RelationshipsbetweenBreakthroughCurvesandX-rayComputed TomographyAnalyzedMacroporeCharacteristics

TenundisturbedsoilmonolithsofclayeyPelosolatGottingen,Germanycoveringthehorizons$A_h$andPwerecollected .Somecolumnswereleftatnaturalhumidity,somewereoven-driedtosimulatedrought situationsinforestsoilsinconsequenceofclimatechange.Insevencolumns,fourmicro-lysimeters,each, wereinstalledathalfheightinordertoobtaindataforanalysisofsinglesolutepathways.Afixedamount ofKBrtracerwasappliedtothehumuslayer.Thecolumnswereirrigatedwith$CaCl_2$.Columnoutputand lysimeteroutputwerecollectedandanalyzedtorecordbreakthroughcurves.Bimodalanalyticalconvection dispersionequation(CDE)solutionswerefittedforthecolumnoutputsusinganon-linearleastsquarefit. AsimpleCDEsolutiondidnotfitwell.Thissupportsthemodeloftwooverlayingtransportphenomena. Afterbreakthroughrecordingwascomplete,allcolumnswerescannedusingX-raycomputedtomography (CT).FromtheCTdata3-Dreconstructionsoftheporoussystemwerecreatedforvisualinspection,and theexactpathwaysformacroporesalongthemicro-lysimetersweredetermined.Additionally,indicesof theporestructurewerecomputedtocomparewiththeslowandfastdispersivityvaluesfromthebimodal CDEfit.Thevariationinmicro-lysimeterperformancecouldbeexplainedusingthe3-Dreconstruction. Statisticallysignificantdifferencesbetweentheporestructureofwetanddriedcolumnsaftertheendof irrigationcouldnotbeidentified.Theporeindexhasgenerallyanegativelinearrelationshipwiththefast dispersivity,andapositivelinearrelationshipwiththeslowdispersivity.Theserelationsarestrongerin topsoil.TheCTpicturesand3-Dre-constructionsprovideaninterestinginsightintothesoilporesystem andmayhelptounderstandman-madedroughtproblemsduetoclimatechange.

Keywords: Tracertransport,X-raycomputedtomography,3-Dvisualization,bimodality,CDE,dispersivity, BTC/breakthroughcurves

Themainresearchquestionofthisworkwastofind out,ifsinglepathwaysinunsaturatedflowofwetand driedsoils(withregardtodroughtsduetoclimate change)couldbecharacterizedintheirfunctions. Quantitativerelationshipsbetweensoilstructure (especiallymacroporecharacteristics,namelytheirsize, number,type,distributionandcontinuity)and soilhydraulicpropertiesareessentialforimproving ourabilitytomodelflowandtransportinstructured soils.Bouma(1979)andothershaveusedchloride breakthroughcurvesfromundisturbedsoilcolumns asanindirectmeansofcharacterizingmacropores.In recentyears,X-raycomputertomography(CT)data, whichisbasedonvariedlinearattenuationofwater, airandsolidmaterials,providedanattractivetoolfor soilscientiststonon-invasivelyobservesoilstructure (GantzerandAnderson2002;Luo*etal*.2008;Taina *etal*.2008;Kumar*etal*.2010).Warner*etal*.(1989) usedCTdatatoinvestigatethemacroporesystem, *e.g*.characterizationofcracks,earthwormholesand rootingchannels.Peyton*etal*.(1992)concentrated onmacropores,quantifyingmacroporeperimeters,the pathsurroundingmacroporeshapes.Arelationship betweenmacroporesvisualizedbyCTdataand preferentialflowwasinvestigatedbyHeijs*etal*. (1996).Luo*etal*.(2010)relatedmacropore characteristicsquantitativelytosolutetransport parametersundersaturatedconditions.Borgesand Pires(2012)havestudiedtherepresentative

Table1. Descriptionofexperimentaldesign

Columnnumber	Treatment (type)	watercontent(%) (mean)	Br-Pulset_0[day] (Bramount[mg])	Recoveryrate(%)
1-4	Naturalhumidity (1)	37.5	0.833 (14.9-16.4)	76.9-85.9
5-7	Oven-dried (2)	30.7	0.833 (15.8-18.3)	55.2-91.1
10-12	Oven-dried (3)	30.7	0.0833 (15.3-17.3)	46.6-68.0

elementaryarea(REA) ofsoilsamplesusingCTdata, andconcludedthatsampleswithvolumesfrom50 cm^3to100cm^3withminimumcrosssectionof640 mm^2areenoughtoberepresentativeforthesoil structure.Oursoilsampleshadvolumesofabout5000 cm^3withacrosssectionof169cm^2.

