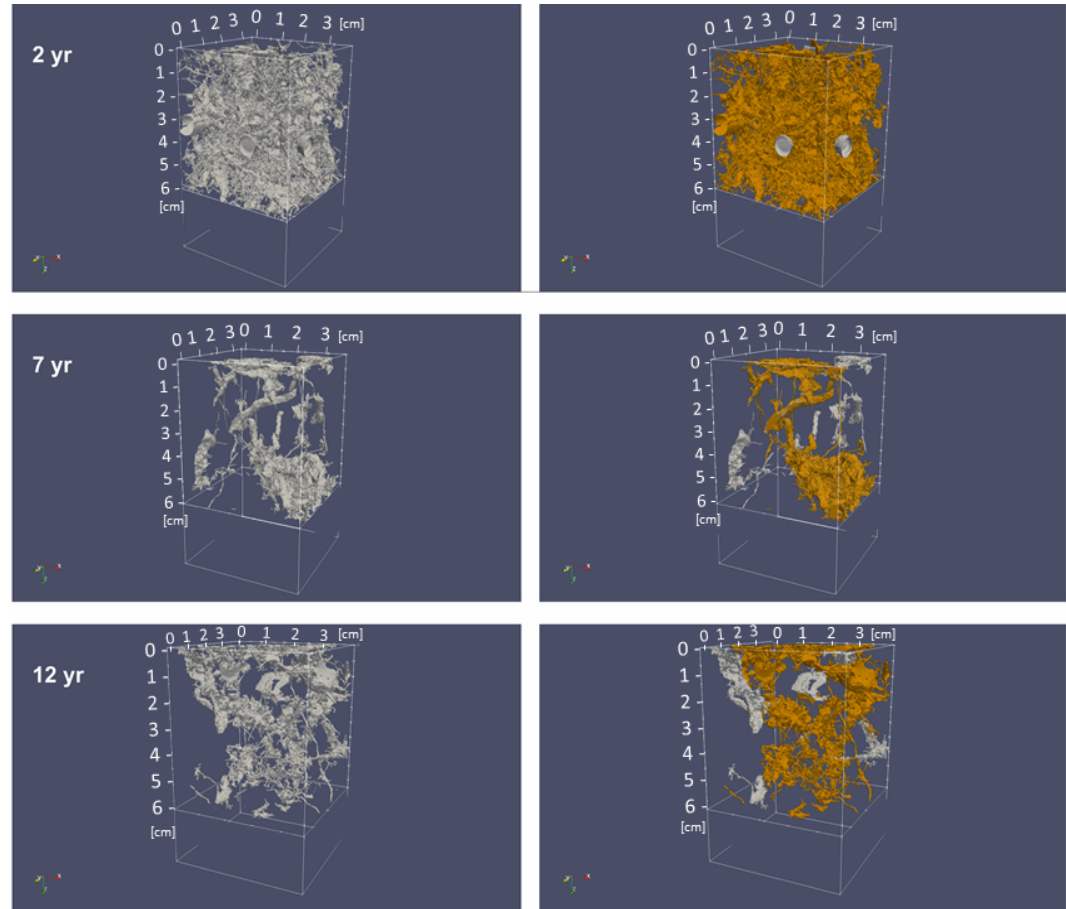


Figure 6.5: Volume subsections of the pore networks corresponding to different ZT ages. Effective percolation (orange) overlaps total porosity (gray).

6.4.2 CDE and MIM models fit parameters

The CDE model was fitted to the measured distribution of solution concentration (Figure 6.6). The fit was realized with a Markov chain Monte Carlo algorithm. This allowed us to estimate empirical parameters such as dispersivity and pore water velocity (Figure 6.7). Pore size was closely linked to pore water velocity, hence smaller pores result in a smaller pore water velocity.

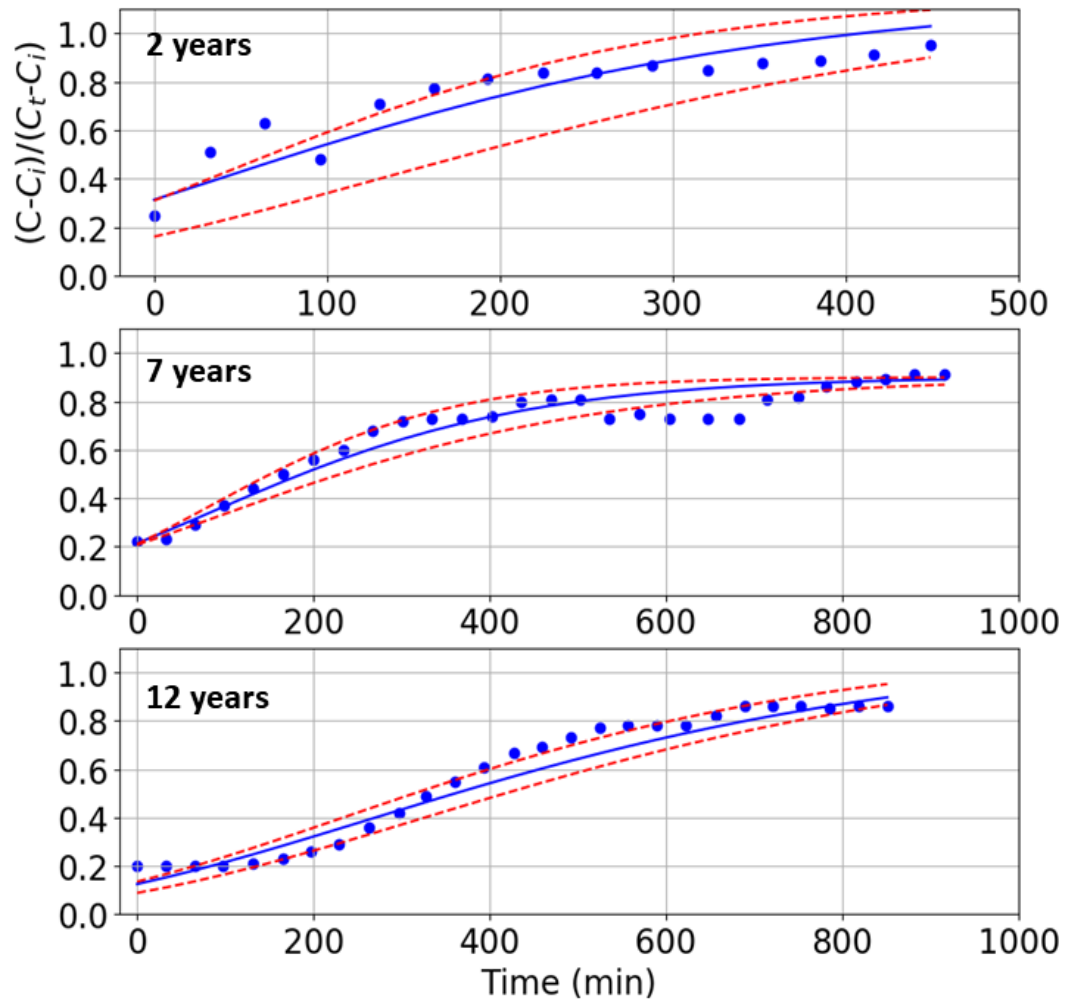


Figure 6.6: CDE model fit (blue line) to effluent electrical data (blue dots) with corresponding standard deviations (red discontinuous lines). 0 min marks the start of the high molarity infiltration.

According to previous literature (6.1.2), in ZT soils, dispersivity is expected to increase with the reduction of tillage (Besson et al., 2011). A similar trend is observed here, as with ZT duration, pore size decreases determining preferential flow hence greater dispersivity. Also, the 7 year ZT soil showed a lower porosity and percentage of the pore volume connected to the surface. Therefore, a lower outward flow implies a higher percentage of pore fluid stored in the soil system. This is also reflected by the high value of immobile water content exhibited by the same soil type.

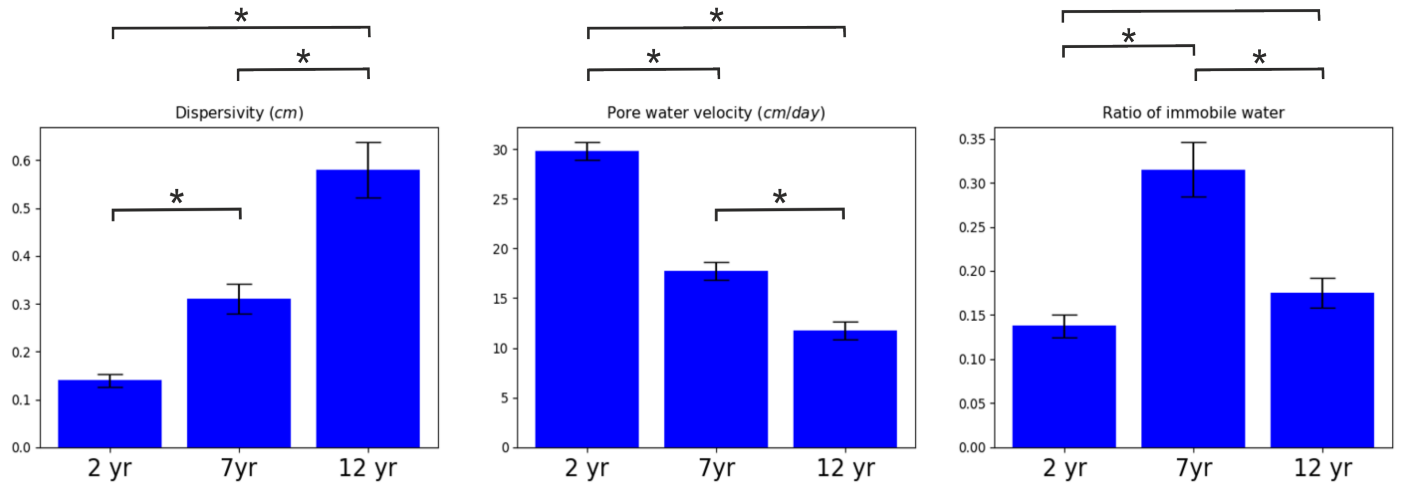


Figure 6.7: CDE and MIM estimated model flow parameters corresponding to every ZT age. * indicates statistical significance ($p < 0.05$)

6.4.3 Inferences from ERT time-lapse infiltration monitoring

It is expected that ERT measured values of electrical conductivity should agree with the results obtained from effluent data (ground truth). The effluent electrical conductivity was compared with the average bulk electrical conductivity of the topmost 3 cm of ERT model voxels, as described in Koestel et al. (2008). Figure 6.8 shows a good agreement between the two datasets, validating the ERT model estimations.

ERT models give us a 3D distribution of electrical resistivity in soil samples.

Every voxel obtained by mesh discretization of the volume has a value of electrical resistivity associated to it. Throughout the infiltration, ERT acquisition ran continuously, which allowed us to compute the changes in electrical resistivity distribution over time. Such differences were quantified following the methodology explained in Chapter 5. For every timestep, the number of voxels with a change in resistivity greater than a chosen 30 % threshold were counted. Figure 6.9 shows that change reached a higher steady state value with age of ZT. In addition, change happened at a faster rate.

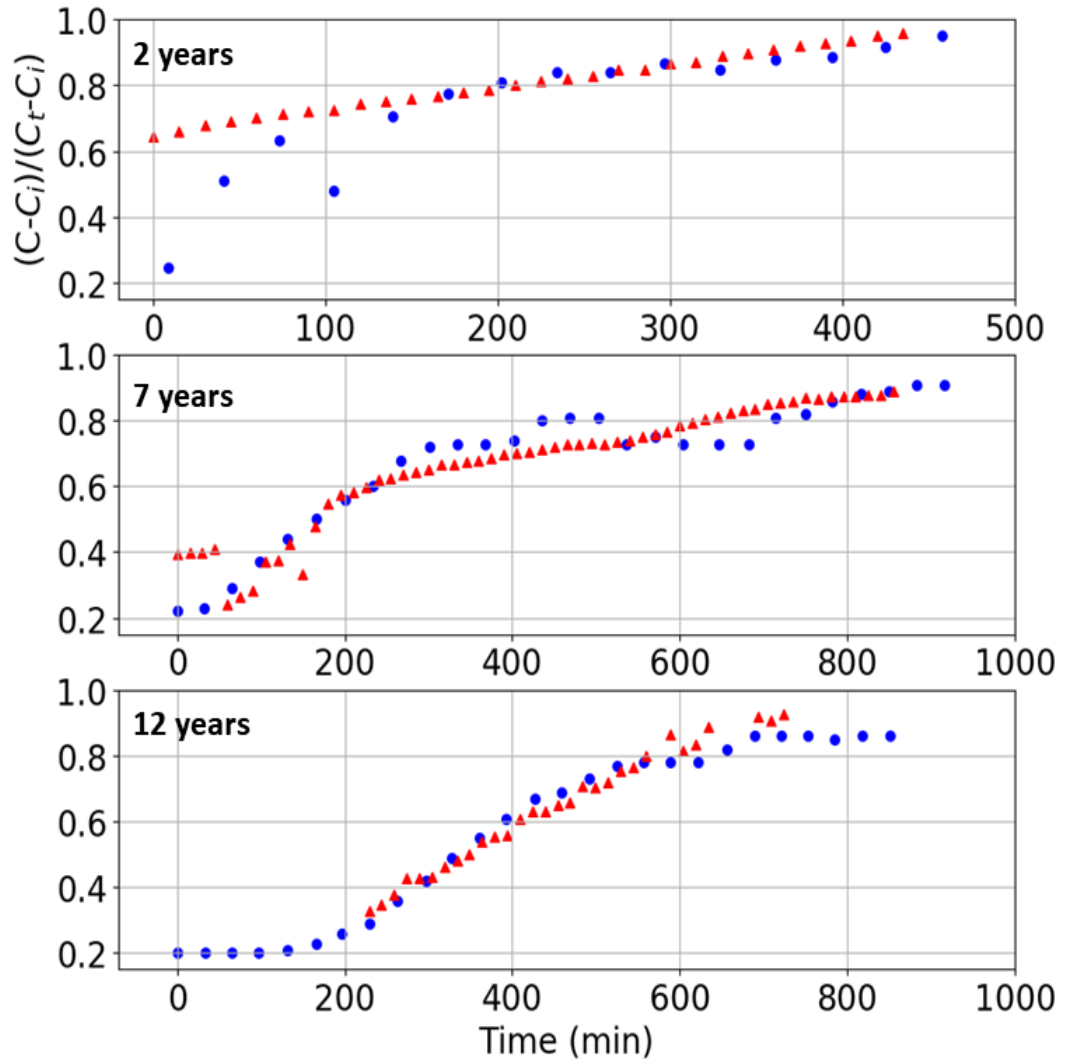


Figure 6.8: Comparison between resistivity values resolved from ERT models and effluent recordings. 0 min marks the start of the high molarity infiltration.

The assumption was that the only variable in the system was the saline solution concentration in the pore network. As conductivity is proportional to the concentration of the saline solution, the higher the ratio of cells with a modified bulk resistivity, the more dispersive the flow. This is confirmed by CDE model fitting as well, which showed the dispersivity was higher with age of ZT. However, a greater change in resistivity normally implies a greater total porosity. More available pores to be occupied by the high salinity tracer would decrease the recorded bulk resistivity recordings. However, a decrease in total porosity between 2 and 7 year ZT was observed. On the other hand, a decrease in average pore size was seen, which implies, at a constant infiltration rate, a faster change in pore solution concentration, which is what the ERT estimates indicated.

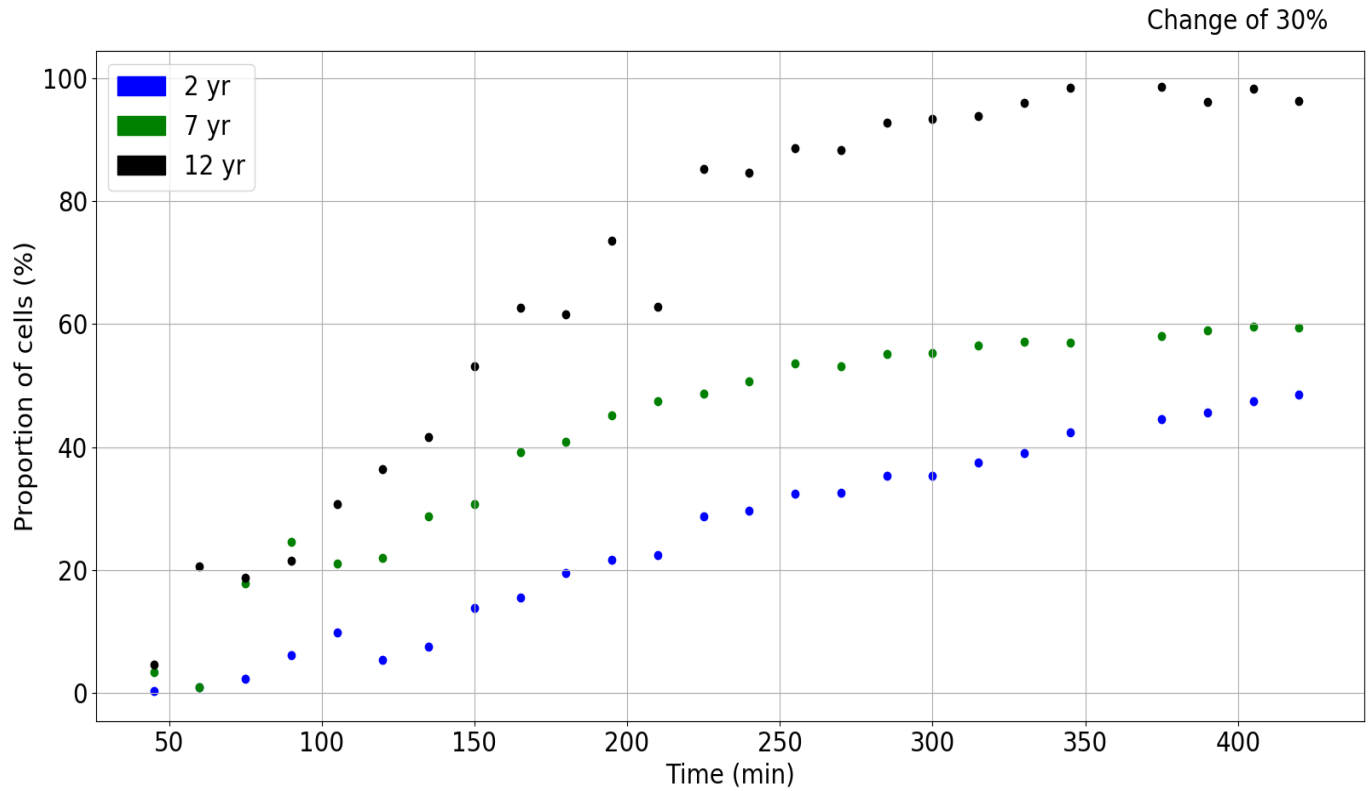


Figure 6.9: Percentage of ERT model cells which changed their resistivity by at least 30 % with respect to the first time-step. 0 min marks the start of the high molarity infiltration.

The maximum proportion of ERT model cells that suffered a 30 % change in electrical resistivity increased with ZT age. This effectively means that the soil volume occupied by the infiltrating fluid is greater with ZT age. Therefore, the solute tracer has a more expansive lateral distribution. However, the proportion of cells does not explain the absolute changes in resistivity over time. The same solute with the same molarity has been injected into all columns, hence it would be expected that given enough time the pore solution would reach the same concentration and electrical conductivity. Figures 6.8 and 6.6 that show the evolution of effluent concentration over time confirm this. Even though the pore solution is the same for all columns, the bulk resistivity of the soil was expected to be different due to different porosities and effluent expansion rates. In figure 6.10 it is noticeable that the bulk resistivity was indeed different with higher values for the 2 year ZT soil. In addition, the changes between timesteps for the 2 year ZT are almost indistinguishable, therefore the solute does not seem to have reached parts of the soil volume and had a faster infiltration (high rate of effluent change in concentration Figure 6.6) with a narrower distribution channel. This implies that a 2 yr ZT soil did not retain the infiltrating solution as well as one under ZT for a longer duration. This is perhaps the effect of a less cohesive structure formed of large macropores, which enhance a rapid passage of solution and a reduced retention.

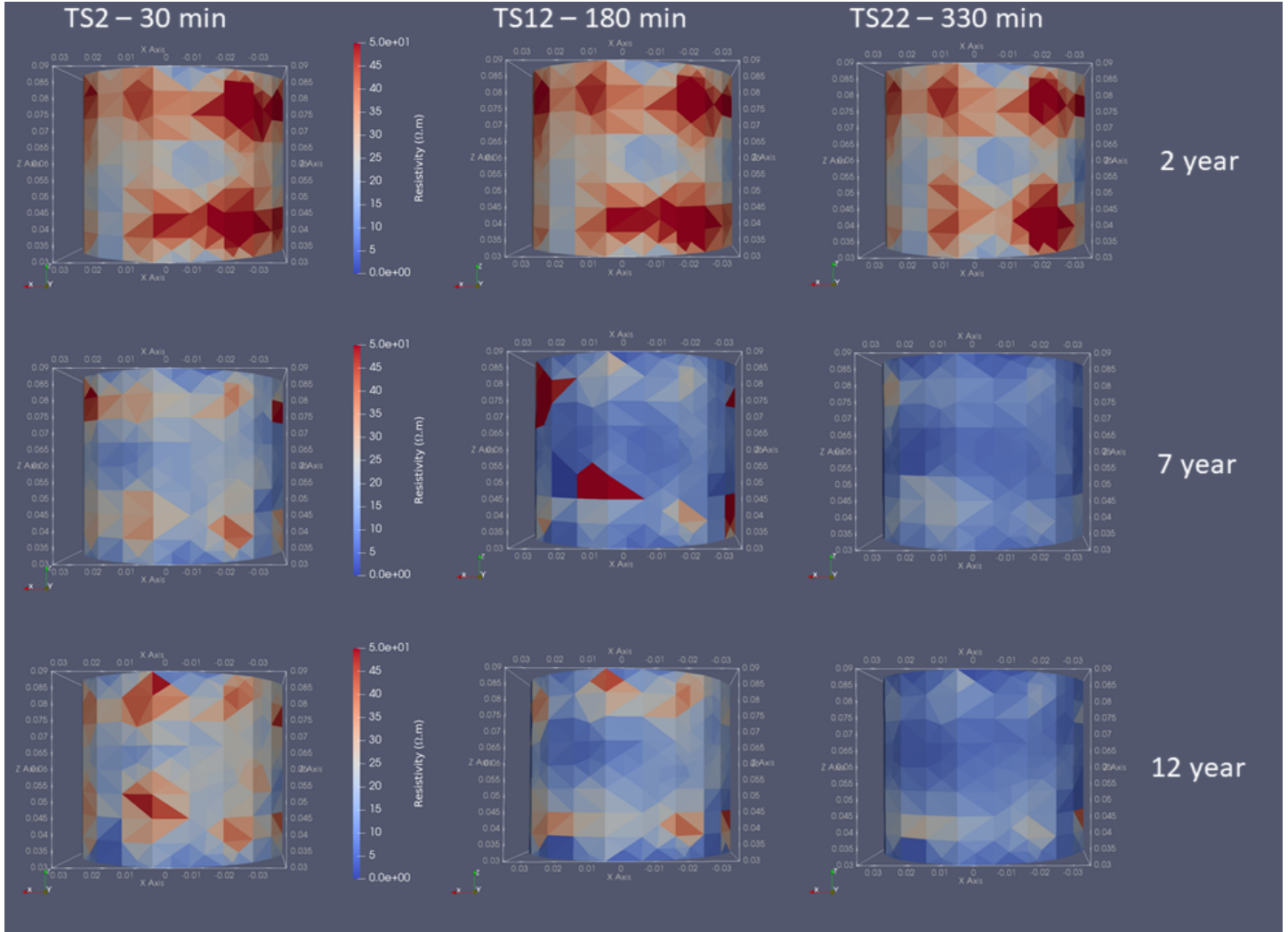


Figure 6.10: Soil column ERT inversion results corresponding to the 3 ZT durations at 3 different TS. Minute labels indicate time after start of the last high molarity infiltration stage.

6.4.4 Discussion

Several correlations between different parametric datasets e.g. electrical resistivity, porosity, effluent flow, percolation network, were established in the Results section. Figure 6.11 represents a visualization tool, which serves as an aid to the summary discussion. Hopefully, it will become clear that all the estimated parameters are, in the end, interconnected and contribute towards a robust description of the effect that ZT has over time on soil structure.

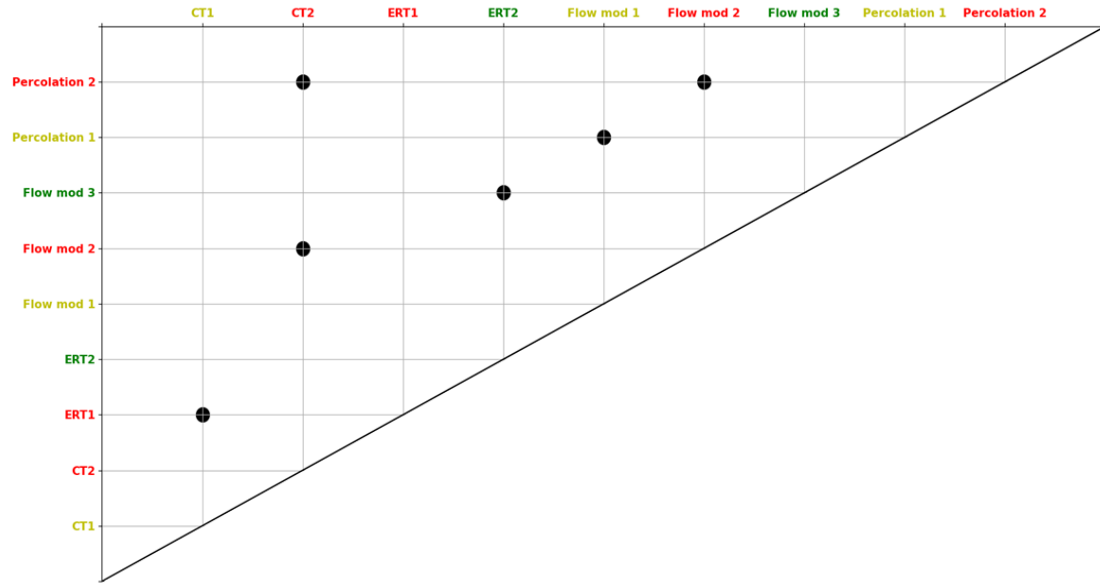


Figure 6.11: Methods (CT - X-ray CT, ERT - ERT, Flow mod - Flow modelling, Percolation - Percolation analysis) and their corresponding measurable parameters (CT1 - Total porosity, CT2 - Average Pore Size; ERT1 - Bulk soil electrical resistivity, ERT2 - Tracer lateral distribution; Flow mod1 - MIM water content ratio, Flow mod2 - Pore water velocity, Flow mod3 - Dispersivity; Percolation1 - Surface connected porosity, Percolation 2 - Pore critical diameter) evaluated in this chapter. Color legend: Red - Decrease with ZT duration; Yellow - Decrease for 7 yr ZT followed by an increase; Green - Increase with ZT duration. The dark points indicate that a correlation was established between specific parameters.

Over time, under ZT, CT image analysis indicated that the average pore size decreases, which determines a reduced pore critical diameter and in turn a reduced pore water velocity. Also, flow modelling estimated an increase in dispersivity, which was confirmed by ERT, which determined that during infiltration the solute has a higher lateral distribution. This would imply a tendency towards preferential flow with increased duration of ZT. Previous studies indicated a decrease in macroporosity (Alegre et al. 1991; Strudlley et al. 2008) for soils under ZT. However, macroporosity only decreased for the 7 year soil, and then started to increase again. The same behaviour reflected onto measurements of surface connected porosity and proportion of immobile

water content. Helgason et al. (2010) reported that ZT soils have a 30 % larger biomass than ConT soils. Therefore, this could suggest that the soil undergoes an initial phase of increase in compaction and reduction of porespace, followed by a rebound due to undisturbed bioactivity, which in turn also lowered the proportion of immobile water. This was advocated in Soracco et al. (2012) where it is indicated that ZT reduces the proportion of water conducting macropores. The manifestation of bioactivity could be suggested by the apparent shape of the pore network, which shows a more cohesive structure resembling naturally occurring macropores. This could ameliorate preferential flow and regulate the soil hydrodynamic behaviour. It is therefore estimated that for this specific type of soil at least 7 years of ZT are required to recover the natural water conducting capacity given by its pore space and improve its water storage initially inhibited by compaction. However, this result should be verified for a greater spectrum of soil textures, as different physicochemical properties dictated by local soil formation factors may inhibit or accelerate the soil's bioactivity (Beyer et al., 1992).

6.5 Conclusions

This study investigated the effect of ZT over time on soil structure and consequently on solute transport. An initial analysis of previous studies showed that ZT is typically to decrease macroporosity and infiltration, but increase bulk density and water storage. Soil columns corresponding to three different ZT durations (2,7 and 12 years) were analyzed by observing the internal pore structure using X-ray CT and monitoring a 9 hours high molarity (5M) KCl tracer solution infiltration using ERT. X-ray CT scanning and image processing revealed an initial decrease in total porosity from the 2 yr ZT to 7 yr ZT soil, followed by an increase for the 12 yr ZT. 3D images of the pore network

revealed pore channels with a more continuous and cohesive structure for the 7 and 12 yr ZT. By monitoring a saline solution infiltration through the column, ERT and flow modelling showed a more laterally expansive solute transport behaviour with an increasing dispersivity and decreasing pore water velocity with ZT duration. Analysis of the percolation porosity indicated a marginally higher proportion of water conducting pores for 12 yr ZT and a reduction in critical pore diameter to 2 mm (half of 2 yr ZT values) after 7 yr ZT duration. The results suggest an initial phase of compaction and flow inhibition followed by a later stage of porosity expansion, which in turn improved solution percolation through soil. The latter could possibly be accounted by increasing biomass in ZT soils (Helgason et al., 2010), thus further studies are encouraged to include biomass calculations in order to establish a correlation between ZT duration and biological activity. Furthermore, different soil types may respond differently to the absence of tillage, therefore a more comprehensive approach, which includes columns of soil of various proveniences and textures should be considered by future research.

7 INTEGRATED ERT AND X-RAY APPRAISAL OF PORE WATER DYNAMICS IN CHARCOAL ENRICHED SOILS

This work was conducted as part of a research placement in collaboration with University of Liège. For three months, M.O.C joined the ongoing CHAR research project (Garré et al., 2014). This work could not have been possible without the significant contribution of Prof. Sarah Garré, Prof. Frederic Nguyen and Postdoctoral Researcher Edmundo Placencia.

7.1 Abstract

Over time, amending soil with biochar has the potential to change its structure and consequently its hydraulic properties. Studies have focused only on the biochar's short-term effects on agricultural soils, with the long-term effects largely unknown. Geoelectrical methods, such as ERT and Spectral Induced Polarization (SIP), are well-established methods used for monitoring soil hydraulic properties in near real-time. X-ray CT is a method well-suited for imaging soil structure at high resolutions ($<100\text{ }\mu\text{m}$). This study used ERT to monitor in 2D the change in electrical resistivity over six months in an 100 year old charcoal enhanced agricultural field (CHAR) and compared it with its naturally occurring counterpart. The results revealed a larger variability in electrical resistivity over time in CHAR soils, a proxy for greater changes in moisture content. Columns of soil (5 and 6.8 cm diameter) sampled from the same locations used for ERT monitoring were brought to the laboratory for further investigations. SIP was used on the columns to observe patterns of electrical polarization in soils as they dry from saturation, revealing a higher

polarization for the CHAR soils. X-ray CT was used to investigate the structure of the pore network and revealed that the CHAR soil had larger and better interconnected pores. This demonstrates the two tomographic methods, ERT and X-ray CT, provide complementary information at fieldscale, reporting that century old charcoal amended soils have a distinctive structure, which manifests through greater variability in moisture content.

7.2 Introduction

Biochar has been reported to have a positive impact on agricultural soil by enhancing nutrient availability (Glaser et al., 2015), increasing water holding capacity (Liu et al., 2012) and plant yields (Major et al., 2010). A suitable analogue for long-term application of Biochar are charcoal accumulations in ancient kiln sites. Previous research on soil chemical properties indicates an increased C:N ratio and Cation Exchange Capacity (CEC) per unit carbon in charcoal kiln soils (Hardy et al., 2016). In addition, Kerré et al. (2017) found that long-term presence of charcoal contributed to the formation of soils with higher available water content, which in turn has the potential to increase plant yield and reduce water stress. One of the CHAR project aims is to quantify the long-term charcoal effects on soils using non-invasive geophysical methods. This work will focus on determining the structural properties of the soils with and without the addition of charcoal. A particular focus was determining the total porosity, pore size and pore connectivity. Furthermore, the aim was to correlate such findings with the trends resolved by the geoelectrical data representative for corresponding physical indicators such as temperature, precipitation and variability in soil water content.

7.3 Methodology

The experimental work took place at CHAR observatory located in the vicinity of the city of Gembloux, Wallonia Province, Belgium. The site consists of an agricultural field where multiple charcoal accumulations created, over the course of more than 100 years, dark patches of soil, with an approximate depth of 20-25 cm below ground level (Figure 7.1). Upon the analysis of 14 soil samples, the particle size distribution showed that the soil has no more than 7% sand, clay ranging between 15-20 % and silt ranging between 75-80 %. This classifies the soil texture as a Silt loam from a Luvisol class (Zanutel, 2019).

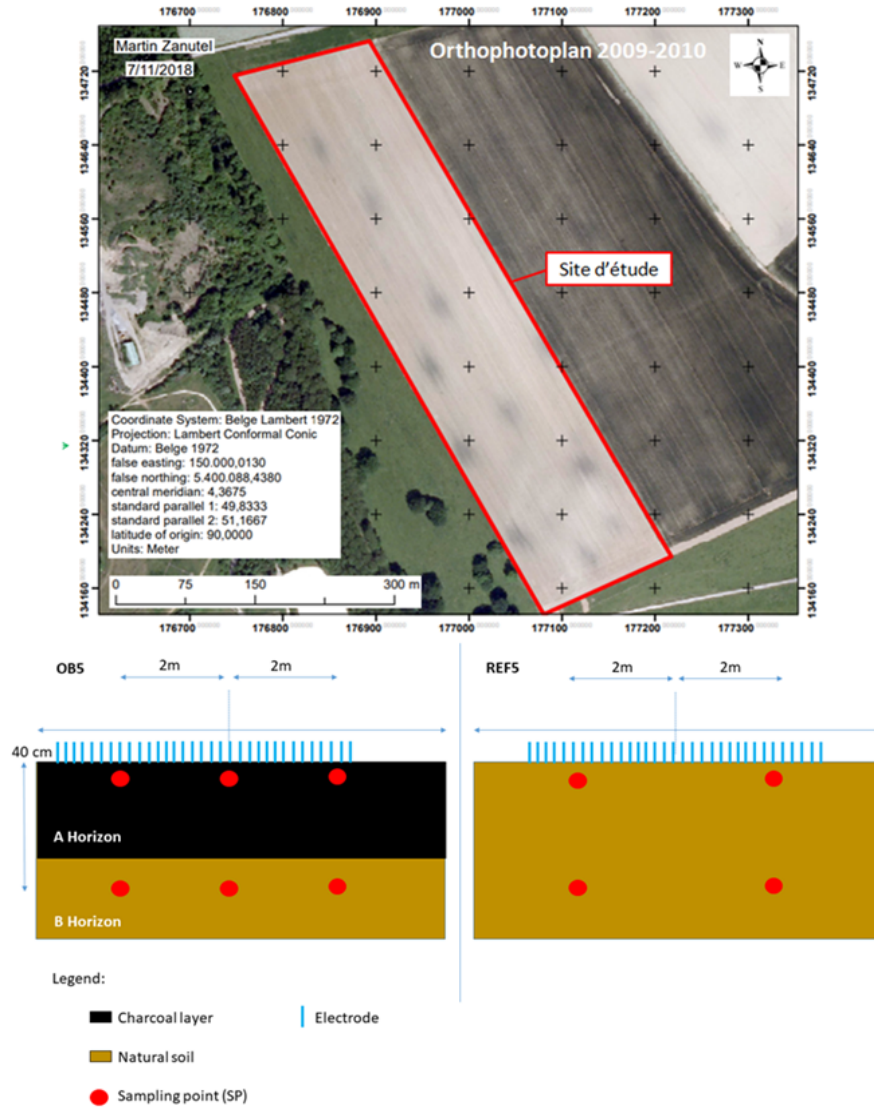


Figure 7.1: Top: Aerial view of CHAR observatory. Red symbols mark the sampling locations and areas of interest: OBC and REF. Adapted from Zanutel (2019). Bottom: Schematic of sampling locations along ERT survey line of electrodes

7.3.1 Soil sampling

In order to capture the natural distribution of soil pores, undisturbed soil cores were collected. In order to obtain such cores, plastic cylindrical containers were used (6.8 cm diameter, 12 cm height), which were carefully pushed into the ground and extracted by removing the surrounding soil (Figure 7.2).



Figure 7.2: One of the five soil sampling locations with its corresponding triplicate cylindrical soil cores.

The soil core sampling was undertaken 2 m away from two of the six ERT transects installed on the CHAR monitoring field site, namely OBC5 (overlying a charcoal patch) and REF5 (overlying a reference soil of natural occurrence). Figure 7.1 Top, shows the map of the entire observatory, including the details regarding the sampling locations situated along transect 5. In total, 30 soil cores were collected. These were collected in triplicates at two different depths (20 and 40 cm - A and B horizons) from three sampling points (SP1, SP2 and SP3) along OBC5 and from two sampling points (SP4 and SP5) along REF5 (Figure 7.1 Right). From this point onwards the reference to samples taken from charcoal enhanced soil will be CHAR A, B depending on the soil horizon of origin and from reference soil REF A, B respectively.

7.3.2 X-ray scanning and image processing

Upon extraction, all the samples were wrapped in cling film to preserve their integrity and to avoid drying, which might have a significant impact on pore structure. Afterwards, they were transported to the Hounsfield Facility at the University of Nottingham where they were scanned using a v|Tome|x M X-ray scanner (Scan settings: 190 kV , 180 μ A, 2400 projections, 23 minutes fast scan time) achieving a 40 μ m resolution. The obtained radiograms were digitally reconstructed and processed using Volume Graphics 2.2, over an 8-bit value range. From the 3D representation of the soil core volume, stacks of cross-sectional 2D images were imported on multiple Cartesian directions. Further image processing was realized using the open source program ImageJ (Schindelin et al., 2012). On each cross sectional image, a representative sub-area of $30 \times 90 \text{ mm}^2$ was selected (Figure 7.3) in order to exclude pores adjacent to the core casing edges, which might have been subjected to artificial cracking upon extraction or drying. These soil samples were made of different macroscopic components: soil aggregates, air-filled pore space, water-filled pore space, minerals and charcoal aggregates. These were all identifiable on the X-ray CT scans due to their distinct X-ray absorption coefficients. The scans were reconstructed over an 8-bit range. Therefore, we are working with 256 grey scale values from 0 (no absorption – black colour on the scans, usually representative for air-filled space) to 255 (maximum absorption – white colour on the scans, high values representing denser materials such as minerals).

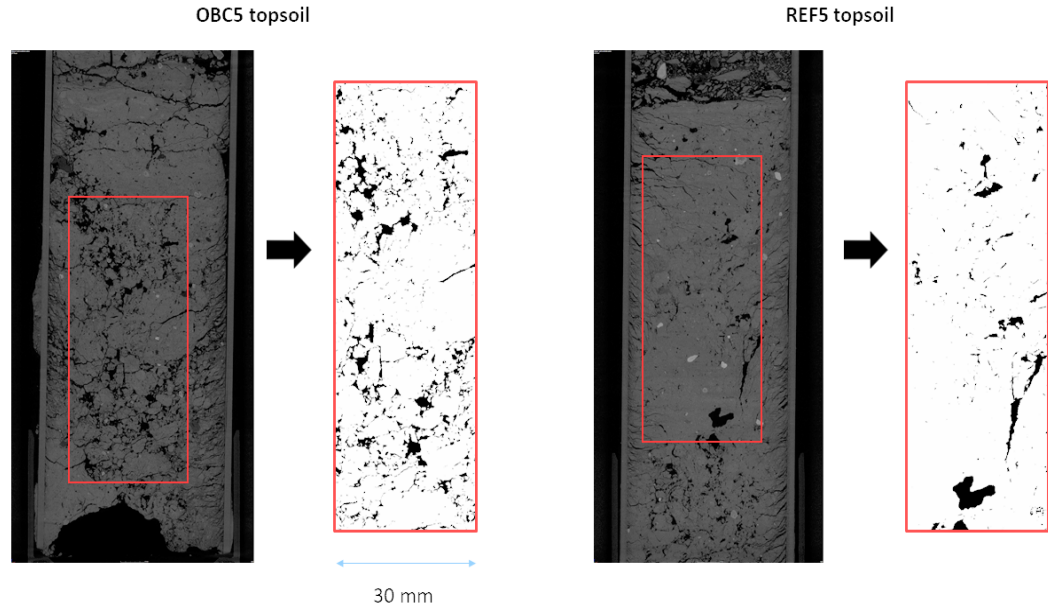


Figure 7.3: Representative scan image window selections before (left) and after (right) applying a binary threshold for air-filled space. They correspond to the A horizon of one sample from charcoal soil and one sample of reference soil.

The sub-volume ($30 \times 90 \times 42 \text{ mm}^3$) of stacked cross-sectional selections was then subjected to two process filters: Sharpen and Median, in order to improve image quality (enhance the border between pixels of different grey scale values). Afterwards, an Otsu algorithm (Otsu, 1979) was applied on the grayscale distribution in order to find the optimal threshold between the two classes of pixels present: air-filled pore space and background. The product of the segmentation was a binarized image, where the non-zero area represents the pore space. These can be selected and subjected to further analysis, which computes pore structural parameters, such as: total porosity (% of the total area), equivalent pore size (diameter of the equivalent circle with the same area as the pore), connectivity density (number of connected pore segments per sub-volume) or the anisotropy factor (pore orientation from 0 isotropic to 1 anisotropic). An one-way Analysis Of Variance (ANOVA) test was computed using Python 3.6.

in order to see if there is a statistical significant difference ($p < 0.05$) between the four parametric datasets.

7.3.3 Field-scale ERT

7.3.3.1 Measurement acquisition The field geoelectrical surveys were performed using an MPT DAS-1 EIT System. Every survey line was 12.6 m with 64 electrodes equally spaced at 20 cm (Figure 1). Even though the surveys allowed phase measurements, only measurements of electrical resistivity are presented here. Every measurement used two pairs of electrodes, one for current and one for electrical potential, in a dipole-dipole configuration with a dipole length of 20 cm and inter dipole spacings between 20-160 cm ($1-8 \times$ dipole length). Figure 7.4 indicates the XZ position of every measurement of apparent resistivity. One survey contained 920 measurements, normal and reciprocal, and six surveys were completed. These are labeled according to the number of days since the start of the experiment (March 8th 2019), namely: 57, 79, 102, 120, 143 and 164 days.

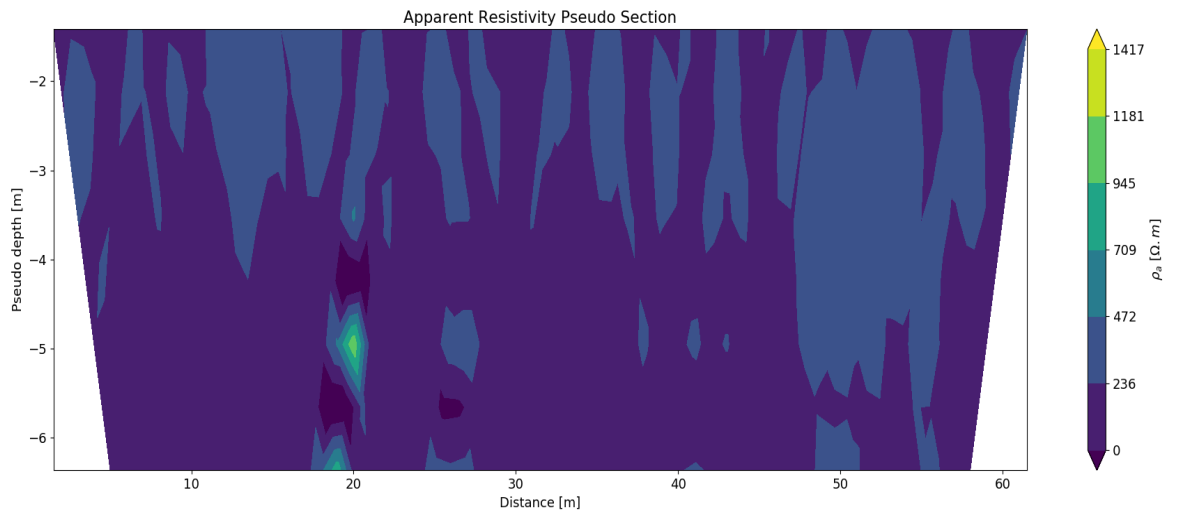


Figure 7.4: Contour plot of an ERT 2D field survey pseudosection.

The first stage of data processing involved data filtering. Any data points with physically unreasonable values (e.g. abnormally high resistance values 10 k Ω), high contact resistance (over 3 k Ω) or a reciprocal error higher than 5% were discarded (thresholds based on empirical observations).

7.3.3.2 Adjacent soil physicochemical indicators The CHAR observatory encompasses a range of other soil monitoring methods. To be used in correlation with geoelectrical inferences, a few datasets were chosen, such as:

1. Net precipitation: This was one of the measurable parameters available from the weather station installed on site. One of the main sources of electrical resistivity fluctuations are changes in soil water content;
2. Macro Aggregation: This was determined as part of the soil physicochemical analysis. It was used to reveal if there is a relationship between pore and aggregate size; and
3. Soil Temperature: Probes were installed at three different depths (20, 40, 80 cm) across the profiles of investigation. Thus, this enabled the calibration of electrical resistivity measurements across the profile of investigation.

7.3.3.3 Electrical resistivity raw data processing and inversion As described in Chapter 3 and applied here using the same inversion strategy as in Chapter 5, the algorithm finds the best fitting 2D model to the dataset in order to obtain a 2D tomographic image of the subsurface electrical resistivity. Since in this case time-lapse geoelectrical data are available, one can perform either an independent inversion, obtaining the electrical resistivity model at every individual time-step separately, or a time-lapse difference inversion.

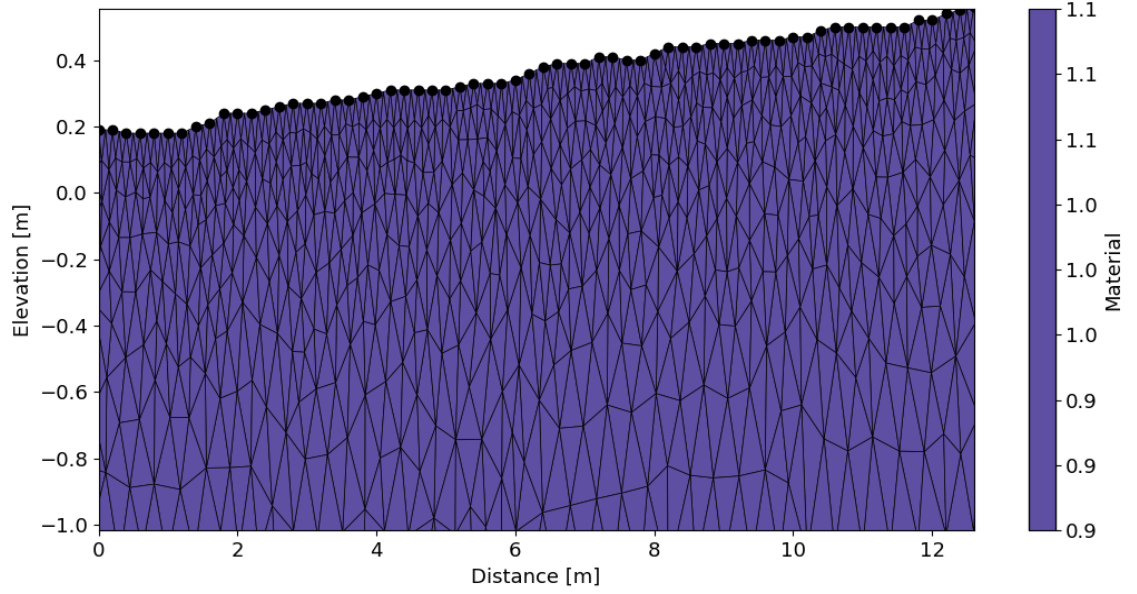


Figure 7.5: Triangular 2D mesh used for ERT inversions. Depth axis length is exaggerated for visual purposes.