ThepresentstudywascarriedoutatUniversity ofGöttingen,InstituteforSoilScienceandForest Nutrition,Büsgenweg,GermanyonsoilcolumnsofaclayeyPelosol(VerticCambisol)withwelldescribed swell-shrinkcharacteristics(Spangenberg*etal.*2011).Theobjectivesweretostudytheroleofporecontactofmicro-lysimetersinthesoilcolumnontracertransportinrelationtothestructure,asassessedby X-rayCTunderdifferentinitialconditionsand irrigation.Asitisnotpossibletocarryoutthese investigationsunderfieldconditions,non-destructive CTdatawereused,makingitpossiblefor3-Dreconstructionofthestructureoftheinvestigatedsoil columns.Furthermore,usingCTdata,anattemptwas madetounderstandtherelationshipbetweenthe breakthroughcurvesofthetracers(velocity, dispersionanddispersivity)andthemeasuredvolume andstructureofthepores.

MaterialsandMethods

Thesoilstudied

ThesoilinthepresentstudyisaclayeyPelosol(Vertic Cambisol),developedfromaMuschelkalk(shell-lime)plateauderivedfromTriassicsediment layers.CollectedhorizonswereO$_{l(f)}$–A$_h$–P,O$_{l(f)}$wasremoved,onlyA$_h$–Premained.ThePhorizon showedapolyedricstructure(loamyclay).Inthis horizon,swell-shrinkcharacteristicsarewell expressed,andswellingclaymineralsaccountedfor26±5 %.Mineralcompositionsshowquartz,illite, corrensite,orthoclase,albiteandgoethite.Thedetails ofthesoilsandtheexperimentalsetupweregivenin Spangenberg*etal.*(2011).Arepresentativesample wastakenintheareawherethesoilcolumnswere taken.Thissamplewasanalyzedforsoildensityin variousdepths.Bulkdensityrangedfrom0.908Mg m^{-3}(topsoil,A$_h$)to1.569Mgm^{-3}(subsoil,P,20-30 cmdepth).

Thecolumnexperiment

Originally,twelveundisturbedsoilcolumnswerecollectedinplexiglasscylindersof14.7cm diameterandabout30cmheightfroma4m^2sampling area.Tencolumnswereselectedforthisstudy,butin ordertoreducethetotalamountoffiguresonly columns1,5and12arepresentedanddescribedin detail.Table1showsanoverviewoftheexperimental design.Fourcolumns(1-4)werekeptattheirnatural meanwatercontentofabout37.5%(meanvalue, n=4).Columns5-7and10-12weredriedat105°Cin aheatingcabinettoawatercontentof30.7%(Table1).Four micro-lysimeters,each,wereinstalledin sevensoilcolumns.Thesemicro-lysimeterswere equippedwithahydrophilicporouspolymertube (diameter2.3mm),madebyEijkelkampAgrisearchEquipment,Netherlands(Spangenberg*etal.*1997). Theyweredesignedspecificallytominimizethe impactofinstallationintosoil.Theywereinstalledat abouthalftheheightofthecolumninordertoallowobservationoftheflowparametersinhighertemporal andspatialresolutioninadditiontothebottomoutput. Allcolumnswereirrigatedinavacuumpacked plexiglascontainer,whichisacompletesoil microcosm(describedinSpangenberg*etal.*2011). Irrigationwasappliedusinganelectronicdeviceevery 2h.Atthebottomofeachmonolith,unsaturatedflowwasadjustedto300hPa.Abromidepulsewasapplied toeachcolumnatthebeginningoftheexperiment. Thenregularirrigationwith$CaCl_2$wasstarted,which lastedforatleast30days,*i.e.*untilnomorebromide wasfoundinthecolumnoutput.Solutionsampleswerecollecteddailyatthebottomandfromthemicro-lysimetersofeachcolumn.Theywereanalyzedfor chlorideandbromide.AnalysesweredonebyHPLC ionchromatography.Elutionmixturecontained

Na_2CO_3(2mmol)and$NaHCO_3$(0.75mmol). Detectionlimitofbothelementswas300µgL^{-1}.The statisticalanalysiswasdoneusingSAS(Statistical AnalysisSystem,SASInstitute,Inc.,Cary).The procedure“nlin”ofSASwasusedtoprovideleast squaresmodeling.Ananalyticalsolutionofthe convectiondispersionequation(CDE)wasusedtofit thebreakthroughcurvesoftheexperiment(vanGenuchten1982).Modelparameterswereestimatedusingbimodality,sinceitresultedinthebestfit (Spangenberg*etal*.2011).