In addition to apparent resistivity datapoints, for an accurate estimate of the subsurface model we require information regarding topography (XZ position of electrodes) and soil temperature. Fortunately, these datasets were also available for the CHAR observatory. Soil temperature variations influence the recorded values of electrical resistivity, therefore the model needs to be calibrated accordingly. Topography becomes important when constructing a model mesh based on the specified position of the electrodes (Tsourlos et al., 1999). Without this information included, the estimation of an erroneous geometric factor and an inaccurate mesh discretization are possible. Figure 7.5 shows the mesh generated based on the topography details provided. However, it is acknowledged that the topography in this case is very shallow and therefore produces little difference to the inversion result.

Normally, electrical resistivity values are corrected to a reference temperature of 25 °C, as suggested by Samouëlian et al. (2005), and using the experimental

equation from Campbel et al. (1948):

$$\rho_T = \rho_{25^\circ C} [1 + \alpha \times (T - 25)], \quad (7.1)$$

where ρ_T is the electrical resistivity measured at a given temperature (T), $\rho_{25^\circ C}$ is the electrical resistivity to a reference temperature of 25 °C, and α is a correction factor which is typically approximated to 0.02. As mentioned above, temperature data was available at three depths for both survey lines. For the purpose of this exercise, another temperature correction strategy, proposed by Hayley et al. (2007), was used. This method applies to time-lapse field monitoring data by producing a standard temperature equivalent model with a response d_{est} (inverted resistivity model at time t_i , in days), which is then used to calculate the temperature-correction resistivity model (d_{est}^{TC}) relative to one standard reference temperature T_{std} using the expression:

$$\rho_{std} = \rho_i \times \frac{m(T_i - 25) + 1}{m(T_{std} - 25) + 1}, \quad (7.2)$$

where ρ_{std} is the electrical resistivity at T_{std} , T_i and ρ_i are the in situ temperature recorded from field sensors and the electrical resistivity response from the inversion, respectively. In this case the average of all recorded temperature was used as a reference and T_i as the average temperature recorded over all depths at time t_i . m is assigned to a value of 0.02°C^{-1} , which represents the slope of the linear approximation for the soil electrical resistivity temperature dependence (estimated empirically by Hayley et al. (2007)). The raw conductivity measurements (d_{obs}) are then corrected for temperature variations (d_{Obs}^{TC}) using the following equation:

$$d_{Obs}^{TC} = d_{Obs} + (d_{est}^{TC} - d_{est}), \quad (7.3)$$

d_{Obs}^{TC} are subsequently inverted independently at each time t_i on which time-lapse inversion analysis is carried out in order to obtain the percentage variation with time. In terms of error processing, a linear error model was fitted to the measured datasets as shown by Mwakanyamale et al. (2012). The weight parameters describing the model (slope and intercept) were used subsequently in the inversions.

As a final exercise a time-lapse data error model was also computed as proposed and subsequently used by Lesparre et al. (2017) for time-lapse inversions in order to improve the resulting image quality. Lesparre et al. (2017) also used envelope fitting in order to encompass the whole dataset. Here, an envelope fit of 2 standard deviations was used. Similarly to the independent inversion case, appropriate weight parameters (a and b) that describe the best fit error model to time-lapse errors ϵ_{TL} are required:

$$\epsilon_{TL} = |\Delta \log R_N - \Delta \log R_R|, \quad (7.4)$$

where R_N and R_R are the Normal and Reciprocal electrical resistance measurements and ΔR represents the difference between initial time t_0 and subsequent time-steps t_i . In this case the best fit line was a straight horizontal line (Figure 7.6).

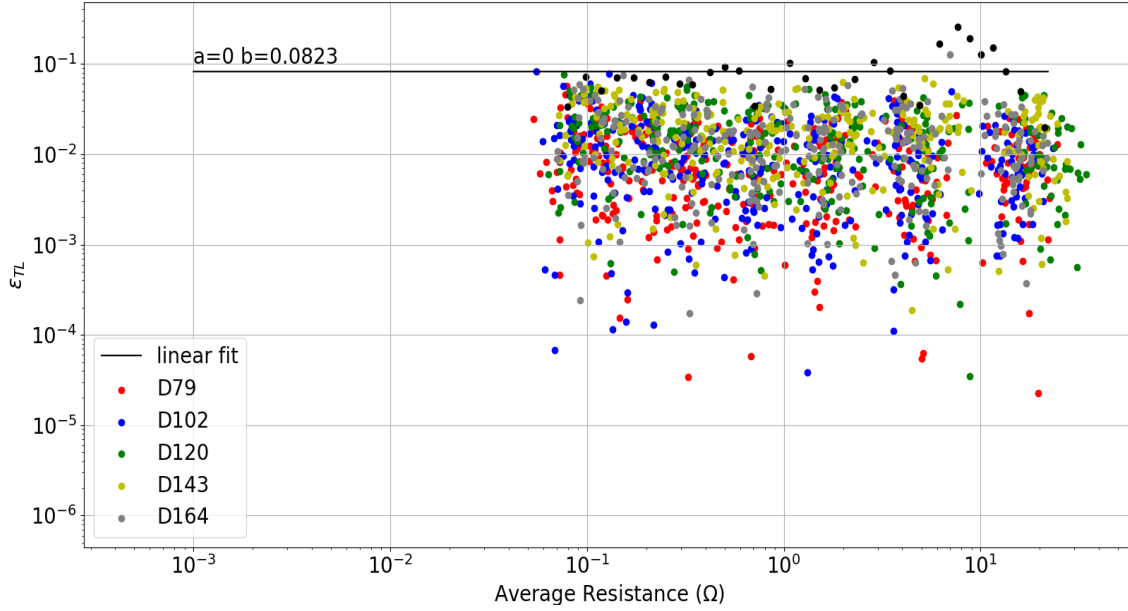


Figure 7.6: Time-lapse error model fit to the distribution of reciprocal errors. Dark points represent the bins average.

7.3.4 Exploring the electrical polarization

As part of this study, a laboratory pedophysical calibration set-up was initiated. Soil cylindrical cores (5 cm diameter, 10 cm height) in duplicates were sampled from three different depths (20, 40 and 80 cm) at the same locations mentioned previously in this work (OBC5 and REF5). This time the sampling method was slightly changed as a soil corer was used, which reduced the artificial disturbance previously observed. The cores have been instrumented, as seen in Figure 7.7, to allow SIP electrical measurements by attaching copper plates on both ends and cylindrical spike electrodes (AgCl wires in an agarose solution) in the median section. Subsequently, they were subjected to an experiment which aimed to derive the relationships between soil sample saturation and two parameters: electrical resistivity and phase shift. The experiment started on 7th of November 2019 when the samples were fully saturated. Afterwards, the samples were left to desaturate due to evaporation under room temperature. A phase spectrum was recorded periodically as the samples lost moisture

content.

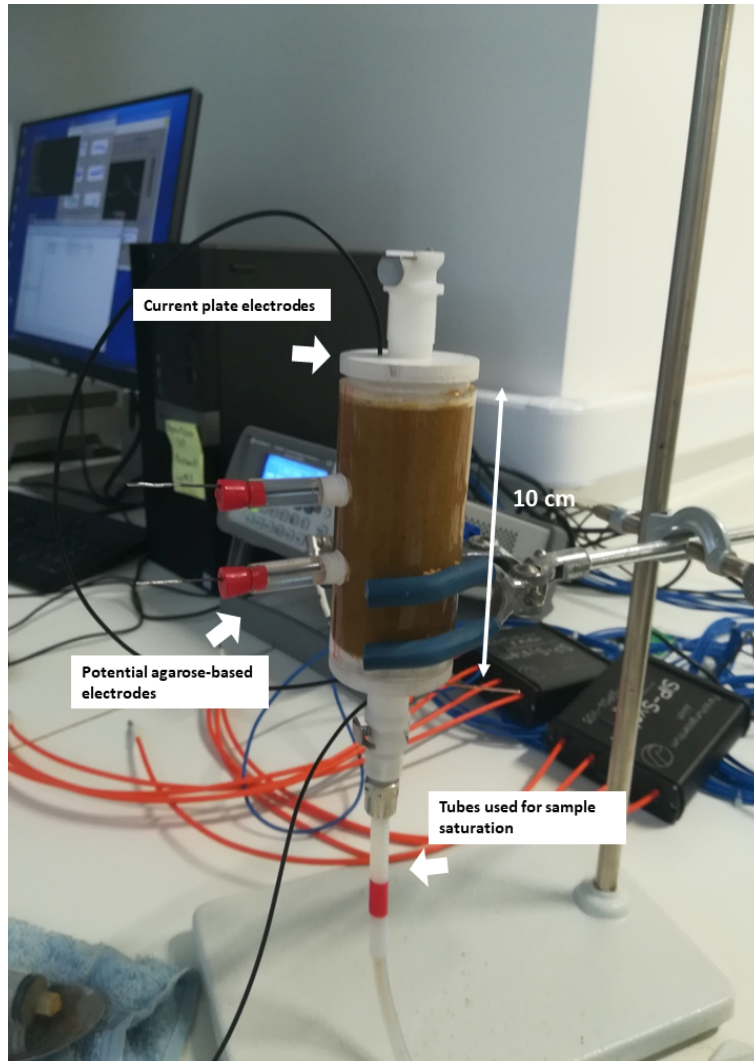


Figure 7.7: Soil sample modified to accommodate SIP measurements. Annotations indicate different components of the set-up.

7.4 Results and discussion

7.4.1 X-ray derived structural indicators

Primarily, this work aimed to explore if there was a difference between air-filled pore space in CHAR and REF soils. It might be already intuitive from Figure 7.3, but upon a visual inspection, CHAR soil had a more developed pore-space than the soil without biochar. This is also visible if the whole stack

of cross-sectional images is shown as collated into a 3D pixel distribution of the representative sub-volume chosen for subsequent analysis (Figure 7.8).

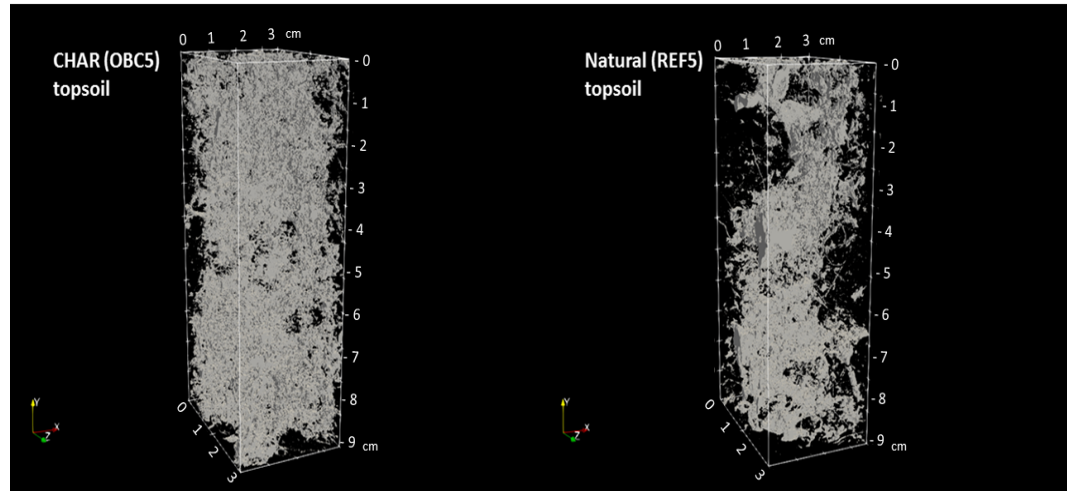


Figure 7.8: 3-Dimensional volume of pixels corresponding to air-filled pore space segmented from the X-ray digitally reconstructed images.

A more systematic way to consider the results is to quantify the difference between pore structural parameters corresponding to the four sampling groups, corresponding to the two soil types in question and the two depths of sampling. The ANOVA test revealed CHAR A is indeed significantly different from CHAR B and REF B in terms of pore size, macroporosity and connectivity density (Figure 7.9). However, when comparing CHAR A and REF A, even though the average parameter value (connectivity density and pore size) was higher for CHAR A, a significant difference was found only in terms of macroporosity. The degree of anisotropy was similar for all layers with a slightly lower average corresponding to CHAR B.

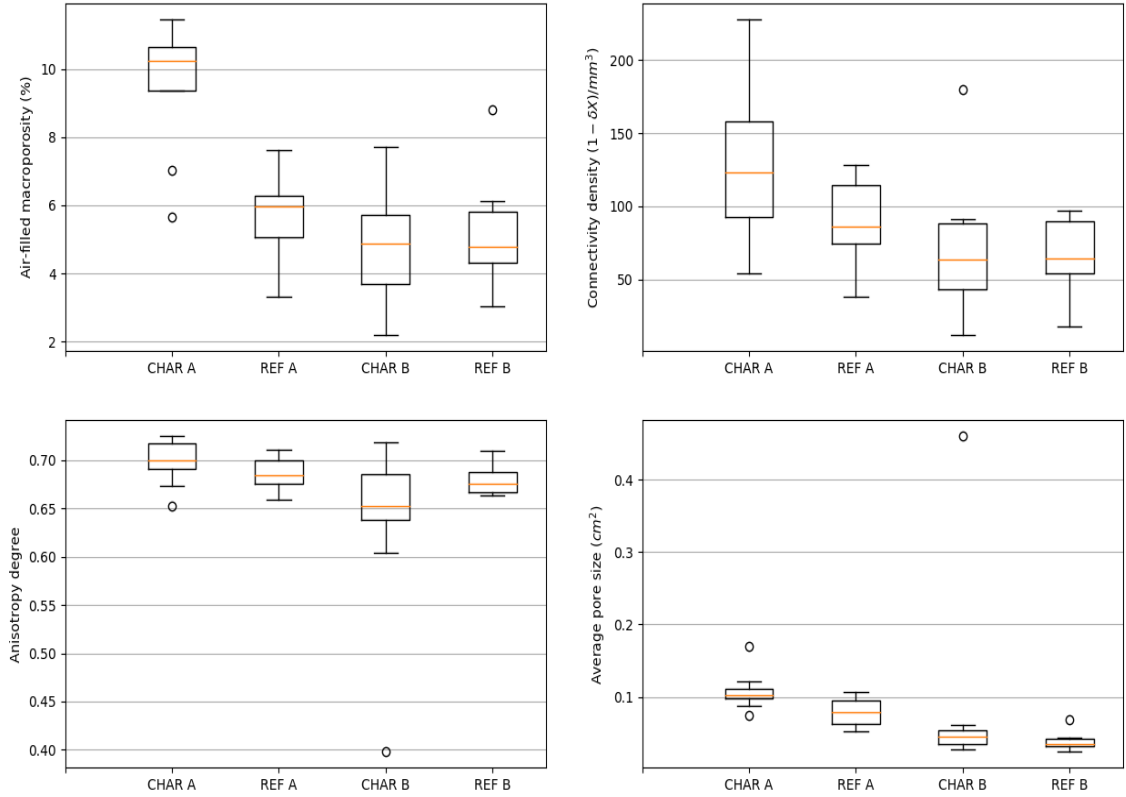


Figure 7.9: Boxplots showing the distribution of 4 pore structural parameters corresponding to the 4 sampling groups: charcoal enhanced soil - horizon A (CHAR A), horizon B (CHAR B) and reference soil - horizon A (REF A), horizon B (REF B).

The presence of artificial cracking identified on the scans was most likely caused by the method of soil core extraction which occurred on dried, hard soil. Even though upon image processing, avoiding such areas was attempted as much as possible by selecting a cylinder-centred soil sub-volumes, there might still have been areas where the structural parameters were overestimated. However, these results are presented not to express the absolute values of structural parameters mentioned, but in order to underline the difference between different soil types.

Due to the observed difference in macroporosity, the distribution of pore sizes was investigated across the samples in order to assess what range of dimensions

is responsible for such difference. The pore size distribution was divided into five classes, 40-50 μm (the lower limit is due to the scan resolution), 50-250, 250-500, 500-1000, 1000-10000 μm . The decision was not arbitrary, but done in order to match macroaggregate size classification. CHAR A shows a clear increase in the number of pores for all sizes when compared to REF A, but the macroporosity difference between different depths comes mainly from the high values of the spectrum (1000-10000 μm) (Figure 7.10).

The aim was to quantify how much of the macroporosity is accounted for by each of these classes. It is also shown that both CHAR A and REF A have more pores corresponding to the middle size classes (50-250 and 25-500). However, the top size class pores account for the majority of surface area. In addition, when comparing CHAR A with REF A, a higher number and consequently a higher surface area is associated to pores of $>250 \mu\text{m}$.

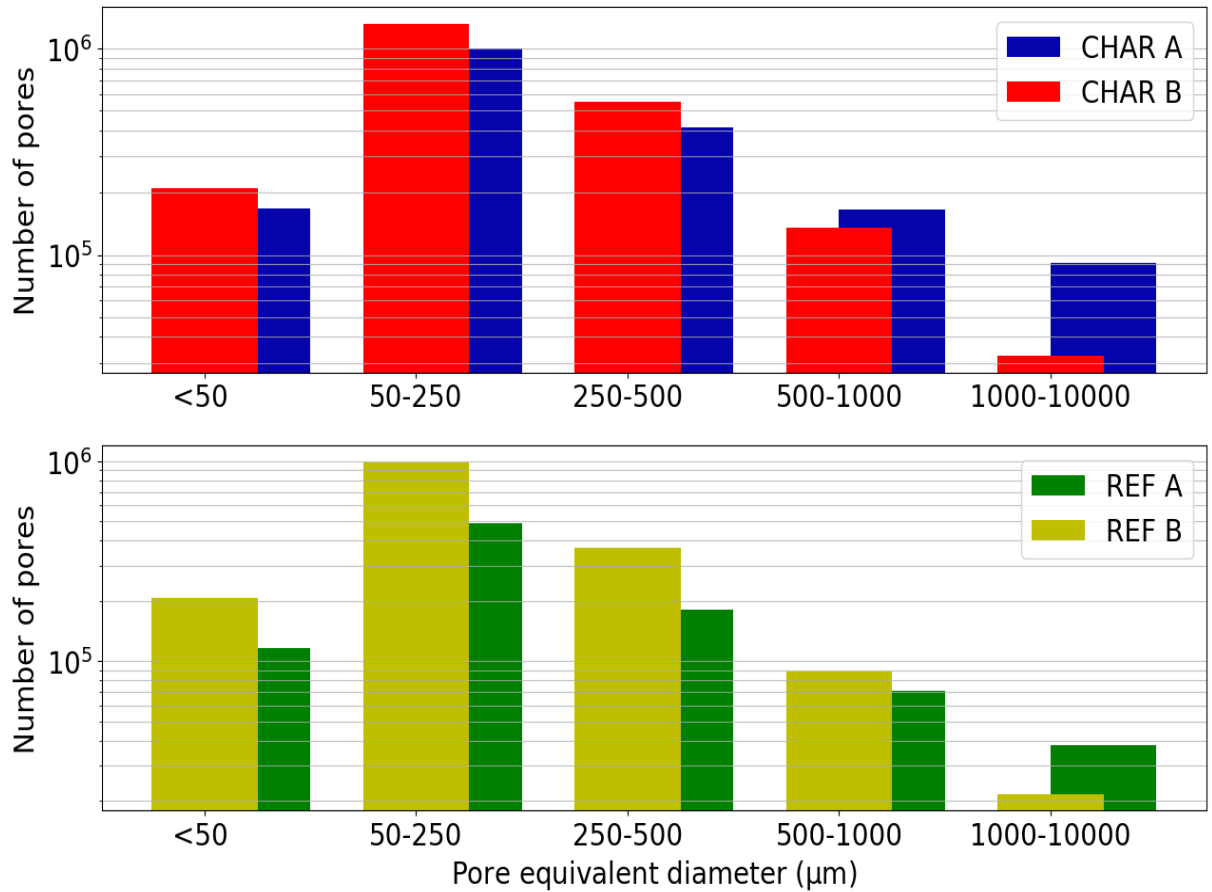


Figure 7.10: Histograms showing the pore size distribution. Values represent the totals over 6 samples in each category (CHAR A, B; REF A, B)

There was a clear structural difference between the enriched charcoal topsoil and other sampled layers. This difference manifests through increased values of macroporosity, pore size and connectivity density. However, the B-horizon samples at the charcoal location do not share the same properties, underlining the fact that there is also a change in properties with depth and that the charcoal only had an effect on the A-horizon. The structural difference at depth was observed by a decrease in macropores (ranging from 1000-10000 μm).

One may realise that a consequence of a change in structure will be the change in soil hydraulic properties. It was therefore sought to confirm this by the

geoelectrical, soil physical and chemical measurements employed on the same monitoring field site.

7.4.2 Time-lapse difference ERT

For this set of time-lapse inversions D57 was used as a reference and the difference in resistivity (%) with subsequent time-steps was computed. Measurements before D57 did not contain reciprocals and were not deemed to be suitable. In order to perform the difference inversion, after the first data filtering, the same data points across all time-steps were needed (previously detailed in chapter 3.1.4). Therefore approximately 410 datapoints were discarded (around 45 %) per time-step, which yielded different model sensitivities (Figure 7.11). Sensitivities below 10^{-3} were considered to reflect areas of poor data coverage. These were cropped out and were not used for subsequent data interpretation. The sensitivity plots reveal the disadvantage of this time-lapse difference strategy. The large gaps corresponding to low sensitivities are a consequence of many measurements being discarded for time-lapse inversion. Furthermore, the currently used temperature corrections implied scaling the resistivity results according to a fixed reference temperature.

7. INTEGRATED ERT AND X-RAY APPRAISAL OF PORE WATER DYNAMICS IN CHARCOAL ENRICHED SOILS

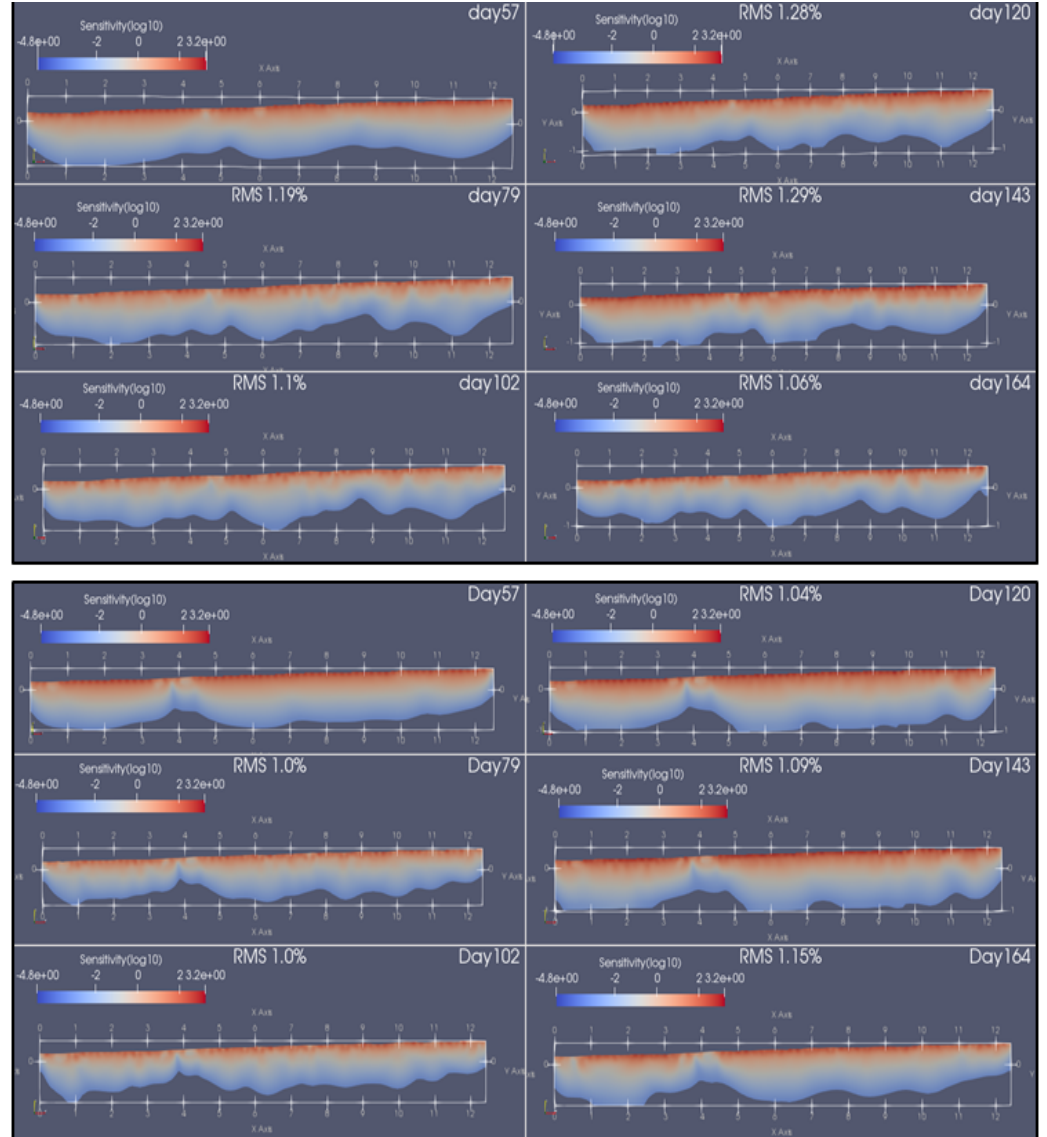


Figure 7.11: Time-lapse difference inversion sensitivity models (corrected for topography) corresponding to all time-steps. OBC5- top 6; REF5 - bottom 6. X-Y axis scale is in metres.

Figure 7.12 complements Figure 7.11 and shows the corresponding inversion results. Firstly, for both soil types, the static inversion results corresponding to day 57 show a clearly defined more resistive A horizon that goes down to approximately 25 cm. Secondly, day 120 and day 143 show greater overall positive electrical resistivity changes than the other time-steps. As both soils display similar patterns, presumably this is a consequence of a field scale phe-

7. INTEGRATED ERT AND X-RAY APPRAISAL OF PORE WATER DYNAMICS IN CHARCOAL ENRICHED SOILS

nomena such as precipitation input. Also, in OBC5, the right half of the first horizon seems to be showing higher difference values, which could be accounted by pore water drainage determined by increasing topography.

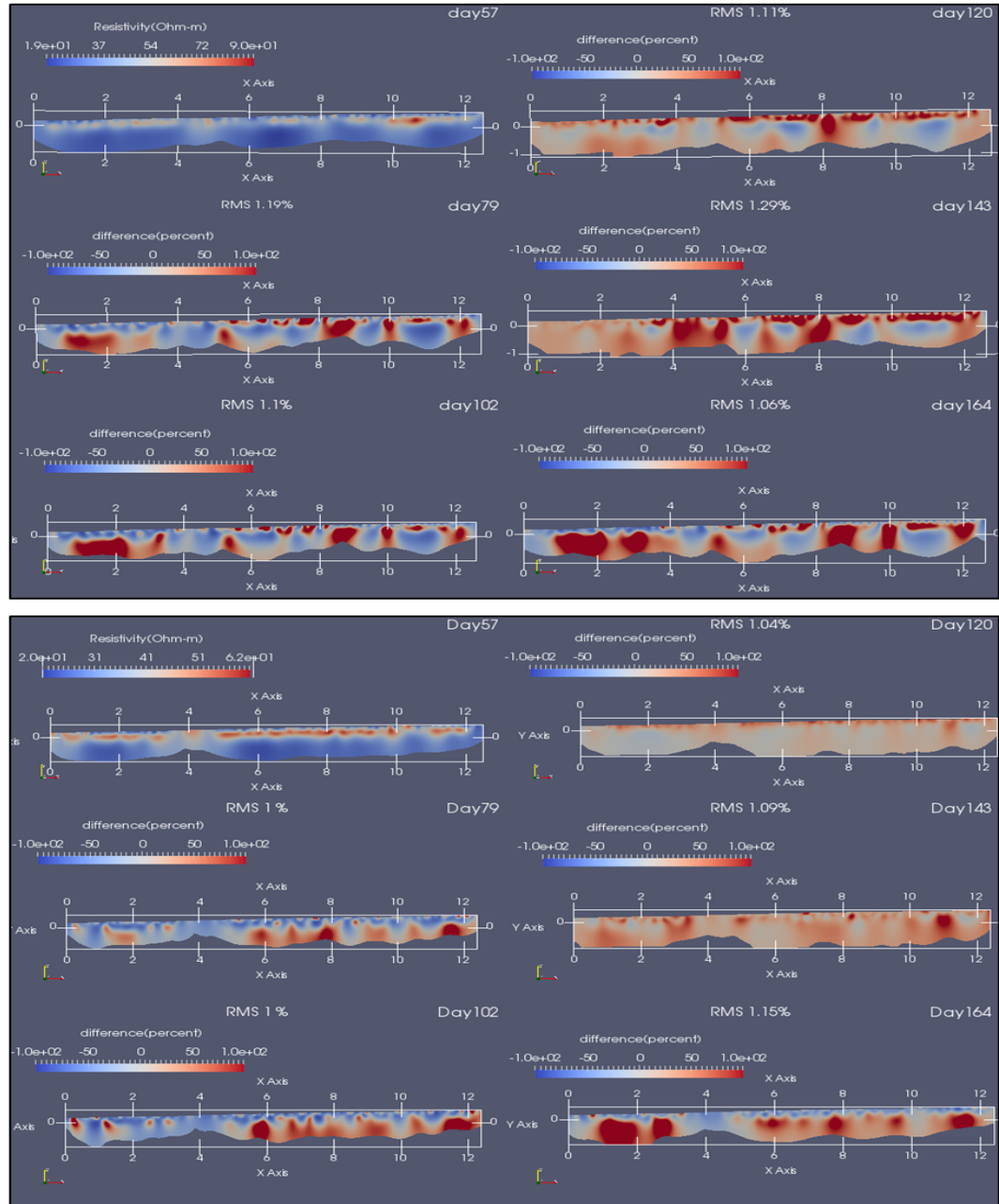


Figure 7.12: Time-lapse difference inversion resistivity models (corrected for topography) corresponding to all time-steps. OBC5 - top 6; REF5 - bottom 6. X-Y axis scale is in metres.

7.4.3 Correlations between resistivity models, structural parameters and soil physicochemical properties

7.4.3.1 Resistivity and weather data As discussed in the previous chapter, field scale effects on the time-lapse inversion results were identified. The assumption was that these must be correlated with precipitation quantities around the time of the survey. Using weather data collected by a weather station present on site, Figure 7.13 shows the net precipitation (rainfall minus evapotranspiration) and temperature distribution across year 2019. As expected, a decrease is noticed in net precipitation around the time of surveys from days 120 and 143, hence a drier soil with a respective higher resistivity.

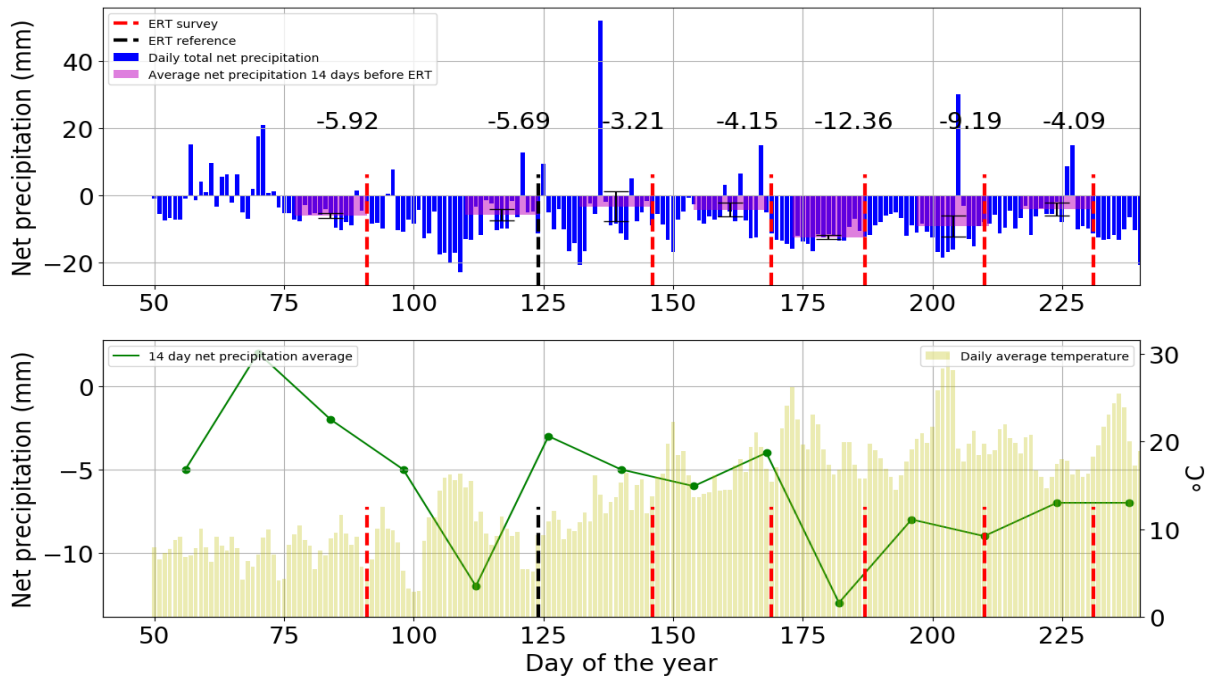


Figure 7.13: Weather data acquired on the CHAR monitoring field site during 2019. Numbers displayed are the average net precipitation values represented graphically by the violet bars.

7.4.3.2 Resistivity and structural parameters The aim of the CHAR project is to provide a joint interpretation of soil hydrodynamic properties using different soil assessment methods. Up until now, resistivity and structural

data were examined separately, but now one can draw quantifiable correlations between them.

The time-lapse inversion model results are composed of multiple model cells. Each cell has a XZ position and a value of electrical resistivity ($\Omega.m$)/resistivity difference (%) associated. Therefore, this allows us to compute the electrical resistivity change in time or depth over an area of choice. Previously a distinctively more resistive A-horizon was observed. Therefore, Figure 7.14 shows the average model cell values of electrical resistivity (top) and resistivity difference (bottom) corresponding to individual soil horizons and how they change for every time-step. The charcoal enhanced soil was more resistive and had more accentuated resistivity differences in time when compared to its reference counterpart. An increased proportion of air-filled macropores, as observed on the X-ray scans, can be used to account for the increase in resistivity. It was also observed a sharp increase in electrical parameters (125 $\Omega.m$ and 40 %) between wet and dry events. However, this discrepancy diminished in the second layer where the electrical signatures of the two locations, especially in the wet events, are indistinguishable. In addition, the rise in air temperature and reduction in precipitation caused a smaller (60 $\Omega.m$ and 20 %) and steadier increase in electrical resistivity.

7. INTEGRATED ERT AND X-RAY APPRAISAL OF PORE WATER DYNAMICS IN CHARCOAL ENRICHED SOILS

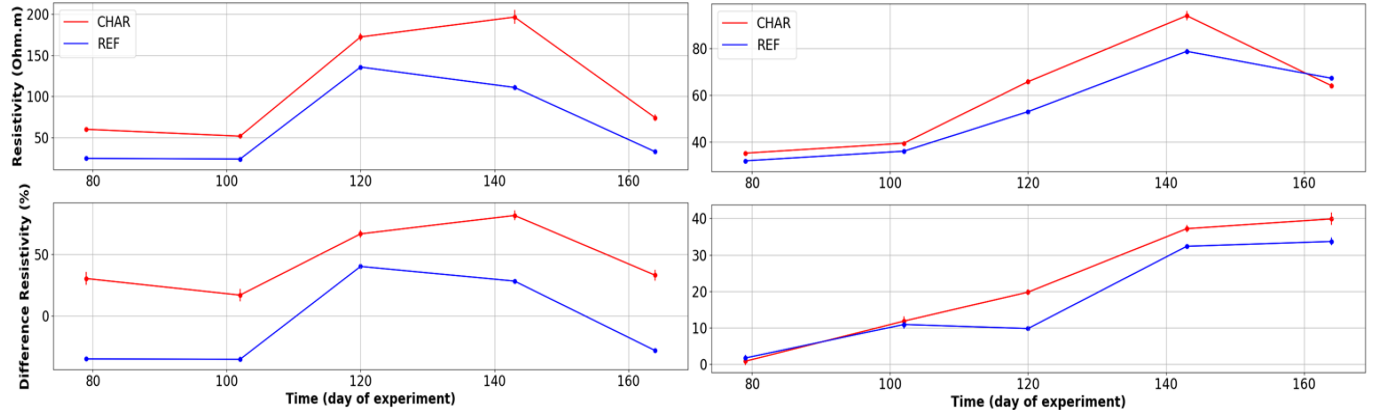


Figure 7.14: Average resistivity of inversion model cells above 25 cm depth - A horizon (left) and below 25 cm depth - B horizon (right)

Using the X-ray soil core sampling location information, the model cells corresponding to areas adjacent to the sampling points (SP) were also identified (Figure 7.15). It is worth mentioning that SP5 has a very poor resolution in its vicinity. Therefore, the respective analysis could display anomalous behaviour.

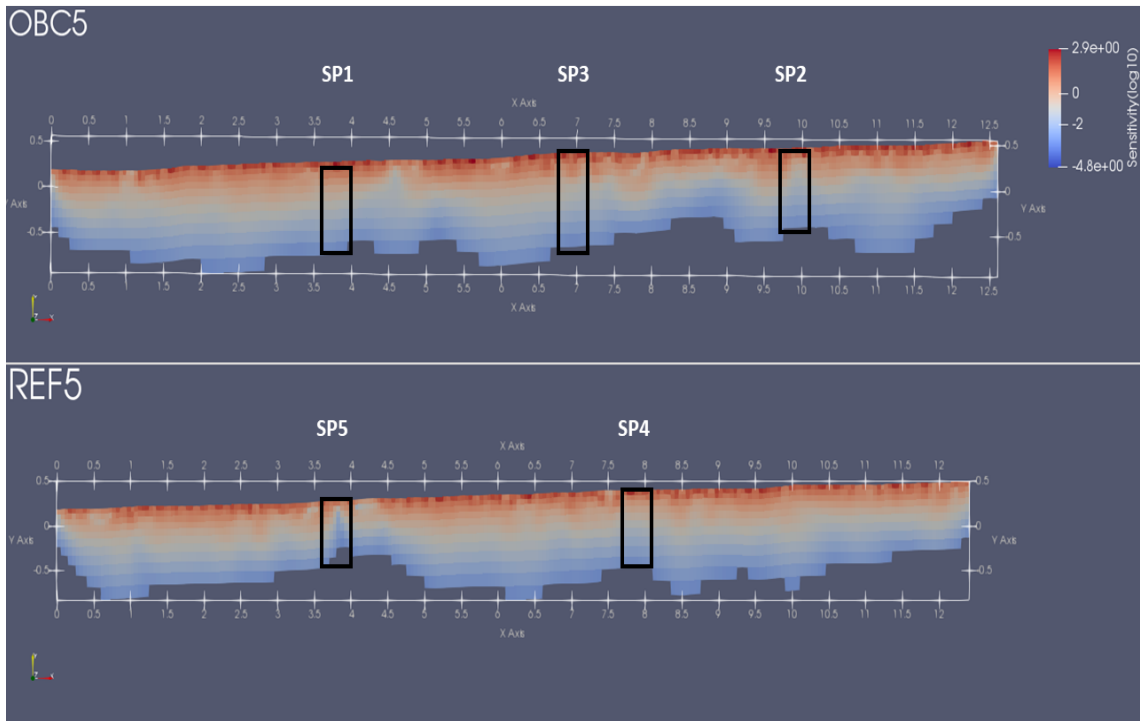


Figure 7.15: Areas of model cell selection corresponding to soil core sampling locations

Therefore, for every separate sampling point selection area, the evolution of average resistivity in time and in depth was computed along the overall standard deviation. It is conclusive, from the resistivity profile with little variation with depth at SP5, that this sampling point lacks data coverage. The resistivity distribution in time reveals that every SP location responds to changes in precipitation, but with different magnitudes of change (Figure 7.16 top). SP1 seems to have the overall most pregnant increase in resistivity at days 120 and 143 which doesn't return to the pre-drying levels, not even during higher levels of precipitation. SP2, SP3 and SP4 have a similar response to the first drying event (day 120) and to the comeback of precipitation (day 164). However, during the second drying event, SP2 shows the steepest increase in resistivity. The resistivity distribution with depth reveal larger values of resistivity in the top 25 cm as previously discussed (Figure 7.16). In addition,

7. INTEGRATED ERT AND X-RAY APPRAISAL OF PORE WATER DYNAMICS IN CHARCOAL ENRICHED SOILS

a much larger step in resistivity was observed in the top horizon for SP2 and SP3 than for SP4 and SP1, especially in the dry days. The greater variability noticed in SP from the CHAR location is an indicator that the charcoal top layer enables a more dynamic exchange of water, nutrients and heat with the atmosphere. This could explain the reduction in plant water stress, as Kerré et al. (2017) reported.

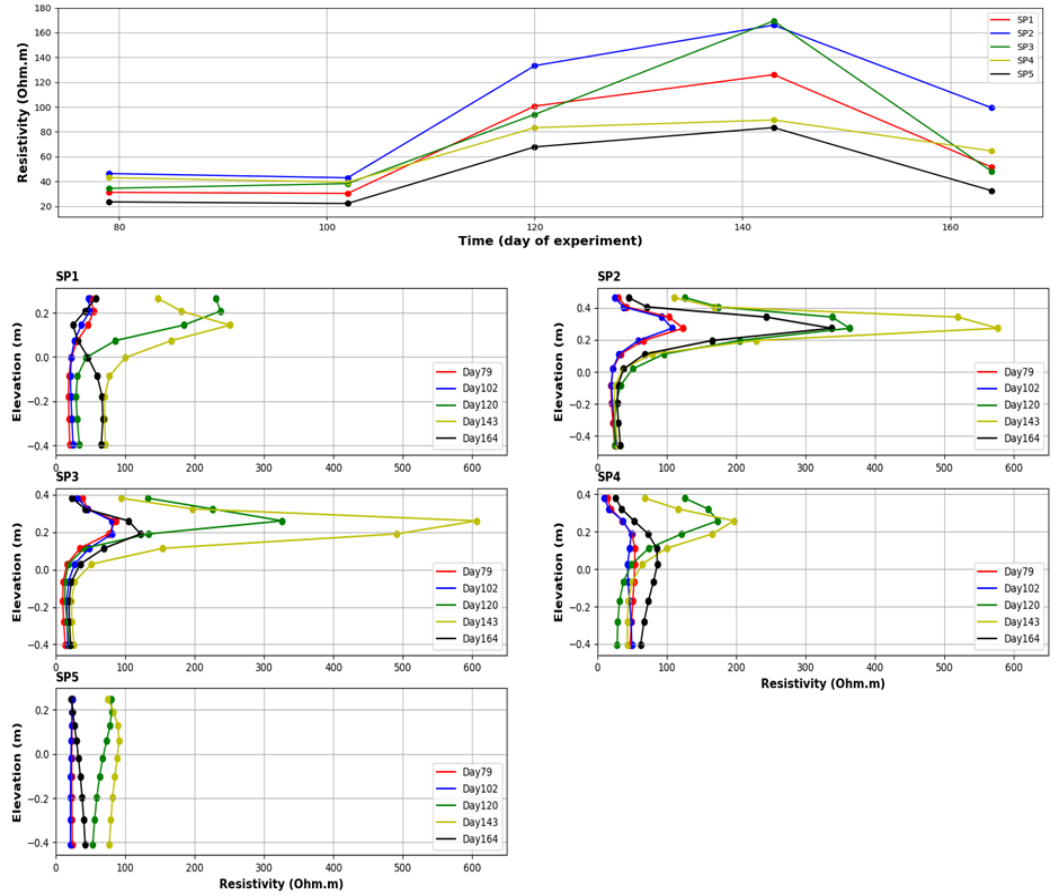


Figure 7.16: SP selected model cells average resistivity values and their variation in time (top) and depth (bottom)

As the structural parameters corresponding to different soil types and depths were computed, the parameters corresponding to individual sampling points were also resolved. By considering the values of porosity, a similar pattern with the resistivity standard deviation values of the entire dataset was ob-

served (Figure 7.17). Correlation was reportedly high (Pearson r of 0.94), but this does not necessarily imply causation, but it is at least hypothesized there is a connection between the two, which has to be confirmed by further investigation. The implication behind this correlation is that a soil with a bigger pore space and consequently a higher water storing capacity, upon changes in net precipitation and temperature, determines a greater potential to exchange energy and matter with the bounding mediums.

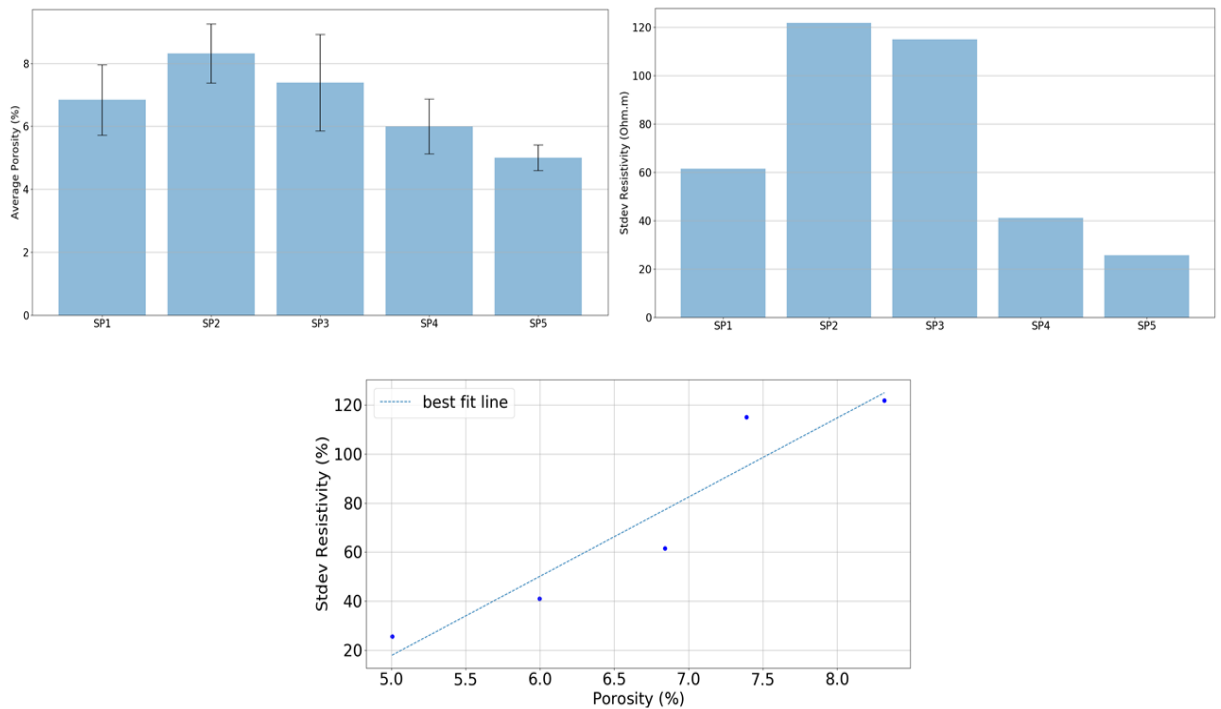


Figure 7.17: Apparent correlation between average porosity (left) and Resistivity standard deviation ($\Omega.m$) corresponding to the 5 SP

7.4.3.3 Pore structure and macroaggregation Sun and Lu (2014) and Yu et al. (2016), identified an increase in macroaggregation and macroporosity for biochar-amended soils. Similarly to what is shown in Figure 7.18, Yu et al. (2016), in their study on Vertisols, identified an increase in total porosity for pores larger than $50 \mu m$. Also for Vertisols, Sun and Lu, (2014) found a significant increase in macroaggregation for size ranges $250-500 \mu m$ and $2000-5000$

μm . In this study, for a Luvisol, a similar correlation between macroaggregation and macroporosity was noticed, where the difference in total surface area coming from pores larger than $50 \mu\text{m}$ reflects in an increase in OBC macroaggregates (Figure 7.18). The results regarding macroaggregation (7.18 right) are presented here just for comparison with X-ray derived porosity.