BTCModeling

Themostimportantmodelforsolutiontransport insoildescribesconcentrationchangesintimeand spaceusingtheCDEaccordingtoNielsenandBiggar(1962).

$$R\frac{\partial C}{\partial t} = D\frac{\partial^2 C}{\partial x^2} - v\frac{\partial C}{\partial x} \qquad \ldots(1)$$

where,C=concentration[ML^{-3}];t=time[days]; x=spatialdistance[L];D=dispersioncoefficient; v=averageporevelocity[LT^{-1}]

R=Retardation(dimensionless) $$R = 1 + \frac{\rho_b K_d}{\theta} \qquad \ldots(2)$$

where,
ρ_b=soildensity[ML^{-3}];K_d=constantfactor[L^{3}M^{-1}];ρ=volumetricwatercontent[L^{3}L^{-3}]

AccordingtoToride*etal*.(1995)Rcanbeset on1.

Starting(1.0)andboundaryconditions(1.1and 1.2)are:

$$C(x,0) = C_i \qquad \ldots(1.0)$$

$$\left(-D\frac{\partial C}{\partial x} + v\right)\Big|_{x=0} = \begin{cases} vC_0 & 0 < t \le t_0 \\ 0 & t > t_0 \end{cases} \qquad \ldots(1.1)$$

$$\frac{\partial C}{\partial x}(\infty, t) = 0 \qquad \ldots(1.2)$$

Assumingalteredinfiltrationanddisturbedwaterflowduetosoildroughttheconditionsforapplication oftheCDEontreatmenttype2and3(Table1)were incomplete.Butconcentratingontheaimofthe investigation-acomparisonbetweendifferent experimentalvariantsofdriedandhumidsoils-the samemethodsofdataanalysishadtobechosen.To considerdifferentflowbehaviorofdriedandnon-driedsoilsomenewboundaryconditionsfortheuse ofananalyticalsolutionoftheCDEwereinvolved (NielsenandBiggar1962).Abimodalvariantofthis CDEwasused,moredetailsonthispartareprovided inSpangenberg*etal*.(2011).

X-raycomputedtomography

Aftertheirrigationphase,thecolumnswith installedmicro-lysimetersweretomographedina HospitalofGoettingenUniversity.AmedicalCTscanner (HiSpeedAdvantage,GeneralElectric)wasused.Forthepurposeofour30cmlongsoilcolumns, thehead-necksettingswerechosen.Tounderstand thedifferencesbetweenmoistanddrytreatments,each soilcolumnwastomographedindividually.Theoutput oftheCTunitisinHounsfieldUnits(HU),whichisaninternationallystandardizednumberingscale (Petrovic*etal*.1982).Thenumericalvalueof HounsfieldUnitdependsontheattenuation coefficientsofthesubjectmatterrelativetothatof water(Hainsworth1983;Grevers*etal*.1989;Heijs*et al*.1995),whichisgivenasH=1000(μ-μ_w)/(μ_w-μ_a). Here,µisthelinearattenuationcoefficientofthe materialorpixelinquestion,$\mu_w$and$\mu_a$arethe attenuationcoefficientsofwaterandair,respectively. A512by512matrixofpixeldatawasobtainedfor eachscan.Apixelhadthewidthofabout0.76mm. Thescanwastakenatintervalsof2mm(ca140 scanspercolumn).Aconstant1000wasaddedto everyvalue,whichisusedonallCTscanners,and giveninformulaforH.Afterthisaddition,airhasa valueof0andwater1000.Foreachpixel,theX-ray attenuationvalueswerestoredasvaluesfrom0to 4095.Thisrangewasduetothe12-bitprocessingof thetomographyequipment.Thehighvaluescorrespondtothemetalofthemicro-lysimeter.The PV–WAVEwasusedforcomputeranalysis,which allowedreconstructing,visualizingandquantifying3-Dmacroporestructureinthesoilcolumn(Pierret*et al*.2002).

Indicatorsforporestructure

ThemostimportantoutcomeoftheCTdataistheinformationonthecontentofsolidsandsoil porosity.The12-bitdatawasreducedto8-bitdata andthewholedatasetwasscaledbydividingallthe valuesbyafactor16,sothatwehavevaluesranging from0-255.Goodspatialresolutioncanbeachieved whenthereisalargedifferenceinHvaluesbetween asubject(*e.g.*asoilpore)andthebackground(*e.g.* soilmatrix)assuggestedbyGrevers*etal*.(1989).