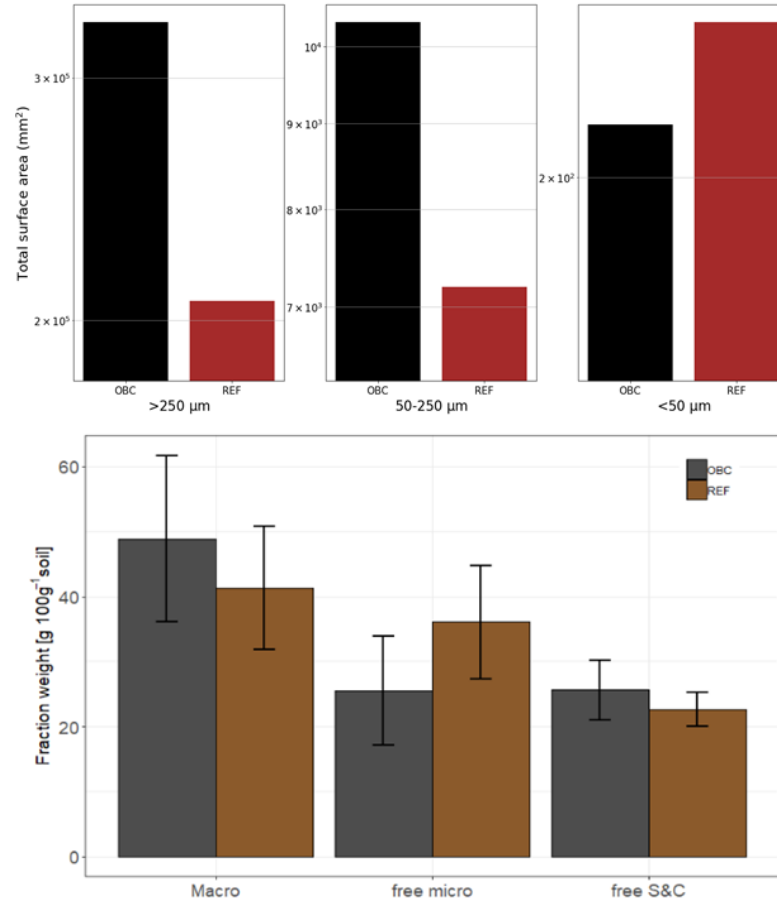


Figure 7.18: Top: Total surface area corresponding to air-filled pores grouped by the size of their equivalent diameter. Bottom: Fraction weight of macroaggregates - data analysis produced by PhD candidate Victor Burgeon - University of Liège. Macroaggregate fraction (Macro) represents particles larger than $250 \mu\text{m}$, Microaggregate fraction (free micro) represents particles $50\text{-}250 \mu\text{m}$ and Silt and Clay fraction (S&C) represents particles smaller than $50 \mu\text{m}$

7.4.3.4 Pedophysical calibration and electrical polarization Ultimately, geoelectrical measurements need to be translated into soil properties. This can be achieved through a pedophysical relationship, which expresses the electri-

cal resistivity as a function of multiple soil physicochemical parameters. An important factor in these relationships, often assumed without direct empirical data is pore solution conductivity. Therefore, it is encouraged that future research to measure such values *in-situ* and subsequently use them for a more accurate translation between bulk electrical resistivity and moisture content. A setup for pedophysical calibration experiments was devised as such where the soil's hydraulic parameters can be predetermined and their impact on electrical properties consequently derived. Preliminary results (Figure 7.19) show an increased polarization for the charcoal enhanced topsoil (sampling depth 20 cm) around an electrical frequency of 10 Hz. However, this behaviour cannot be explained at the moment and requires further investigation of polarization mechanisms.

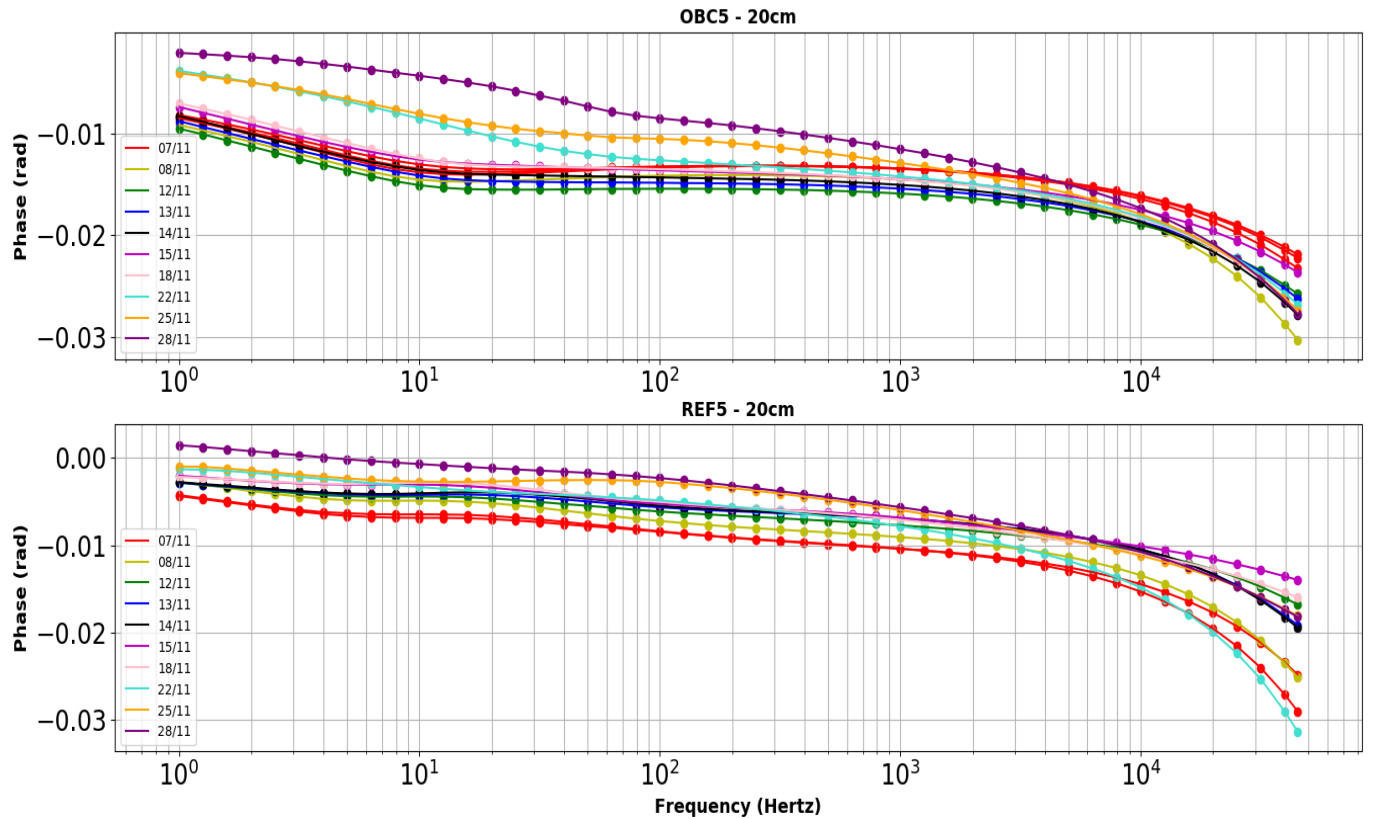


Figure 7.19: Spectral electrical response during desaturation. The legend indicates the day (07/11 - 7th November 2019) each phase spectrum was recorded.

7.4.4 Limitations and future perspectives

In this study, electrical resistivity measurements were calibrated using a reference average soil temperature. Such methodology might not provide sufficient accuracy if one is considering the spatial variability in soil temperature. Therefore, future studies may consider the calibration according to more complex temperature flux models (Brunet et al., 2010), which encompass such variability.

The laboratory SIP set-up, briefly mentioned in this study, provided only some preliminary results. The CHAR soil showed a clear polarization effect, but further modelling is required to understand its cause and how it is correlated with the more developed porosity and pore connectivity.

This study looks at the hydrodynamics of charcoal amended soils. Even though changes in soil structure and water availability are identified, the study does not explore how such changes reflect on plants. Therefore, future studies are encouraged to consider coupling geophysical measurements with plant measurements (e.g. transpiration, yield).

7.5 Conclusions

By coupling time-lapse ERT monitoring with X-ray CT analysis of soil structure the physical properties of charcoal enhanced soil (CHAR) were compared with its naturally occurring correspondent. The X-ray scans indicated that the CHAR soil exhibited a significantly more developed total air-filled pore space and a larger pore size and connectivity. This in turn reflected on the CHAR electrical properties which showed larger variations in electrical resistivity over time and a distinctive polarization manifested by a phase difference peak (0.01 radians at 10 Hz) during desaturation. However, such differences were only sig-

nificant for the A horizon (0-25 cm). Below this depth the results were similar between the compared soils. Furthermore, higher levels of macroaggregation (for CHAR particles $> 250 \mu\text{m}$) were complemented by high surface area values of air-filled pores with similar sizes. These results imply that the distribution of charcoal particles affects the pore structure of soil macroaggregates. This in turn determined a more hydrodynamically active medium with wider pore channels, which increases the ability of air, water and nutrients to exchange with the adjacent soil matrix (Yu et al., 2016) and reduce plant water stress (Kerré et al., 2017). In addition, electrical resistivity standard deviation corresponding to different sampling points was strongly correlated with the average porosity of the soil sampled at the same locations. This shows the complementarity between X-ray CT and ERT at fieldscale, because even at these low resolutions (dm) the electrical parameters resolved still reflect the spatial variations in soil macropore structure. Future studies are encouraged to explore the underlying mechanisms of the observed electrical polarization effect and to consider coupling geophysical and plant measurements in order to grasp the long term impact of charcoal depositions on agricultural productivity.

8 GENERAL DISCUSSION AND CONCLUSIONS

In the study of near-surface hydraulic processes there is a gap in knowledge between monitoring instrumentation and assessment of effective soil properties. There are fast tools to monitor such processes (e.g. geoelectrical methods), but a quantitative link with their drivers (e.g. soil texture, structure, bioactivity) is missing. One of the most extensively used geoelectrical method is ERT, which has a robust background in instrumentation, data acquisition, error processing and model interpretation. One of the most efficient methods of resolving soil structure is X-ray CT, which provides μm scale non-invasive mapping of soil composition. This project aimed to close this gap by providing a joint methodology that brings together high spatial resolution details about soil structure, facilitated by X-ray CT, and high temporal resolution details about solute balance and flow, facilitated by ERT.

In the attempt to summarize this work its conclusions are listed as follows:

1. Geoelectrical methods are a prominent tool in root zone research (Literature review Chapter 1).
2. ERT and X-ray CT can be utilized in a joint methodology, combining their respective capabilities, used to monitor, temporally and spatially, soil hydrodynamic processes (Method description Chapter 3).
3. A pedophysical relationship between bulk X-ray absorption and electrical resistivity was developed (First experimental Chapter 4).
4. In a controlled column experiment, a joined ERT-X-ray CT methodology estimated and visualized how the rate of 4D solute infiltration is affected

by the soil pore architecture under different levels of compaction. An increasing bulk density decreased pore connectivity, which in turn lowered estimated lateral solute infiltration rates (Second experimental Chapter 5).

5. In a controlled column experiment, a joined ERT-X-ray CT methodology revealed how the solute flow behaviour changes in soils with the duration of ZT practice. Initially, the soils saw a decrease in porosity and consequently flow inhibition followed by a porosity expansion with a greater proportion of water conducting pores and enhanced lateral percolation (Third experimental Chapter 6).
6. Field ERT monitoring and X-ray CT analysis of pore structure revealed that long term charcoal soils have a more developed pore network which enables a greater soil water variability over time (Forth experimental Chapter 7).

8.1 Geophysical assessment of soil hydraulic properties across scales

The experimental work was conducted across three scales: a small - micrometre scale, a medium - centimetre scale and a large - decimetre scale. Each offers a different perspective on the link between ERT and X-ray CT, or the link between hydraulic properties and soil structure. One can imagine the three scales as in Figure 8.1, which underlines that such link is facilitated by 1. microstructures - fine soil aggregates 2. macropore channels and 3. bulk soil volumes. By all means, the information regarding each scale is not independent, but there is a certain degree of correlation between each of them. This however represents a challenge on its own as it is desirable to understand how the three scales

inform each other and how can such information be translated to the point where it becomes tangible and usable for non-scientists.

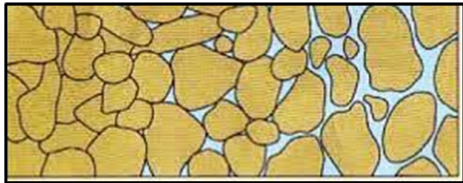
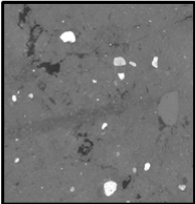
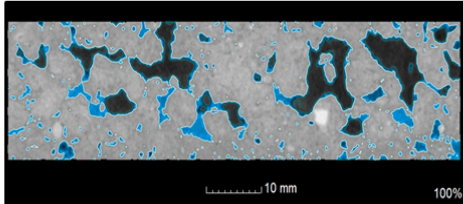
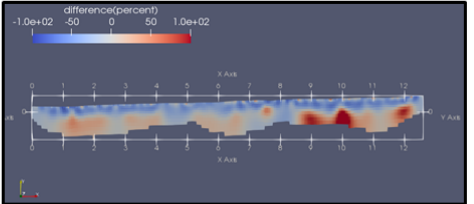
Effective measurable parameters link	Solute transport monitoring	Field soil water balance
Small scale (40-100 μm)	Column scale (cm)	Field scale (dm)
		
		

Figure 8.1: Synthesis diagram of project results across three scales.

8.1.1 Small scale interaction between structure and electrical resistivity

The pedophysical relationship between bulk X-ray attenuation and electrical resistivity was achieved because both parameters share a sensitivity to changes in soil moisture content (Baker et al. (2007), Samouëlian et al. (2005)). Therefore, a tool was obtained to quantitatively relate observations between the two soil assessment methods. However, the experiment was undertaken on compacted small (44 cm^3) soil samples moisturized at different levels. In this setting, the applied moisture occupied the micro and mesoporosity available. In a situation where soil maintains its structural integrity, macroporosity plays

a key role, determining preferential flow (Steenhuis et al., 1990), hence one of the main driver of changes in bulk electrical resistivity. Therefore, failing to account for macroporosity represents the principal limitation of this scale. However, estimations of bulk electrical resistivity do not depend on the size of individual pores, but on their total volume, hence if an accurate estimation of porosity is available, the electrical measurements can be translated into soil hydraulic properties. Even though the operation was performed at a smaller scale, the scanning resolution did not allow direct observation of mesoporosity or lower. In order to take advantage of the X-ray's capability to non-invasively characterize pore architecture, because ERT imposes a certain sample size and consequently an upper boundary in scan resolution (around 30 μm), a larger soil volume containing macropores needed to be appraised.

8.1.2 Observing the impact of macroporosity on column scale flow

The second experimental chapter 5 concerned an infiltration monitoring study on undisturbed soil columns, although at the current operating resolution (40 μm) micropores remained undetectable. Providing the sample remains undisturbed, it is therefore impossible to locally estimate their volume. In order to account for their effect on changes in bulk electrical resistivity, the relationship developed in chapter 4 can now be used. Interestingly, it was seen in chapter 5.4.4.2 that estimates of macroporosity were sufficient to account for changes in bulk resistivity during solute infiltration. However, for soils where macroporosity is highly reduced, a combination of a direct empirical estimation of porosity as used in chapter 5 and a pedophysical estimation of porosity using the relationship derived in chapter 4 is needed.

The column scale can be viewed as an intermediate scale. It was focused on a relatively restricted volume of soil, but nonetheless, a volume large enough

to be relevant for a plant-root system development. At this scale, the experimental conditions were still controlled (e.g. constant rate of solute infiltration, constant air temperature), but ran on an undisturbed sample. In addition, it represents the scale at which both tomographic methods can provide most volume of information. Other studies employed the two methods in conjunction at this scale for the study of soil processes. Olsen et al. (1999) used the two methods to characterize solute transport in soils, but the linkage between the two methods was purely qualitative. Cassiani et al. (2009), in a study on soil columns, used X-ray CT scanning to reveal that a non-aqueous phase liquid distribution after injection in soil was the source of DC signal variability and not the chemical interactions. Both X-ray CT and ERT have the capability to operate in 3D, which allows us to collocate the soil properties they assess over the appraised soil volume.

A larger scale becomes more problematic for ERT from an inversion modelling perspective, as more external factors (with unpredictable and uncontrolled inputs into the soil system e.g. precipitation) imply more uncertainty. On the other hand, a smaller scale does not physically allow a tomographic reconstruction if multiple electrodes cannot be attached to the sample. X-ray CT allows higher resolution/smaller scale investigation which could theoretically provide more information, however strictly for plant-scale hydraulic processes a smaller scale would just not be representative. As for the field scale, X-ray CT is constrained by the size of the X-ray chamber. In addition, if the sample size increases the resolution and the X-ray energy are likely to increase up to a point where root zone features are unobservable and consequently the experimental conditions unfeasible (Mooney et al., 2012).

Column scale experimental conditions provided some of the most notable contributions from this work. Flow movement through soils was monitored at a

high temporal resolution, which revealed the rate at which different stages of compaction inhibit 4D infiltration. This result can inform the right soil bulk density conditions, which, depending on crop type, would determine a suitable water availability regime that reduces plant water stress (Chaves et al., 2002). The impact of ZT with time was also assessed and revealed that after an initial decrease in total porosity due to compaction, 12 year ZT soils showed a rebound in total porosity and a decrease in immobile water content, which can be explained by the rejuvenation of bioactivity. In studies comparing ZT soils and ConT soils, Helgason et al. (2010) found an increased microbial biomass in ZT soils and Francis and Knight (1993) found a greater earthworm population. This result can serve as a reference for future planning in ZT farming, suggesting that an initial period (minimum 7 years) of reduced productivity is possible, which would require economical readjustments or crop rotation strategies in order to match concurrent soil water holding potential. Furthermore, the high spatial resolution of these column studies facilitated the correlation between subvolumes of the pore network and their impact on bulk electrical resistivity estimates. This result can be used for future models which attempt to finely discretize properties of the root zone.

8.1.3 Perspectives and limitations of field scale assessment

For the first time in this study, at field scale, both tomographic assessments over the same soil volume could not be performed. This time, because the scale gap between the methods systematically increased, X-ray images only provided one bulk soil structural parameter value per sample, their spatial variability throughout the sample being redundant. However, some parameters, such as pore connectivity cannot be computed by regular laboratory assessments. X-ray image processing obtained a clear correlation between total porosity, pore

connectivity variability with depth and soil type (charcoal enhanced vs. natural reference soil).

The complexity of an ERT model increases at field scale (Vanderborght et al., 2013). Topography, temperature, precipitation rates, etc. are just some of the variables that must now be taken into account when modelling soil electrical resistivity distribution. However, the system's applicability also increases. From an agricultural/industrial perspective, the farmer is mainly interested in field scale processes and effective ways of quantifying and monitoring them as such. For example, from ERT investigations, the soil water balance can also be estimated at field scale as shown by Cassiani et al. (2012). This estimate will not be as accurate as one could obtain at column scale, but much more relevant for an open system such as an agricultural crop field. It is however possible to propagate controlled estimations (e.g. infiltration rates, pore connectivity, RWU) obtained ex situ to inform and enhance larger scale models. In this study, ERT revealed a greater variability in electrical resistivity in time for charcoal enhanced soil than its reference counterpart. Together with X-ray estimates of pore structure, this demonstrates that long term charcoal enhancement is manifested by enlarging the pore channels and changing the soil water holding capacity. These facilitate a more dynamic energy exchange between soil and surrounding mediums (Yu et al., 2016) and reduces water stress as shown by Kerré et al. (2017) in their study on long term charcoal amended soils. This information could be used to direct future land management practices, which have the capacity to raise the current crop potential.

8.2 Outlook

Soil is a complex medium that is highly dynamic in space and time. It was demonstrated here how geoelectrical methods can systematically contribute

to soil hydraulic property interpretation across multiple scales. However, an essential complement to geoelectrical data was a-priori information about soil structure resolved by X-ray CT. Nonetheless, efforts do not stop here and this project is considered to be just one of many to follow which make use of an interdisciplinary methodology to develop our understanding of root zone processes.

8.2.1 Electrical impedance - the whole picture of the electrical response

For all the electrical surveys in this project electrical impedance was the parameter measured (Equation 1.1). As stipulated in Chapter 2, ERT uses the magnitude of electrical impedance, electrical resistivity. However, Z is in fact a complex parameter ($\mathbb{C}$), with a real and an imaginary component. Their variability can be explored in part, which could provide additional information about the study material properties. Many studies are already using the complex definition of impedance for root zone research (Mary et al., 2017; Weigand and Kemna, 2017, 2018), but this topic is in its infancy stages and requires immediate attention due to its potential to further characterize and explain the evolution of soil physicochemical processes. Furthermore, root material, electrically indistinguishable from electrical resistivity measurements (Rossi et al., 2011) shows strong polarizations effects (Ehosioko et al., 2018). In this project, the electrical polarization signal was briefly emphasized through preliminary results presented at the end of chapter 7. Here, during desaturation, soil samples with a higher porosity and charcoal content showed an increased polarization. This could improve our understanding of how electrical current travels through soil (e.g. the large size of charcoal particles determine a pore network with characteristics that enhance electrical polarization), allowing us

to develop our root zone measurement and instrumentation strategies.

8.2.2 Roots - observation and monitoring

The column experiments used in this study took place on bare soil. An effective way forward would be to include/grow plants in a controlled system. This way it would be possible to monitor root activity and its impact to soil hydraulic properties. Several studies have conducted electrical measurements on 1. bare roots: by injecting the current into the plant's stem: Ehosioke et al. (2018) showed that Maize and Brachypodium root segments exhibit a much stronger polarization (over 400 mrad) of electrical current than surrounding soil, 2. roots in hydroponic solutions: Tsukanov and Schwartz (2020) obtained a direct link between wheat root outer surface area and polarization and 3. by synthetic modelling: Rao et al. (2018), through a virtual rhizotron study, demonstrated that the electrical response holds valuable information about the root architecture only when the root system is surrounded by a very conductive medium (e.g. highly moisturised soil). Therefore, one can use all this preliminary knowledge as a basis to conduct a geoelectrical monitoring study of root growth in soil columns, which allows us to non-invasively monitor in near real time root development in soils.

In order to use complementary information from CT data, roots, growing in soil cores, in different stages of development can be non-invasively scanned in order to determine the impact root architecture has on the electrical response. This root system architecture could also be used in combination with model estimated transpiration flux (e.g. by the R-SWMS model (Javaux et al., 2008)) to simulate root water and nutrient uptake distributions (Koch et al., 2019). This will allow us to determine the link between root activity patterns and electrical signatures. This can, on one hand, potentially improve the shortfalls

in electrical theory (e.g. model of root-water-soil interface polarization), and on the other hand, ground truth the model estimations (Figure 2.9). However, because such assessments are currently only possible at column scale, one should consider the effect the shape and size of the soil container has on root development (Biran and Eliassaf, 1980) and what impact removing the soil from its natural setting has on plant growth.

8.2.3 Towards an interdisciplinary study of soil

The foundation of this project is the coupling between two methods of non-invasive soil tomography. Combining them, unified their capabilities and improved our understanding of soil hydraulic processes, such as the 4D infiltration rates or flow velocity and dispersivity. Furthermore, this project enabled the comparison between laboratory and field measurements, between high and low resolution structural parameters, and between dynamic and static observations. Therefore, more collaborations are desirable between complementary soil related disciplines in the near future. This should not be restricted to inorganic processes, but include inferences about soil biomass and bioactivity. This would imply further coupling with biological studies in order to appraise root development (Dalton, 1995), activity (Weigand and Kemna, 2018) and modelling (Javaux et al., 2008). Even though in the last experimental chapter an ERT field trial was conducted, the survey's spatial coverage was limited to a few metres. Also, the assessment implied the redeployment of the ERT system every time a survey was attempted. In consequence, future instrumentation development calls for autonomous continuous ERT measuring systems, that offer an unsupervised monitoring of the field's hydraulic properties, and wireless data acquisition and transmission channels, which have the potential to automatize data processing and the construction of resistivity models. This

could improve data continuity and offer a more comprehensive, real-time understanding of hydraulic processes across all seasons without intensive manual labour and physical disturbance of soil. Such ERT autonomous systems are already in use for other applications such as monitoring moisture dynamics in an embankment (Chambers et al., 2014) or during landslide reactivation (Uhlenmann et al., 2017).

There are however other geophysical methods able to estimate and map soil properties at agricultural plot scale, such as EMI (Brogi et al., 2019) or remote sensing satellite images (Triantafyllis et al., 2009). These lack depth penetration, but cover a wider surface area. Therefore, a combined methodology to monitor soil property variability in 3D is highly desirable. Finally, considering one of the main outputs of this project: assessment of soil hydraulic properties across scales. The ability to translate information about soil properties between scales is considered to be vital, providing the necessary link between existing micro and macro processes. Future research is therefore encouraged to put every result in the perspective of multiple scales in order to provide a more comprehensive interpretation of soil physicochemical mechanisms.

References

- Agbogun, H. M., Al, T. A., and Hussein, E. M. (2013). Three dimensional imaging of porosity and tracer concentration distributions in a dolostone sample during diffusion experiments using X-ray micro-CT. *Journal of Contaminant Hydrology*, 145:44–53.
- al Hagrey, A. S. (2007). Geophysical imaging of root-zone , trunk, and moisture heterogeneity. *Journal of Experimental Botany*, 58(4):839–854.
- Alegre, J., Cassel, D., and Amezquita, E. (1991). Tillage systems and soil properties in latin america. *Soil and Tillage Research*, 20:147–163.
- Alm, D., Cavelier, J., and Nobel, P. (1992). A finite-element model of radial and axial conductivities for individual roots - development and validation for 2 desert succulents. *Annals of Botany*, 69:87–92.
- Amato, M., Basso, B., Celano, G., Bitella, G., Morelli, G., and Rossi, R. (2008). In situ detection of tree root distribution and biomass by multi-electrode resistivity imaging. *Tree Physiology*, 28(10):1441–1448.
- Amato, M., Bitella, G., Rossi, R., Gómez, J. A., Lovelli, S., and Gomes, J. J. (2009). Multi-electrode 3D resistivity imaging of alfalfa root zone. *European Journal of Agronomy*, 31(4):213–222.
- Amin, M. H. G., Richards, K. S., Chorley, R. J., Gibbs, S. J., Carpenter, T. A., and Hall, L. D. (1996). Studies of soil-water transport by MRI. *Magnetic Resonance Imaging*, 14(7-8):879–882.
- Anderson, S. H., Peyton, R. L., Wigger, J. W., and Gantzer, C. J. (1992). Influence of aggregate size on solute transport as measured using computed tomography. *Geoderma*, 53:387–398.
- Anderson, S. H., Wang, H., Peyton, R. L., and Gantzer, C. J. (2003). Estimation of porosity and hydraulic conductivity from X-ray CT-measured solute breakthrough. *Geological Society, London, Special Publications*, 215(1):135–149.
- Archie, G. (1942). The Electrical Resistivity Log as an Aid in Determining Some Reservoir Characteristics. *Transactions of the AIME*, 146(01):54–62.

- Aulen, M. and Shipley, B. (2012). Non-destructive estimation of root mass using electrical capacitance on ten herbaceous species. *Plant and Soil*, 355(1-2):41–49.
- Bailly, D., Campbell, M., Poffa, N., Sun, J., Galbraith, G., Mclean, R., Sanders, C., and Nelsen, G. (September 2003). Moisture transport studies in building materials. *Proceedings of Institute of Physics Conference: Sensors and their Applications XII*, pages 551—557.
- Baker, P. H., Bailly, D., Campbell, M., Galbraith, G. H., McLean, R. C., Poffa, N., and Sanders, C. H. (2007). The application of X-ray absorption to building moisture transport studies. *Measurement: Journal of the International Measurement Confederation*, 40(9-10):951–959.
- Banin, A. and Anderson, D. (1974). Effects of salt concentration during freezing on the unfrozen content of porous materials. *Water Resources Research*, 10:124–128.
- Basso, B., Amato, M., Bitella, G., Rossi, R., Kravchenko, A., Sartori, L., Carvahlo, L. M., and Gomes, J. (2010). Two-Dimensional Spatial and Temporal Variation of Soil Physical Properties in Tillage Systems Using Electrical Resistivity Tomography. *Agronomy journal*, 102:440–449.
- Bedmar, F., Costa, L., and Gime, D. (2008). Column tracer studies in surface and subsurface. *Soil Science*, 173(4).
- Beff, L., Günther, T., Vandoorne, B., Couvreur, V., and Javaux, M. (2013). Three-dimensional monitoring of soil water content in a maize field using Electrical Resistivity Tomography. *Hydrology and Earth System Sciences*, 17(2):595–609.
- Besson, A., Javaux, M., Biolders, C. L., and Vanclooster, M. (2011). Impact of tillage on solute transport in a loamy soil from leaching experiments. *Soil and Tillage Research*, 112(1):47–57.
- Beyer, L., Wachendorf, C., Balzer, F., and Balzer-Graf, U. (1992). The effect of soil texture and soil-management on microbial biomass and soil enzyme-activities in arable soils of northwest germany. *AGRIBIOLOGICAL RESEARCH-ZEITSCHRIFT FUR AGRAR-BIOLOGIE AGRIKULTURCHEMIE OKOLOGIE*, 45:276–283.

- Bhaduri, D. and Purakayastha, T. (2014). Long-term tillage, water and nutrient management in rice– wheat cropping system: Assessment and response of soil quality. *Soil and Tillage Research*, 144:83–95.
- Binley, A. (1995). Regularised Image Reconstruction of Noisy Electrical Resistance Data. *Proceedings of the 4th Workshop of the European Concerted Action on Process Tomography*, pages 401–410.
- Binley, A. (2018a). *R2 software*. <http://www.es.lancs.ac.uk/people/amb/Freeware/R2/R2.htm> [Accessed: 18/01/2019].
- Binley, A. (2018b). *R3 software*. <http://www.es.lancs.ac.uk/people/amb/Freeware/R3t/R3t.htm> [Accessed: 18/01/2019].
- Binley, A., Shaw, B., and Henry-Poulter, S. (1996). Flow pathways in porous media : electrical resistance tomography and dye staining image verification. *Measurement Science and Technology*, 7:384–390.
- Biran, I. and Eliassaf, A. (1980). The effect of container shape on the development of roots and canopy of woody plants. *Scientia Horticulturae*, 12(2):183–193.
- Boaga, J., D’Alpaos, A., Cassiani, G., Marani, M., and Putti, M. (2014). Plant-Soil interactions in salt marsh environments: Experimental evidence from electrical resistivity tomography in the Venice Lagoon. *Geophysical Research Letters*, 41(17):6160–6166.
- Boaga, J., Rossi, M., and Cassiani, G. (2013). Monitoring Soil-plant Interactions in an Apple Orchard Using 3D Electrical Resistivity Tomography. *Procedia Environmental Sciences*, 19:394–402.
- Bouma, J., Dekker, L., and Muilwijk, C. (1981). A field method for measuring short-circuiting in clay soils. *Journal of Hydrology*, 52:347–354.
- Brillante, L. (2016). Electrical imaging of soil water availability to grapevine : a benchmark experiment of several machine-learning techniques. *Precision Agriculture*, 17:637–658.
- Brillante, L., Bois, B., Lévêque, J., and Mathieu, O. (2016). Variations in soil-water use by grapevine according to plant water status and soil physical-chemical characteristics-A 3D spatio-temporal analysis. *European Journal of Agronomy*, 77:122–135.

- Brillante, L., Bois, B., Mathieu, O., Bichet, V., Michot, D., and Lévêque, J. (2014). Monitoring soil volume wetness in heterogeneous soils by electrical resistivity . A field-based pedotransfer function. *Journal of Hydrology*, 516:56–66.
- Brogi, C., Huisman, J. A., Pätzold, S., von Hebel, C., Weihermüller, L., Kaufmann, M. S., van der Kruk, J., and Vereecken, H. (2019). Large-scale soil mapping using multi-configuration EMI and supervised image classification. *Geoderma*, 335(September 2017):133–148.
- Brunet, P., Clément, R., and C., B. (2010). Monitoring soil water content and deficit using electrical resistivity tomography (ert) – a case study in the cevennes area, france. *Journal of Hydrology*, 380:146–153.
- Burger, R., Craig, J., and Sheehan, A. (2006). *Introduction to Applied Geophysics: Exploring the shallow subsurface*. W.W.Norton and Company.
- Campbel, R., Bower, C., and Richard, L. (1948). Change in electrical conductivity with temperature and the relation with osmotic pressure to electrical conductivity and ion concentration for soil extracts. *Soil Science Society of America*, 13:33–69.
- Cao, Y., Repo, T., Silvennoinen, R., Lehto, T., and Pelkonen, P. (2010). An appraisal of the electrical resistance method for assessing root surface area. *Journal of Experimental Botany*, 61(9):2491–2497.
- Cao, Y., Repo, T., Silvennoinen, R., Lehto, T., and Pelkonen, P. (2011). Analysis of the willow root system by electrical impedance spectroscopy. *Journal of Experimental Botany*, 62(1):351–358.
- Cassiani, G., Boaga, J., Rossi, M., Putti, M., Fadda, G., Majone, B., and Bellin, A. (2016). Soil-plant interaction monitoring: Small scale example of an apple orchard in Trentino, North-Eastern Italy. *Science of the Total Environment*, 543:851–861.
- Cassiani, G., Boaga, J., Vanella, D., Perri, M. T., and Consoli, S. (2015). Monitoring and modelling of soil-plant interactions: The joint use of ERT, sap flow and eddy covariance data to characterize the volume of an orange tree root zone. *Hydrology and Earth System Sciences*, 19(5):2213–2225.

- Cassiani, G., Kemna, A., Cassiani, G., Kemna, A., Villa, A., and Zimmermann, E. (2009). Spectral induced polarization for the characterization of free-phase hydrocarbon contamination of sediments with low clay content. *Near Surface Geophysics*, 7:547–562.
- Cassiani, G., Ursino, N., Deiana, R., Vignoli, G., Boaga, J., Rossi, M., Perri, M. T., Blaschek, M., Duttman, R., Meyer, S., Ludwig, R., Soddu, A., Dietrich, P., and Werban, U. (2012). Noninvasive Monitoring of Soil Static Characteristics and Dynamic States: A Case Study Highlighting Vegetation Effects on Agricultural Land. *Vadose Zone Journal*, 11(3).
- Cavé, L., Al, T., Xiang, Y., and Vilks, P. (2009). A technique for estimating one-dimensional diffusion coefficients in low-permeability sedimentary rock using X-ray radiography: Comparison with through-diffusion measurements. *Journal of Contaminant Hydrology*, 103(1-2):1–12.
- Celano, G., Palese, A., Tuzio, A., Zuardi, D., L., L., and C., X. (2010). Geo-electrical survey on the soil of an apricot orchard grown under semi-arid conditions. *Acta Horticulturae*, 862:425–428.
- Celano, G., Palese, A. M., Ciucci, A., Martorella, E., Vignozzi, N., and Xiloyannis, C. (2011). Evaluation of soil water content in tilled and cover-cropped olive orchards by the geoelectrical technique. *Geoderma*, 163(3-4):163–170.
- Čermák, J., Ulrich, R., Staněk, Z., Koller, J., and Aubrecht, L. (2006). Electrical measurement of tree root absorbing surfaces by the earth impedance method: 2. Verification based on allometric relationships and root severing experiments. *Tree Physiology*, 26(9):1113–1121.
- Chambers, J. E., Gunn, D. A., Wilkinson, P. B., Meldrum, P. I., Haslam, E., Holyoake, S., Kirkham, M., Kuras, O., Merritt, A., and Wragg, J. (2014). 4D electrical resistivity tomography monitoring of soil moisture dynamics in an operational railway embankment. *Near Surface Geophysics*, 12(1):61–72.
- Chaves, M. M., Pereira, J. S., Maroco, J., Rodrigues, M. L., Ricardo, C. P., Osório, M. L., Carvalho, I., Faria, T., and Pinheiro, C. (2002). How plants cope with water stress in the field. Photosynthesis and growth. *Annals of Botany*, 89(SPEC. ISS.):907–916.
- Chloupek, O. (1972). The relationship between electric capacitance and some other parameters of plant roots. *Biologia Plantarum*, 14:227–230.

- Cole, K. S. and Cole, R. H. (1941). Dispersion and Absorption in Dielectrics . *J. Chem. Phys.*, 9(1913):98–105.
- Consoli, S., Stagno, F., Vanella, D., Boaga, J., Cassiani, G., and Roccuzzo, G. (2017). Partial root-zone drying irrigation in orange orchards: Effects on water use and crop production characteristics. *European Journal of Agronomy*, 82:190–202.
- Cseresnyés, I., Fekete, G., Végh, K. R., Székács, A., Mörtl, M., and Rajkai, K. (2012). Monitoring of herbicide effect in maize based on electrical measurements. *International Agrophysics*, 26:243–247.
- Cseresnyés, I., Szitár, K., Rajkai, K., Füzy, A., and Mikó, P. (2018). Application of Electrical Capacitance Method for Prediction of Plant Root Mass and Activity in Field-Grown Crops. *Frontiers in Plant Science*, 9(February):1–11.
- Cseresnyés, I., Takács, T., Végh, K. R., Anton, A., and Rajkai, K. (2013). European Journal of Soil Biology Electrical impedance and capacitance method : A new approach for detection of functional aspects of arbuscular mycorrhizal colonization in maize. *European Journal of Soil Biology*, 54:25–31.
- Dahlin, T. and Zhou, B. (2004). A numerical comparison of 2D resistivity imaging with 10 electrode arrays. *Geophysical Prospecting*, 52(5):379–398.
- Daily, W., Ramirez, A., Binley, A., and LaBrecque, D. (2005). 17. Electrical Resistance Tomography—Theory and Practice. *Soc. Exploration Geophysics: Near-Surface Geophysics (Investigation in Geophysics No. 13)*, pages 525–550.
- Dalton, F. (1995). In-situ root extent measurements by electrical capacitance methods. *Plant and Soil*, 173:157–165.
- Davidson, E. A., Belk, E., and Boone, R. D. (1998). Soil water content and temperature as independent or confounded factors controlling soil respiration in a temperate mixed hardwood forest. *Global Change Biology*, 4(2):217–227.
- Debye, P. (1929). Polar molecules. *New York: Chemical Catalogue Co.*, page 172.
- Denison, C., Carlson, W., and Ketcham, R. (1997). Three- dimensional quantitative textural analysis of metamorphic rocks using high-resolution computed x-ray tomography: Part i. methods and techniques. *Journal of Metamorphic Geology*, 15:45–57.

- Denmead, O. T. (1961). *Availability of soil water to plants*. Iowa State University.
- Dietrich, R. C., Bengougha, A. G., Jones, H. G., and White, P. J. (2012). A new physical interpretation of plant-root capacitance. *Journal of Experimental Botany*, 63:6149–6159.
- Doube, M., Klosowski, M. M., Arganda-carreras, I., and Fabrice, P. (2010). UKPMC Funders Group BoneJ : free and extensible bone image analysis in ImageJ. *Bone*, 47(6):1076–1079.
- Draye, X., Kim, Y., Lobet, G., and Javaux, M. (2010). Model-assisted integration of physiological and environmental constraints affecting the dynamic and spatial patterns of root water uptake from soils. *Journal of Experimental Botany*, 61(8):2145–2155.
- du Plessis, A., Broeckhoven, C., Guelpa, A., and le Roux, S. G. (2017). Laboratory x-ray micro-computed tomography: A user guideline for biological samples. *GigaScience*, 6(6):1–11.
- Duliu, O. (1999). Computer axial tomography in geosciences: an overview. *Earth Science Reviews*, 48:265–281.
- Ehosioke, S., Garré, S., Kremer, T., Kemna, A., Huisman, A. J., Zimmermann, E., Javaux, M., and Nguyen, F. (2018). A new method for characterizing the complex electrical properties of root segments. *ISRR 10th International Symposium "Exposing The Hidden Half - Roots Research at the Forefront of Science", Yearim Hotel, Israel*.
- Ellis, T., Murray, W., and Kavalieris, L. (2013). Electrical capacitance of bean (*Vicia faba*) root systems was related to tissue density-a test for the Dalton Model. *Plant and Soil*, 366(1-2):575–584.
- Everett, M. E. (2013). *Near-surface applied geophysics*. Cambridge University Press.
- Farzamian, M., Monteiro, F. A., and Khalil, M. A. (2015). Application of EM38 and ERT methods in estimation of saturated hydraulic conductivity in unsaturated soil. *Journal of Applied Geophysics*, 112:175–189.
- Francis, G. S. and Knight, T. L. (1993). Long-term effects of conventional and no-tillage on selected soil properties and crop yields in Canterbury, New Zealand. *Soil and Tillage Research*, 26(3):193–210.

- Free, E. E. (1911). Studies in soil physics ii, the movements of soil water. *The Plant World*, 14:59–66.
- Fukue, M., Minato, T., Horibe, H., and Taya, N. (1999). The micro-structures of clay given by resistivity measurements. *Engineering Geology*, 54:43–53.
- Furman, A., Arnon-Zur, A., and Assouline, S. (2013). Electrical resistivity tomography of the root zone. In *Soil-Water-Root Processes: Advances in Tomography and Imaging*, pages 223–245. SSSA Special Publications.
- Garré, S., Coteur, I., Wongleecharoen, C., Kongkaew, T., Diels, J., Vanderborght, J., and Province, R. (2013). Noninvasive Monitoring of Soil Water Dynamics in Mixed Cropping Systems : A Case Study in Ratchaburi Province, Thailand. *Vadose zone journal*, 12:1–12.
- Garré, S., Günther, T., Diels, J., and Vanderborght, J. (2012). Evaluating Experimental Design of ERT for Soil Moisture Monitoring in Contour Hedgerow Intercropping Systems. *Vadose zone journal*, 11:1–14.
- Garré, S., Javaux, M., Vanderborght, J., Pagès, L., and Vereecken, H. (2011). Three-Dimensional Electrical Resistivity Tomography to Monitor Root Zone Water Dynamics. *Vadose Zone Journal*, 10(1):412–424.
- Garré, S., Nguyen, F., and Cornelis, J.-T. (2014). *CHAR project*. <https://www.gembloux.ulg.ac.be/echanges-eau-sol-plante/recherche/garre/char/> [Accessed: 04/02/2020].
- Germann, P., Edwards, W., and Owens, L. (1984). Profiles of bromide and increased soil moisture after infiltration into soils with macropores. *Soil Sci. Soc. Am. J.*, 48:237–244.
- Glaser, B., Wiedner, K., Seelig, S., Schmidt, H. P., and Gerber, H. (2015). Biochar organic fertilizers from natural resources as substitute for mineral fertilizers. *Agronomy for Sustainable Development*, 35(2):667–678.
- Gomez, J., Giraldez, J. V., Pastor, M., and Fereres, E. (1999). Effects of tillage method on soil physical properties , infiltration and yield in an olive orchard. *Soil and Tillage Research*, 52:167–175.

- Grayling, K. (2015). *PhD Thesis: Imaging the flow paths of solutes and suspensions in soil using X-ray Computed Tomography*. University of Nottingham.
- Grayling, K. M., Young, S. D., Roberts, C. J., de Heer, M. I., Shirley, I. M., Sturrock, C. J., and Mooney, S. J. (2018). The application of x-ray micro computed tomography imaging for tracing particle movement in soil. *Geoderma*, 321(September 2017):8–14.
- Green, S. R., Kirkham, M. B., and Clothier, B. E. (2006). Root uptake and transpiration: From measurements and models to sustainable irrigation. *Agricultural Water Management*, 86(1-2):165–176.
- Günther, T., Rucker, C., and Spitzer, K. (2006). Three-dimensional modelling and inversion of dc resistivity data incorporating topography – ii. *Geophysical journal international*, 166:506–517.
- Guyot, A., Ostergaard, K. T., Lenkopane, M., Fan, J., and Lockington, D. A. (2013). Using electrical resistivity tomography to differentiate sapwood from heartwood : application to conifers. *Tree Physiology*, 33:187–194.
- Hamza, M. A. and Anderson, W. K. (2005). Soil compaction in cropping systems: A review of the nature, causes and possible solutions. *Soil and Tillage Research*, 82(2):121–145.
- Hardy, B., Cornelis, J.-T., Houben, D., Lambert, R., and Dufey, J. (2016). The effect of pre-industrial charcoal kilns on chemical properties of forest soil of Wallonia , Belgium. *European journal of Soil Science*, 67:206–216.
- Hayley, K., Bentley, L. R., Gharibi, M., and Nightingale, M. (2007). Low temperature dependence of electrical resistivity: Implications for near surface geophysical monitoring. *Geophysical Research Letters*, 34(18):1–5.
- Haynes, R. and Beare, M. H. (1997). Influence Stability of Six Crop Species on Aggregate and Some Labile Organic Matter Fractions. *Science*, 29(1):1647–1653.
- Heijs, A. W., Ritsema, C. J., and Dekker, L. W. (1996). Three-dimensional visualization of preferential flow patterns in two soils. *Geoderma*, 70(2-4):101–116.
- Helgason, B. L., Walley, F. L., and Germida, J. J. (2010). No-till soil management increases microbial biomass and alters community profiles in soil aggregates. *Applied Soil Ecology*, 46(3):390–397.

- Hill, K., Porco, S., Lobet, G., Zappala, S., Mooney, S., Draye, X., and Bennett, M. J. (2013). Root Systems Biology : Integrative Modeling across Scales , from Gene Regulatory Networks to the Rhizosphere. *Plant Physiology*, 163:1487–1503.
- Hounsfield, G. (1973). Computed transverse axial scanning (tomography).part i.description of system. *British Journal of Radiology*, 46:1016–1022.
- Hunt, A., Ewing, R., and Ghanbarian, B. (2014). Percolation theory for flow in porous media. lecture notes in physics 880. *Heidelberg, Germany:Springer-Verlag*.
- Jarvis, N., Larsbo, M., and Koestel, J. (2017). Geoderma Connectivity and percolation of structural pore networks in a cultivated silt loam soil quantified by X-ray tomography. *Geoderma*, 287:71–79.
- Javaux, M., Couvreur, V., Vanderborght, J., and Vereecken, H. (2013). Root Water Uptake : From Three-Dimensional Biophysical Processes to Macroscopic Modeling Approaches. *Vadose Zone Journal*, 12:1–16.
- Javaux, M., Schroeder, T., Vanderborght, J., and Vereecken, H. (2008). Use of a Three-Dimensional Detailed Modeling Approach for Predicting Root Water Uptake. *Vadose Zone Journal*, 7(3):1079–1088.
- Javaux, M. and Vanclooster, M. (2003). Scale- and Rate-Dependent Solute Transport within an Unsaturated Sandy Monolith. *Soil Science Society of America Journal*, 67(May 2002):1334–1343.
- Jaynes, D. B., Logsdon, S. D., and Horton, R. (1995). Field Method for Measuring Mobile/Immobile Water Content and Solute Transfer Rate Coefficient. *Soil Science Society of America Journal*, 59(2):352–356.
- Johnson, T., Versteeg, R., Ward, A., Day-Lewis, F., and Revil, A. (2010). Improved hydrogeophysical characterization and monitoring through parallel modeling and inversion of time-domain resistivity and induced polarization data. *Geophysics*, 75(4):27–41.
- Jones, G. M., Cassidy, N. J., Thomas, P. A., Plante, S., and Pringle, J. K. (2009). Imaging and monitoring tree-induced subsidence using electrical resistivity imaging. *Near Surface Geophysics*, 7(3):191–206.

- Katz, A. and Thompson, A. (1987). Prediction of rock electrical conductivity from mercury injection measurements. *Journal of Geophysical Research*, 92(B1):599–607.
- Kelly, B. F., Acworth, R. I., and Greve, A. K. (2011). Better placement of soil moisture point measurements guided by 2D resistivity tomography for improved irrigation scheduling. *Soil Research*, 49(6):504–512.
- Kelter, M., Huisman, J. A., Zimmermann, E., Kemna, A., and Vereecken, H. (2015). Quantitative imaging of spectral electrical properties of variably saturated soil columns. *Journal of Applied Geophysics*, 123:333–344.
- Kemna, A. (2000). *PhD Thesis: Tomographic inversion of complex resistivity – theory and application*. Ruhr-Universität Bochum.
- Kemna, A., Kulessa, B., and Vereecken, H. (2002). Imaging and characterisation of subsurface solute transport using electrical resistivity tomography (ERT) and equivalent transport models. *Journal of Hydrology*, 267(3-4):125–146.
- Kerré, B., Willaert, B., Cornelis, Y., and Smolders, E. (2017). Long-term presence of charcoal increases maize yield in Belgium due to increased soil water availability. *European Journal of Agronomy*, 91(April):10–15.
- Kim, J. H., Yi, M. J., Park, S. G., and Kim, J. G. (2009). 4-D inversion of DC resistivity monitoring data acquired over a dynamically changing earth model. *Journal of Applied Geophysics*, 68(4):522–532.
- Koch, A., Meunier, F., Vanderborght, J., Garré, S., Pohlmeier, A., and Javaux, M. (2019). Functional-structural root-system model validation using a soil MRI experiment. *Journal of Experimental Botany*, 70(10):2797–2809.
- Koestel, J., Dathe, A., Skaggs, T. H., Klakegg, O., Ahmad, M. A., Babko, M., Giménez, D., Farkas, C., Nemes, A., and Jarvis, N. (2018). Estimating the Permeability of Naturally Structured Soil From Percolation Theory and Pore Space Characteristics Imaged by X-Ray. *Water Resources Research*, 54(11):9255–9263.
- Koestel, J., Kasteel, R., Esser, O., Kemna, A., Javaux, M., and Binley, A. (2007). Imaging brilliant blue stained soil by means of electrical resistivity tomography. *Vadose Zone Journal*, 8:963–975.

- Koestel, J., Kemna, A., Javaux, M., Binley, A., and Vereecken, H. (2008). Quantitative imaging of solute transport in an unsaturated and undisturbed soil monolith with 3-D ERT and TDR. *Water Resources Research*, 44:1–17.
- Koestel, J. and Larsbo, M. (2014). Imaging and quantification of preferential solute transport in soil macropores. *Water Resources Research*, 50:4357–4378.
- Kowalczyk, S., Zawrzykraj, P., and Mieszkowski, R. (2015). Application of electrical resistivity tomography in assessing complex soil conditions. *Geological Quarterly*, 59(2):367–372.
- LaBrecque, D. and Yang, X. (2000). Difference inversion of ert data: a fast inversion method for 3-d in-situ monitoring. *13th EEGS Symposium on the Application of Geophysics to Engineering and Environmental Problems*, pages 723–732.
- LaBrecque, J., Miletto, M., Daily, W., Ramirez, A., and Owen, E. (1996). The effects of noise on occam’s inversion of resistivity tomography data. *Geophysics*, 61(2):538–548.
- Laloy, E., Javaux, M., Vanclooster, M., Roisin, C., and Bielders, C. L. (2011). Electrical Resistivity in a Loamy Soil: Identification of the Appropriate Pedo-Electrical Model. *Vadose Zone Journal*, 10(3):1023–1033.
- Larney, F. J., Lindwall, C. W., Izaurralde, R. C., and Moulin, A. P. (1994). *M. R. Carter, ed. Conservation tillage in temperate agroecosystems*. CRC Press, Boca Raton, FL.
- Latrille, C. and Néel, M. C. (2013). Transport study in unsaturated porous media by tracer experiment in a dichromatic X-ray experimental device. *EPJ Web of Conferences*, 50.
- Lesparre, N., Nguyen, F., Kemna, A., Robert, T., Hermans, T., Daoudi, M., and Flores-Orozco, A. (2017). A new approach for time-lapse data weighting in electrical resistivity tomography. *Geophysics*, 82:E325–E333.
- Leucci, G. (2010). The use of three geophysical methods for 3d images of total root volume of soil in urban environments. *Exploration Geophysics*, 41:268–278.
- Lewis, J. and Sjostrom, J. (2010). Optimizing the experimental design of soil columns in saturated and unsaturated transport experiments. *Journal of Contaminant Hydrology*, 115(1-4):1–13.

- Linde, N., Binley, A., Tryggvason, A., Pedersen, L. B., and Revil, A. (2006). Improved hydrogeophysical characterization using joint inversion of cross-hole electrical resistance and ground-penetrating radar traveltime data. *Water Resources Research*, 42(12):1–16.
- Lipiec, J., Kus, J., Slowinska-Jurkiewicz, A., and Nosalewicz, A. (2006). Soil porosity and water infiltration as influenced by tillage methods. *Soil and Tillage Research*, 89:210–220.
- Liu, J., Schulz, H., Brandl, S., Miehtke, H., Huwe, B., and Glaser, B. (2012). Short-term effect of biochar and compost on soil fertility and water status of a Dystric Cambisol in NE Germany under field conditions. *Journal of Plant Nutrition and Soil Science*, 175(5):698–707.
- Loke, M. (2018a). *Res2DInv software*. <https://www.geotomosoft.com/products.php#3D> [Accessed: 18/01/2019].
- Loke, M. (2018b). *Res3DInv software*. <https://www.geotomosoft.com/products.php#3D> [Accessed: 18/01/2019].
- Loke, M. and Barker, R. (1995). Least-squares deconvolution of apparent resistivity pseudo-sections. *Geophysics*, 60(6):1682–1690.
- Loke, M. H., Chambers, J. E., Rucker, D. F., Kuras, O., and Wilkinson, P. B. (2013). Recent developments in the direct-current geoelectrical imaging method. *Journal of Applied Geophysics*, 95:135–156.
- Loke, M. H., Wilkinson, P. B., Dahlin, T., Chambers, J. E., Uhlemann, S., and Dijkstra, T. (2019). Time-lapse 4-D resistivity imaging inversion with positivity constraints. *24th European Meeting of Environmental and Engineering Geophysics*, pages 2–7.
- Lu, H.-l., Liu, Z.-d., Zhou, Q., and Xu, R.-k. (2018). Zeta potential of roots determined by the streaming potential method in relation to their Mn (II) sorption in 17 crops. *Plant and Soil*, 428:241–251.
- Luo, L. and Lin, H. (2009). Lacunarity and fractal analyses of soil macropores and preferential transport using micro-X-ray computed tomography. *Vadose Zone Journal*, 8(1):233–241.
- Lyklema, J., Duhkin, S., and Shilov, D. (1983). The relaxation of the double-layer around colloidal particles and the low-frequency dielectric-dispersion .1. theoretical considerations. *Journal of Electroanalytical Chemistry*, 1-2:1–21.

- Mahboubi, A., Lal, R., and Faussey, N. (1993). 28 years of tillage effects on two soils in ohio. *Soil Science Society of America Journal*, 99:232–244.
- Mairhofer, S., Johnson, J., Sturrock, C. J., Bennett, M. J., Mooney, S. J., and Pridmore, T. P. (2016). Visual tracking for the recovery of multiple interacting plant root systems from X-ray μ CT images. *Machine Vision and Applications*, 27(5):721–734.
- Major, J., Rondon, M., Molina, D., Riha, S. J., and Lehmann, J. (2010). Maize yield and nutrition during 4 years after biochar application to a Colombian savanna oxisol. *Plant and Soil*, 333(1):117–128.
- Mangalassery, S., Sjögersten, S., Sparkes, D. L., Sturrock, C. J., Craigon, J., and Mooney, S. J. (2014). To what extent can zero tillage lead to a reduction in greenhouse gas emissions from temperate soils? *Scientific Reports*, 4:1–8.
- Marani, M., Silvestri, S., Belluco, E., Ursino, N., Comerlati, A., Tosatto, O., and Putti, M. (2006). Spatial organization and ecohydrological interactions in oxygen-limited vegetation ecosystems. *Water Resources Research*, 42:1–12.
- Mares, R., Barnard, H. R., Mao, D., Revil, A., and Singha, K. (2016). Examining diel patterns of soil and xylem moisture using electrical resistivity imaging. *Journal of Hydrology*, 536:327–338.
- Marshall, D. J., Madden, T. R., The, A., February, E., and Associates, N. A. (1959). Induced polarization, a study of its causes,. *Geophysics*, 24(4):790–816.
- Marsili, A., Servadio, P., and Pargliai, M. Vignozzi, N. (1998). Changes of some physical properties of a clay soil following passage of rubber- and metal-tracked tractors. *Soil Tillage Research*, 49:185–199.
- Martin, T. (2012). Complex resistivity measurements on oak. *European Journal of Wood and Wood Products*, 70(1-3):45–53.
- Mary, B., Abdulsamad, F., Saracco, G., Peyras, L., Vennetier, M., Mériaux, P., and Camerlynck, C. (2017). Improvement of coarse root detection using time and frequency induced polarization: from laboratory to field experiments. *Plant and Soil*, 417(1-2):243–259.

- Mary, B., Peruzzo, L., Boaga, J., Schmutz, M., Wu, Y., Hubbard, S. S., and Cassiani, G. (2018). Small-scale characterization of vine plant root water uptake via 3-D electrical resistivity tomography and mise-à-la-masse method. *Hydrology and Earth System Sciences*, 22:5427–5444.
- Mary, B., Saracco, G., Peyras, L., Vennetier, M., Mériaux, P., and Camerlynck, C. (2016). Mapping tree root system in dikes using induced polarization: Focus on the influence of soil water content. *Journal of Applied Geophysics*, 135:387–396.
- Michot, D., Benderitter, Y., Dorigny, A., Nicoullaud, B., King, D., and Tabbagh, A. (2003). Spatial and temporal monitoring of soil water content with an irrigated corn crop cover using surface electrical resistivity tomography. *Water Resources Research*, 39(5):1–20.
- Michot, D., Dorigny, A., and Benderitter, Y. (2001). Mise en évidence par résistivité électrique des écoulements préférentiels et de l’assèchement par le maïs d’un calcaire de beauce irrigué. *Earth and Planetary Sciences*, 332:29–36.
- Mooney, S. J., Pridmore, T. P., Helliwell, J., and Bennett, M. J. (2012). Developing X-ray computed tomography to non-invasively image 3-D root systems architecture in soil. *Plant and Soil*, 352(1-2):1–22.
- Morari, F., Castrignanò, A., and Pagliarin, C. (2009). Application of multivariate geo-statistics in delineating management zones within a gravelly vineyard using geo-electrical sensors. *Computers and Electronics in Agriculture*, 68(1):97–107.
- Moreno, Z., Arnon-Zur, A., and Furman, A. (2015). Hydro-geophysical monitoring of orchard root zone dynamics in semi-arid region. *Irrigation Science*, 33(4):303–318.
- Mualem, Y. and Friedman, S. (1991). Theoretical Prediction of Electrical Conductivity in Saturated and Unsaturated soil. *Water Resources Research*, 27(10):2771–2777.
- Mueller, L., Kay, B. D., Hu, C., Li, Y., Schindler, U., Behrendt, A., Shepherd, T. G., and Ball, B. C. (2009). Visual assessment of soil structure: Evaluation of methodologies on sites in Canada, China and Germany Part I: Comparing visual methods and linking them with soil physical data and grain yield of cereals. *Soil and Tillage Research*, 103(1):178–187.

- Musgrave, H. and Binley, A. (2011). Revealing the temporal dynamics of subsurface temperature in a wetland using time-lapse geophysics. *Journal of Hydrology*, 396(3-4):258–266.
- Mwakanyamale, K., Slater, L., Binley, A., and Ntarlagiannis, D. (2012). Lithologic imaging using complex conductivity: Lessons learned from the Hanford 300 Area. *Geophysics*, 77(6):E397–E409.
- Newill, P., Karadaglı C, D., Podd, F., Grieve, B. D., and York, T. A. (2014). Electrical impedance imaging of water distribution in the root zone. *Measurement Science and Technology*, 25(055110).
- Nijland, W., van der Meijde, M., Addink, E., and de Jong, S. (2010). Detection of soil moisture and vegetation water abstraction in a mediterranean natural area using electrical resistivity tomography. *Catena*, 81(3):209–216.
- Nyberg, L. (1996). Spatial variability of soil water content in the covered catchment at Gardsjon, Sweden. *Hydrological Processes*, 10(October 1994):89–103.
- Olsen, P. A., Binley, A., and Tych, W. (1999). Characterizing solute transport in undisturbed soil cores using electrical and X-ray tomographic methods. *Hydrological Processes*, 13:211–221.
- Otsu, N. (1979). A threshold selection method from gray-level histograms. *IEEE Transactions on Systems, Man, and Cybernetics*, 9(1):62–66.
- Ozier-lafontaine, H. and Bajazet, T. (2005). Analysis of Root Growth by Impedance Spectroscopy (EIS) Analysis of root growth by impedance spectroscopy (EIS). *Plant and Soil*, 255(December):299–313.
- Panissod, C., Michot, D., Benderitter, Y., and Tabbagh, A. (2001). On the effectiveness of 2D electrical inversion results: An agricultural case study. *Geophysical Prospecting*, 49(5):570–576.
- Paradelo, M., Katuwal, S., Moldrup, P., Norgaard, T., Herath, L., and de Jonge, L. W. (2016). X-ray CT-Derived Soil Characteristics Explain Varying Air, Water, and Solute Transport Properties across a Loamy Field. *Vadose Zone Journal*, 15(4):1–13.

- Pelton, W., Ward, S., Hallof, P., Sill, W., and PH, N. (1978). Mineral discrimination and removal of inductive coupling with multifrequency ip. *Geophysics*, 43:588–609.
- Pennell, K. D. (2016). *Reference Module in Earth Systems and Environmental Sciences*. Elsevier.
- Peyton, R. L., Haeffner, B. A., Anderson, S. H., and Gantzer, C. J. (1992). Applying X-ray CT to measure macropore diameters in undisturbed soil cores. *Geoderma*, 53(3-4):329–340.
- Postma, J. A., Kuppe, C., Owen, M. R., Mellor, N., Griffiths, M., Bennett, M. J., Lynch, J. P., and Watt, M. (2017). OpenSimRoot: widening the scope and application of root architectural models. *New Phytologist*, 215:1274–1286.
- Pound, M. P., Atkinson, J. A., Townsend, A. J., Wilson, M. H., Griffiths, M., Jackson, A. S., Bulat, A., Tzimiropoulos, G., Wells, D. M., Murchie, E. H., Pridmore, T. P., and French, A. P. (2017). Deep machine learning provides state-of-the-art performance in image-based plant phenotyping. *GigaScience*, 6(10):1–10.
- Rao, S., Meunier, F., Ehosioka, S., Lesparre, N., Kemna, A., Nguyen, F., Garré, S., and Javaux, M. (2018). A mechanistic model for electrical conduction in soil-root continuum: a virtual rhizotron study. *Biogeosciences Discussions*.
- Revil, A. (1999). Ionic diffusivity, electrical conductivity, membrane and thermoelectric potentials in colloids and granular porous media: A unified model. *Journal of Colloid and Interface Science*, 212:503–522.
- Revil, A., Cathles, L. M., Losh, S., and Nunn, J. a. (1998). Electrical conductivity in shaly sands with geophysical applications. *Journal of Geophysical Research*, 103:23925–23936.
- Revil, A. and Glover, P. (1997). Theory of ionic-surface electrical conduction in porous media. *Physical Review B - Condensed Matter and Materials Physics*, 55(3):1757–1773.
- Rhoades, J., Manteghi, N., Shouse, P., and Alves, W. (1989). Soil electrical conductivity and soil salinity: new formulations and calibrations. *Soil Science Society of America*, 53:433–439.
- Richards, L. (1931). Capillary conduction of liquids through porous mediums. *Physics*, 1:318–333.

- Robinson, J. L., Slater, L. D., and Schäfer, K. V. (2012). Evidence for spatial variability in hydraulic redistribution within an oak-pine forest from resistivity imaging. *Journal of Hydrology*, 430-431:69–79.
- Romero-Ruiz, A., Linde, N., Keller, T., and Or, D. (2018). A Review of Geophysical Methods for Soil Structure Characterization. *Reviews of Geophysics*, 56(4):672–697.
- Rossi, R., Amato, M., Bitella, G., Bochicchio, R., Ferreira Gomes, J. J., Lovelli, S., Martorella, E., and Favale, P. (2011). Electrical resistivity tomography as a non-destructive method for mapping root biomass in an orchard. *European Journal of Soil Science*, 62(2):206–215.
- Rossi, R., Amato, M., Pollice, A., Bitella, G., Gomes, J. J., Bochicchio, R., and Baronti, S. (2013). Electrical resistivity tomography to detect the effects of tillage in a soil with a variable rock fragment content. *European Journal of Soil Science*, 64(2):239–248.
- Sabo, D., McMurray, G., and Rains, G. (2016a). Presymptomatic Disease Detection and Nanoparticle-Enhanced Electrical Capacitance Tomography. *IFAC-PapersOnLine*, 49(16):116–120.
- Sabo, D., McMurray, G., and Rains, G. (2016b). Root monitoring system using electrical capacitance tomography (ect) for pre-symptomatic disease detection. *ASABE Annual International Meeting*.
- Samouëlian, A., Cousin, I., Richard, G., Tabbagh, A., and Bruand, A. (2003). Electrical resistivity imaging for detecting soil cracking at the centimeter scale. *Soil Science Society of America Journal*, 67(4):1319–1326.
- Samouëlian, A., Cousin, I., Tabbagh, A., Bruand, A., and Richard, G. (2005). Electrical resistivity survey in soil science : a review. *Soil and Tillage Research*, 83:173–193.
- Schindelin, J., Arganda-Carreras, I., Frise, E., Kaynig, V., Longair, and M., Pietzsch, T. (2012). Fiji: An open source platform for biological image analysis. *nature methods*. *Nature Methods*, 9:676–682.
- Schnepf, A., Leitner, D., Landl, M., Lobet, G., Hieu, T., Morandage, S., Sheng, C., Zörner, M., and Vanderborght, J. (2017). CRootBox : A structural-functional modelling framework for root systems. *Annals of Botany*, 121(5):1033–1053.

- Schwan, H. (1957). Electrical properties of tissue and cell suspensions. *Advances in Biological and Medical Physics*, 5:147–209.
- Schwartz, N. and Furman, A. (2015). On the spectral induced polarization signature of soil organic matter. *Geophysical journal international*, 200:589–595.
- Segal, E., Kushnir, T., Mualem, Y., and Shani, U. (2008). Water Uptake and Hydraulics of the Root Hair Rhizosphere. *Vadose Zone Journal*, 7(3):1027–1034.
- Séger, M., Cousin, I., Frison, A., Boizard, H., and Richard, G. (2009). Characterisation of the structural heterogeneity of the soil tilled layer by using in situ 2D and 3D electrical resistivity measurements. *Soil and Tillage Research*, 103(2):387–398.
- Shokri, N., Lehmann, P., Vontobel, P., and Or, D. (2008). Drying front and water content dynamics during evaporation from sand delineated by neutron radiography. *Water Resources Research*, 44(6):1–11.
- Slater, L., Binley, A., Versteeg, R., Cassiani, G., Birken, R., and Sandberg, S. (2002). A 3D ERT study of solute transport in a large experimental tank. *Journal of Applied Geophysics*, 49(4):211–229.
- Soracco, C. G., Lozano, L. A., Balbuena, R., and Manuel, J. (2012). Contribution of macroporosity to water flux of a soil under different tillage systems . *R. Bras. Ci. Solo*, 36:1149–1155.
- Sparling, G. P. and West, A. W. (1989). Importance of soil water content when estimating soil microbial C, N and P by the fumigation-extraction methods. *Soil Biology and Biochemistry*, 21(2):245–253.
- Srayeddin, I. and Doussan, C. (2009). Estimation of the spatial variability of root water uptake of maize and sorghum at the field scale by electrical resistivity tomography. *Plant and Soil*, 319(1-2):185–207.
- Steenhuis, T., Staubitz, W., Andreini, M., Surface, J., Richards, T., Paulsen, R., Pickering, N., Hagerman, J., and Geohring, L. (1990). Preferential movement of pesticides and tracers in agricultural soils. *Journal of irrigation and drainage engineering*, 116:50–66.

- Strudley, M. W., Green, T. R., and Ascough, J. C. (2008). Tillage effects on soil hydraulic properties in space and time: State of the science. *Soil and Tillage Research*, 99(1):4–48.
- Sun, F. and Lu, S. (2014). Biochars improve aggregate stability, water retention, and pore-space properties of clayey soil. *Journal of Plant Nutrition and Soil Science*, 177:26–33.
- Taina, I., Heck, R. J., and Elliot, T. R. (2008). Application of X-ray computed tomography to soil science: A literature review. *Canadian Journal of Soil Science*, 88:1–19.
- Topp, G., Davis, J., and Annan, A. (1980). Electromagnetic determination of soil water content: Measurements in coaxial transmission lines. *Water Resources Research*, 14:574–582.
- Tosatto, O., Belluco, E., Silvestri, S., Ursino, N., Comerlati, A., Putti, M., and Marani, M. (2009). Reply to comment by L . R . Gardner on “ Spatial organization and ecohydrological interactions in oxygen-limited vegetation ecosystems ”. *Water Resources Journal*, 45:2–5.
- Tracy, S. R., Daly, K. R., Sturrock, C. J., Crout, N. M. J., Mooney, S. J., and Roose, T. (2015). Three-dimensional quantification of soil hydraulic properties using X-ray Computed Tomography and image-based modelling. *Water Resources Research*, 51(2):1006–1022.
- Triantafilis, J., Kerridge, B., and Buchanan, S. M. (2009). Digital soil-class mapping from proximal and remotely sensed data at the field level. *Agronomy Journal*, 101(4):841–853.
- Tsourlos, P. I., Szymanski, J. E., and Tsokas, G. N. (1999). The effect of terrain topography on commonly used resistivity arrays. *Geophysics*, 64.
- Tsukanov, K. and Schwartz, N. (2020). Relationship between wheat root properties and its electrical signature using the spectral induced polarization method. *Vadose zone journal*, pages 1–12.
- Uhlemann, S., Chambers, J., Wilkinson, P., Maurer, H., Merritt, A., Meldrum, P., Kuras, O., Gunn, D., Smith, A., and Dijkstra, T. (2017). Four-dimensional imaging of moisture dynamics during landslide reactivation. *Journal of Geophysical Research: Earth Surface*, 122(1):398–418.

- Ursino, N., Cassiani, G., Deiana, R., Vignoli, G., and Boaga, J. (2014). Measuring and modeling water-related soil-vegetation feedbacks in a fallow plot. *Hydrology and Earth System Sciences*, 18(3):1105–1118.
- van Genuchten, M. and Pachepsky, Y. (2011). *Encyclopedia of Agrophysics*. Springer Netherlands.
- van Genuchten, M. and Wierenga, P. (1986). *Methods of Soil Analysis. Part 1. Physical and Mineralogical Methods*, chapter Solute dispersion coefficients and retardation factors, pages 1025–1054. American Society of Agronomy and Soil Science Society of America.
- van Genuchten, M. T. (1980). A closed form equation for predicting the hydraulic conductivity of unsaturated soils. *Soil Science Society of America*, 44:892–898.
- Vanderborght, J., Huisman, J., Kruk, J., and Vereecken, H. (2013). Geophysical methods for field-scale imaging of root zone properties and processes. In *Soil-Water-Root Processes: Advances in Tomography and Imaging*, pages 247–282. SSSA Special Publications.
- Vrugt, J., Hopmans, J., and Simunel, J. (2001). Calibration of a Two-Dimensional Root Water Uptake Model. *Soil Science Society of America*, 65(4):1027–1037.
- Wang, B., Ji, H., and Hu, Y. (2012). A novel electrical resistance tomography system based on (cd)-d-4 technique. *29th Annual IEEE International Instrumentation and Measurement Technology Conference*.
- Waxman, M. and Smits, L. (1968). Electrical conductivities in oil-bearing shaly sands. *Society of Petroleum Engineers Journal*, 243:107–122.
- Weigand, M. and Kemna, A. (2016). Debye decomposition of time-lapse spectral induced polarisation data. *Computers and Geosciences*, 86:34–45.
- Weigand, M. and Kemna, A. (2017). Multi-frequency electrical impedance tomography as a non-invasive tool to characterize and monitor crop root systems. *Biogeosciences*, 14(4):921–939.
- Weigand, M. and Kemna, A. (2018). Imaging and functional characterization of crop root systems using spectroscopic electrical impedance measurements. *Plant and Soil*, 435:201–224.

- Werban, U., Al Hagrey, S. A., and Rabbel, W. (2008). Monitoring of root-zone water content in the laboratory by 2D geoelectrical tomography. *Journal of Plant Nutrition and Soil Science*, 171(6):927–935.
- Whalley, W. R., Binley, A., Watts, C. W., Shanahan, P., Dodd, I. C., Ober, E. S., Ashton, R. W., Webster, C. P., White, R. P., and Hawkesford, M. J. (2017). Methods to estimate changes in soil water for phenotyping root activity in the field. *Plant and Soil*, 415(1-2):407–422.
- Wildenschild, D., Hopmans, J. W., Vaz, C. M. P., Rivers, M. L., and Rikard, D. (2002). Using X-ray computed tomography in hydrology : systems , resolutions , and limitations. *Journal of Hydrology*, 267:285–297.
- Wilkinson, P. B., Meldrum, P. I., Chambers, J. E., Kuras, O., and Ogilvy, R. D. (2006). Improved strategies for the automatic selection of optimized sets of electrical resistivity tomography measurement configurations. *Geophysical Journal International*, 167(3):1119–1126.
- Wu, S. Y., Zhou, Q. Y., Wang, G., and Liu, T. M. (2013). Response characteristics and tomographic monitoring of the electric capacitance after irrigation in the soil-plant (ginkgo tree) continuum in a laboratory. *Environmental Earth Sciences*, 68(3):655–666.
- Yu, X., Wu, C., Fu, Y., Brookes, P., and Lu, S. (2016). Three-dimensional pore structure and carbon distribution of macroaggregates in biochar-amended soil. *European Journal of Soil Science*, 67:109–120.
- Zanetti, C., Weller, A., Vennetier, M., and Mériaux, P. (2011). Detection of buried tree root samples by using geoelectrical measurements: A laboratory experiment. *Plant and Soil*, 339(1):273–283.
- Zanutel, M. (2019). *Impact á long terme du biochar sur les propriétés physiques et hydrodynamiques du sol ainsi que sur les flux d’eau en milieu tempéré*. UCLouvain, Faculté des bioingénieurs.
- Zelazny, L., He, L., and Vanwormhoudt, A. M. (1996). Charge analyses of soils and anion exchange. *Methods of soil analysis, Part 3-Chemical methods*, pages 1231–1255.

- Zenone, T., Gianfranco, M., Maurizio, T., Federico, F., Marco, M., Matteo, S., Alessio, A., Chiara, F., Tommaso, C., and Guenther, S. (2008). Preliminary use of ground-penetrating radar and electrical resistivity tomography to study tree roots in pine forests and poplar plantations. *Functional plant biology*, 35:1047–1058.
- Zhang, Z. B., Peng, X., Zhou, H., Lin, H., and Sun, H. (2015). Characterizing preferential flow in cracked paddy soils using computed tomography and breakthrough curve. *Soil and Tillage Research*, 146:53–65.
- Zimmermann, E., Kemna, A., Berwix, J., Glaas, W., and Vereecken, H. (2008). EIT measurement system with high phase accuracy for the imaging of spectral induced polarization properties of soils and sediments. *Measurement Science and Technology*, 19(9):094010.

Appendix A

Authors, year	Study enviroment	Geoelectric method	Dimensionality	Acquisition equipment/ Inversion algorithm	Complementary method
Amato, 2008	Field	ERT	2D	Geostudi Astier / Occam's inversion	Destructive samples
Amato, 2009	Laboratory	ERT	3D	Iris Syscal Pro ten-channel receiver / Occam's inversion	Destructive samples
Aulen and Ship- ley,2012	Laboratory	EC	1D	BK Precision 879	Destructive samples
Basso, 2010	Field	ERT	2D	Iris instruments / Tomolab inversion	soil resistance to penetration data
Beff, 2013	Field	ERT	3D	SYSCAL Pro instrument / BERT Günther et al. (2006)	TDR
Binley,1996	Laboratory	ERT	3D	UMIST Mk1b/Inversion algorithm explained in article	-
Boaga, 2014	Field	ERT	2D	IRIS Syscal Pro / R2T code Binley (2018a)	tensiometer

Boaga, 2013	Field	ERT	3D	IRIS Syscal Pro 72 / R3T Binley (2018b)	TDR
Brillante, 2014	Field	ERT	3D	Syscal Junior Switch 48 / RES2DINV	TDR
Brillante, 2016 a	Field	ERT	2D	Syscal Junior Switch 48 / RES2DINV Loke (2018a)	TDR, Pre-dawn leaf water potential
Brillante, 2016 b	Field	ERT	3D	Syscal Junior Switch 48 / RES2DINV	TDR, Pre-dawn leaf water potential
Cao, 2010	Laboratory	ER	1D	Fluke 8022A Multimeter / -	-
Cao, 2011	Laboratory	EIS	1D	SI1260/-	-
Cassiani, 2016	Field	ERT	3D	IRIS Syscal Pro / R3T	TDR
Cassiani, 2015	Field	ERT	3D	- / R3T	Sap flow and evapotranspira- tion
Cassiani, 2012	Field	ERT	2D	- / Occam inversion R,R2,R3T	EMI, TDR
Cassiani, 2009	Laboratory	SIP	1D	ZELSIP04/-	X-ray micro CT
Celano, 2011	Field	ERT	2D	Iris Syscal Pro / TomoLab/	Soil sample analysis
Celano, 2010	Field	ERT	2D	Iris Syscal Pro / TomoLab/	Soil sample analysis
Cermak, 2006	Field	ER	1D	Megger/-	

Consoli, 2017	Field	ERT	3D	Iris Syscal Pro Switch 72 / Occam R3T	Sap flow
Cseresnyés, 2012	Laboratory	EC/EI	1D	HP 4284A LCR bridge/-	-
Cseresnyés, 2013	Laboratory	EC/EI	1D	HP 4284A LCR bridge/-	-
Cseresnyés, 2014	Laboratory	EC	1D	GW-8101G precision LCR instrument/-	-
Cseresnyés, 2016	Laboratory	EC	1D	GW-8101G precision LCR instrument/-	-
Cseresnyés, 2018	Laboratory/ Field	EC	1D	Agilent U1733C handheld LCR meter/-	TDR
Dietrich, 2012	Laboratory	EC	1D	Passive Component LCR Meter Extech Instruments/-	-
Ellis, 2012	Laboratory	EC	3D	MOTECH YMT-4080D/-	Destructive samples
Fan, 2015	Field	ERT	2D	SYSCAL Pro Switch / RES2DINV	TDR
Garré, 2013	Field	ERT	2D	Syscal Pro resistivity meter /	TDR
Garré, 2012	Field	ERT	2D	Iris Syscal Pro/ Gimli code	TDR
Garré, 2011	Laboratory	ERT	3D	RESECS prototype / Occam inversion	TDR, minirhizotrons

Guyot, 2013	Laboratory	ERT	2D	Picus TreeTronic / Picus Software	Macroscopic analysis of wood moisture an wood density
Jones, 2009	Field	ERT	2D	Campus Tigre 32/64 / RES2DINV	Levelling stations, neutron probe monitoring
Kelly, 2011	Field	ERT	2D	ABEM SAS 4000 Terrameter system / RES2DINV	C-probe
Kelter, 2015	laboratory	EIT	3D	Equipment and inversion developed in Zimmermann et al. (2008)	-
Koestel, 2007	Laboratory	ERT	3D	-/inversion by Binley (1995)	TDR
Koestel, 2008	Laboratory	ERT	3D	GeoServe RESECS/Occam inversion	TDR
Kowalczyk, 2015	Field	ERT	2D	ABEM system / RES2DINV	RCPT sounding
Kuhl, 2018	Laboratory	ER	1D	-/Joined hydrogeophysical inversion algorithm	Hydrological modelling, Plant parameter modelling

Leucci, 2010	Field	ERT	2D/3D	Iris Syscal R1 / RES3DINV Loke (2018b)	GPR, seismic refraction tomography
Lu, 2018	Laboratory	Zeta potential	1D	-/-	CEC;Surface charge measurements
Mares, 2016	Field	ERT	3D	IRIS Syscal Pro Switch 96/R2	Sap flow measurements
Martin, 2012	Laboratory	SIP	1D	SIP 256C / -	-
Mary, 2016	Laboratory	IP	2D	Lippmann Geophysical instrument and Terrameter / RES2DINV	Destructive samples
Mary, 2017	Laboratory	IP/SIP/TDIP	2D	COMSOL Multiphysics , LIPPMANN instrument / Matlab code	-
Mary, 2018	Field	ERT	3D	IRIS Syscal Pro Switch 72/R3T	MALM
Michot, 2003	Field	ERT	2D	Iris Instruments / RES2DINV	TDR
Michot, 2001	Field	ERT	2D	Iris Instruments / RES2DINV	TDR

Morari, 2009	Field	ERT	2D	Iris-Syscal Pro resistivity / ERTLab software	EMI, sampling
Moreno, 2015	Field	ERT	2D	Syscal Pro Switch 96 / R2 software	TDT(time domain transmittance)
Musgrave, 2011	Field	ERT	2D	Geopulse Resistance meter/Occam type inversion	GPR, temperature probes
Newill, 2014	Laboratory	EIT	2D	Hewlett Packard 4192A /-	Compaction measurements
Njland, 2010	Field	ERT	2D	EarthImager2D / AGI algorithms	Soil sampling
Ozier- Lafontaine and Bajazet, 2005	Laboratory	SIP	1D	HP 4992 Impedence Analyzer/-	-
Panissod, 2001	Field	ERT	2D	- / RES2DINV	-
Rao, 2018	Laboratory	ERT	2D	EIDORS electrical modelling	WC modelling; SMARTROOT - root image analyzing tool
Robinson, 2012	Field	ERT	3D	A10 channel instrument / R3	Temperature probes

Rossi, 2011	Field	ERT	2D	Iris Syscal Pro 10 / Tomolab software	Destructive sampling
Sabo, 2016a	Laboratory	EC	1D	BK Precision 879B LCR	-
Sabo, 2016b	Laboratory	EC	1D	BK Precision 879B LCR	-
Srayeddin and Doussan, 2009	Field	ERT	2D	Terrameter SAS 4000 / RES2DINV	Neutron probe and tensiometer measurements
Thierry, 2001	Laboratory	IP	2D	LIPPMANN instrument	-
Ursino, 2014	Field	ERT	2D	- / ProfileR/R2/R	TDR
Weigand, 2017	Laboratory	EIT	2D	EIT-40 / Kemna inversion code Kemna (2000)	-
Weigand and Kemna, 2018	Laboratory	sEIT and EIS	2D	EIT40/CRTomo	-
Werban, 2008	Laboratory	ERT	2D	- / 2D FD-algorithm Loke and Barker (1995)	TDR

Whalley, 2016	Field	ERT	2D	Iris Syscal Pro electrical resistivity meter /inversion strategy in appendix	EMI, neutron probe, penetrometer
Wu, 2013	Laboratory	EC	2D	LCR meter/-	-
Zanetti, 2011	Laboratory	SIP	2D	SIP Fuchs equipment / -	-
Zenone, 2008	Field	ERT	3D	- / ERTLab software	GPR
Zimmerman, 2008	Laboratory	EIT	2D	LABview and MATLAB / Kemna algorithm	-

Table A.1: Research articles mentioned in Chapter 2 literature review and corresponding instrumentation settings mentioned in their methodology.

Appendix B

Authors, year	Area of focus	Pedotransfer model	Plant-soil interaction model
Amato, 2008	Plan organic material detection	No	Root mass density logistical growth model
Amato, 2009	Plant organic material detection	No	Regression model
Aulen and Ship- ley,2012	Plant organic material detection	No	Regression model
Basso, 2010	Root zone water dynamics	Statistical regression model	No
Beff, 2013	Root zone water dynamics	WS	Mualen van Genuchten model (van Genuchten, 1980)
Binley, 1996	Root zone water dynamic	No	Dispersion model
Boaga, 2014	Root zone water dynamics	No	Compared with Marani et al. (2006)
Boaga, 2013	Root zone water dynamics	Archie	No
Brillante, 2014	Root zone water dynamics	Field based function	Pedotransfer model between ER and Soil volume wetness (SVW)

Brillante, 2016 a	Root zone water dynamics	Pedotransfer model obtained by machine learning methods	Soil volume wetness (SVW) available soil water(ASW) and fraction of transpirable soil water (FTSW)
Brillante, 2016 b	Root zone water dynamics	Pedotransfer model obtained by machine learning methods	ASW, FTSW, total transpirable soil water TTSW
Cao,2010	Plant organic material detection	No	Plant system electrical circuit analogue
Cao,2011	Plant organic material detection	No	Plant system electrical circuit analogue
Cassiani, 2016	Root zone water dynamics	Archie	Richards equation modelling
Cassiani, 2015	Root zone water dynamics	Laboratory calibration based on Archie	Van Genuchten model parametrization 1D Richards equation simulations
Cassiani, 2012	Root zone water dynamics	WS	Model of two mass balance equations: 1 for soil moisture, 1 for biomass
Cassiani, 2009	Soil contaminant dynamics	Fit to a Cole-Cole model	No
Celano, 2011	Root zone water dynamics	Laboratory calibration	No

Celano, 2010	Root zone water dynamics	No	Model relating hydraulics saturation, depth and electrical resistivity
Cermak, 2006	Root organic material detection	No	No
Consoli, 2017	Root zone water dynamics	On site calibration	No
Cseresnyés, 2012	Root organic material detection	No	No
Cseresnyés, 2013	Root organic material detection	No	No
Cseresnyés, 2014	Root organic material detection	No	No
Cseresnyés, 2016	Root organic material detection	No	No
Cseresnyés, 2018	Root organic material detection/ WC monitoring	No	Regression model
Dietrch, 2012	Plant organic material detection	No	Root electrical circuit analogue model

Ellis, 2012	Plant organic material detection	No	Compared data with Dalton model — Produced an empirical model
Fan, 2015	Root zone water dynamics	Archie	Derive capacitance model
Garré, 2013	Root zone water dynamics	WS	Hydrological model
Garré, 2012	Root zone water dynamics	WS	No
Garré, 2011	Root zone water dynamics	Simplified WS	No
Guyot, 2017	Sapwood-heartwood electrical differentiation	No	No
Jones, 2009	Tree induced subsidence	No	Tree subsidence model
Kelly, 2011	Root zone water dynamics	Revil model	No
Kelter, 2015	Laboratory soil water dynamics	No	No
Koestel, 2007	Synthetic water dynamics	Laboratory Calibration based on Revil	No
Koestel, 2008	Solute transport	Laboratory Calibration based on Revil	No

Kowalczyk, 2015	Soil peat horizon detection	No	No
Kuhl, 2018	Soil hydraulic parameters, Root parameters and Pedotransfer parameters estimation	Archie	SALUS and HYDRUS and FWD2-5D and SCE-UA
Leucci, 2010	Plant organic material detection	No	No
Lu, 2018	Differentiate between legume and non-legume roots	No	No
Mares, 2016	Root zone water dynamics	No	No
Martin, 2012	Oak impedance signature	No	Simple model based on a system with two parallel pathway for electrical charges (Marshall et al., 1959)
Mary, 2016	Plant organic material detection	No	No

Mary, 2017	Plant organic material detection	No	Cole-Cole model (Cole and Cole, 1941)
Mary, 2018	Plant organic material detection	No	Voltage forward modelling
Michot, 2003	Root zone water dynamics	Field calibration	No
Michot, 2001	Root zone water dynamics	Regression model calibration	No
Morari, 2009	Management zone delimitation	No	Linear model of coregionalisation
Moreno, 2015	Root zone water dynamics	Archie and WS	Model solute transport; separate soil WC from soil water salinity
Musgrave, 2011	Root zone water dynamics	No	No
Newill, 2014	Root zone water dynamics	No	Extend the Wang model (Wang et al., 2012)
Njland, 2010	Root zone water dynamics	Archie based calibration	No
Ozier-Lafontaine and Bajazet, 2005	Plant organic material detection	No	Root circuit analogue model

Panissod, 2001	Root zone water dynamics	No	No
Rao, 2018	Root zone water dynamics	Archie	Root zone water flow modelling
Robinson, 2012	Root zone water dynamics	No	No
Rossi, 2011	Plant organic material detection	No	Regression model — Compare with (Amato et al., 2008) model
Sabo, 2016a	Root health	No	No
Sabo, 2016b	Root health	No	No
Srayeddin and Doussan, 2009	Root zone water dynamics	In situ calibration	No
Thierry, 2001	Wood polarization effect	No	No
Ursino, 2014	Root zone water dynamics	No	Water balance model
Weigand, 2017	Plant organic material detection	No	No

Weigand and Kemna, 2018	Plant organic material detection	No	No
Werban, 2008	Root zone water dynamics	No	No
Whalley, 2016	Root phenotyping	Calibration with neutron probe measurements	No
Wu, 2013	Root zone water dynamics	No	No
Zanetti, 2011	Plant organic material detection	No	No
Zenone, 2008	Plant organic material detection	No	No
Zimmerman, 2008	Soil polarization properties	No	No

Table B.1: Research articles mentioned in Chapter 2 literature review and corresponding models mentioned in their methodology.

Appendix C

Authors, Year	Ksat	K	Macro poros- ity	Micro poros- ity	Total poros- ity (Φ)	Water con- ducting pores (WCP)	Available soil wa- ter/water storage (WS)	Infiltration (I)	Bulk den- sity (ρ)	Mobile water frac- tion (MWF)	Mentions
Coutadeur et al. 2002		ZT									
Horne et al. 1992		NC			CONT			ZT	ZT		
Longsdon and Cam- bardella, 2000					NC				NC		From Strudl- ley et al., 2008

Mahboubi et al. 1993		ZT					ZT				
Kosutic et al. 2001							ZT				
Azooz and Arshad 1996	ZT	ZT	CONT	ZT			ZT	CONT			
Benjamin 2001		ZT			CONT						
Carter et al. 1994		ZT							CONT		From Strudl- ley et al., 2008
Miller et al. 1998		CONT									From Strudl- ley et al., 2008
Wu et al. 1995		ZT									From Strudl- ley et al., 2008

Cornia et al. 1994		ZT	CONT						ZT		From Strudley et al., 2008
Pierce et al. 1994			CONT		CONT				ZT		From Strudley et al., 2008
Derdour et al. 1993					NC						From Strudley et al., 2008
Creswell et al. 1993		ZT	ZT*				NC				From Strudley et al., 2008 *minimum tillage rather than ZT

Brandt 1992							ZT				From Strudl- ley et al., 2008
Ross and Highes 1985								CONT			From Strudl- ley et al., 2008
Alegre et al. 1991								CONT			From Strudl- ley et al., 2008
Lipiec et al. 2006						*CONT	CONT	CONT			*Increased contri- bution from active pores
Gomez et al. 1999								CONT	ZT		
Moreno et al. 1997		ZT					CONT				

Martinez et al. 2008								CONT			
Schwen et al. 2011		CONT				ZT	ZT				
Bhattacha ryya et al. 2005		ZT	CONT								
McVay et al. 2006							NC		ZT		
Moret and Arrue 2007		CONT	ZT			CONT					
Costa et al. 2003		NC			NC				CONT		
Alletto and Coquet 2009									CONT*		*Greater increase with time
Cavalieri et al. 2008		ZT									

Xu and Mermoud 2000								NC			
Swan et al. 1992		ZT									
Bhattacharya et al. 2008		ZT						ZT			
Abid and Lal 2008							ZT	ZT			
Logsdon et al. 1993								ZT	CONT		Due to reduced surface sealing
Schwartz et al. 2010							ZT*				*Depths smaller than 0.2m
Buczko et al. 2006			ZT*								*RT rather than ZT

Blanco- Canqui et al. 2004			NC						NC		
Vervoot et al. 2001						CONT*		NC		CONT	*Less mobile water content in ZT
D'Haene et al. 2007		ZT*					CT		ZT		*RT rather than ZT
Gregorich et al. 1993		CT*									*5-20 cm/ NC in top 5 cm
Trojan and Linden 1998								NC			

Wahl et al. 2004			ZT*					ZT			*Also, greater continuity and connectivity in ZT
Bordovsky et al. 1999		ZT*							ZT		*RT rather than ZT
Alliaume et al. 2013							ZT*				*RT rather than ZT
Chang and Lindwall 1991		NC*					NC		NC^		*Generally K was lower for ZT Generally BD was higher for ZT

Carof et al. 2007		CONT									
Singh 2013		ZT*			ZT		ZT		ZT		*5 and 9 year ZT
Ciollaro and Lamad- dalena 1998		CONT									
Fasinmirin and Reichart 2011					CONT						
Jonard et al. 2013							ZT*				Also, greater variabil- ity in CONT
Daraghmeh et al. 2008		ZT*			CT^		ZT				*RT rather than ZT ^trafficked

Singh 1995		ZT					CT				
Castellini and Venrella 2012		NC									
Datiri and Lowery 1991		NC					CONT				
Kumar 2012		ZT	ZT			ZT					
Matula et al. 2003								CONT			
Slavinski et al. 2012							ZT*				*RT rather than ZT
Nyanad zawo et al. 2008								NC			
Blanco- Canqui et al. 2017		NC			NC		NC				

Tangyuan et al. 2009		CONT			CONT*	CONT					*Capillary porosity
Agostini et al. 2012		CONT							ZT		
Alletto et al. 2010		CONT									
Shukla et al. 2003						ZT		ZT			
Comegna et al. 1999		NC			NC						
Abu and Abubaker 2012 Ruqin et al. 2013							ZT	ZT			
Celik et al. 2011		CONT							ZT		

Abrisqueta et al. 2006		ZT									
Mloza- Banda et al. 2014			NC		NC		ZT		NC		
Ambert- Sanchez et al. 2016			CONT						ZT		
Alletto et al. 2011						ZT				ZT	
Schlunter et al. 2018		CONT	CONT*						ZT		*and connec- tivity
Haruna et al. 2018		CONT	CONT				CONT		ZT		
Jakab et al. 2017								CONT			
Chen et al. 2013							CONT				

Abubaker et al. 2017							ZT				
Golabi et al. 1995			ZT					CONT			
Pelegrin et al. 1989			CONT		CONT			CONT			
Siracco et al. 2012			CONT			ZT					
Reichert et al. 2017		NC	NC	NC	NC		NC		NC		
Sillon et al. 2003		ZT									
Tebrugge and During 1999		CONT	CONT						ZT		

Shipitalo et al. 1999			ZT*								*Increased macrop- ore forma- tion
Vogeler et al. 2005										CONT	
Ball- Coelho et al. 1997				ZT			ZT			ZT	
Chang and Lindwall 1989, 1990, 1992		CONT					CONT		ZT		8 years no dif- ference, after 10 years differ- enced ap- peared

Table C.1: Research articles used in the Chapter 6 literature analysis. ZT or CONT indicates the article quotes a bigger value for the zero-till (no-till) or the convectional-till samples respectively. NC (no change or the difference between ZT and CONT practices is not significant). RT stands for reduced-till.