Inthepresentstudy,thesameinteriorregionof thetop-andsubsoilinallthesoilcolumnswasselected,theareaaroundthemicro-lysimeterswasintentionallyleftout.Theselectedinteriorregionsweredividedintoroughlycubicareas.Thesecubesformthebasisforfurtherdataprocessing.Idealcubes

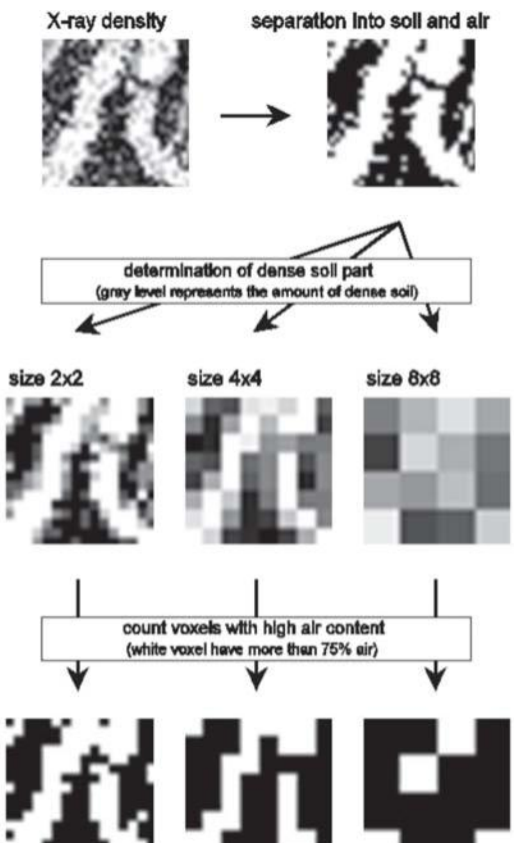

Fig.1. Step-wisecalculationforthethreecube-sizes:(distri-butionofX-rayattenuationvaluesàseparationofsoil solidsandair;determinationofsoilsolids–(grayareas showtheextentofsoilsolids);cubesize2×2cubesize 4×4cubesize8×8countingofcubeswithhighairvol-umes(whitecubeshavemorethan75%airvolume)

arenotpossiblewiththegivenvoxelsize.Therefore, differentsizeswereconsidered,namely,[4,4,1]voxel (labeled2×2),[8,8,2]voxel(labeled4×4)and[16,16, 4]voxel(labeled8×8).Thesecubescorrespondto volumesfrom18mm^3toabout1cm^3.Thestep-wisecalculationforthe3cubesispresentedinfigure1.

Firstathresholdwasselectedtodistinguish betweendensematterandpores.Avalueof110was selected,asthisprovidedthebestseparationbasedon knownmateriallocations.Thepercentageofcubes withlessthan25%densesoilwascomputedforeach sampleareaandcubesize,whicharelabeledP_1,P_2andP_4,dependingoncubesize.Thesewereusedas indexesfortheporestructureofacolumn.Fora completelyhomogeneousmaterial,allindexeswould bethesame.WeusedP_1asanindexforthefinepore structureandP_4isanindexforthecoarsepore structure.Theindexesdonotrepresentthe connectivityofporousvolume,onlytheamountof poresataspecificscale.Thedispersivityvaluesfrom bimodaltracerdescriptionwererelatedtotheseindicesforporestructureatthreedifferentscales.Theseindiceswerecomparedtothedispersivityresultsofthe CDEmodels.

3-Dreconstructionofsoilstructure

Inthecoreofthecolumn,whichhasacross-sectionalareaofabout10cm×10cm,thevoxelswithscaled attenuationvaluesfrom0to30were reconstructedasa3-Dimageofsoilstructure.Thisallowsavisualinspectionofporeconnectivityfor qualitativeanalysis.Avalueof30waschosento allowtheair-filledinnerpartsofmacroporestobe visible.Forabetterviewoftheporecontactofeach lysimeter,theslicewiththelysimeterswasreconstructedseparatelyinthreeviewingangles(40°, 70and85°)withsameviewingangleinallcases,*i.e.* forallcolumns(Figs.2,3and4).However,only slicewith40degreesviewanglewaspresented.In ordertoovercometheeffectofairpocketsinthe outerspacearoundthesoilcolumn,thecentralsquare areaof10cm×10cmwasselectedforthe3-dimensionalreconstruction.Atthetopaswellasat thebottomsomeslicesofthecolumnwerediscarded. Thelocationofthemicro-lysimetersinthecolumn wereestablished,inwhichthex-,y-andz-coordinatesofthelysimeterheadandterminalinthe cross-sectionimageweredetermined.

ResultsandDiscussion

Influenceofplacementofmicro-lysimetersandtheirfunction

Thesuctionlysimetersofthetracerexperiment draindifferentquantitiesofsolution,althoughduring theentireconductoftheexperiment,asuctionof 0.030MPawasmaintained.Thegreatvariabilityin thequantityofdrainedsolutionappearstobecaused bythedifferenceinpositioningofthemicro-lysimetersinthecolumns,relativetotheporoussystemofthecolumn.Preferentialflowmayinitially havebypassedthelysimetersaltogether,butrelative positiontotheporoussystemseemstohaveahigh influence.Inordertoexplainthisphenomenon,one columnineachgroupispresentedinfigures5,6and 7.Eachfigurecontainsacrosssectionimageatthe heightofthemicro-lysimeters,aschematicofmicro-lysimeterplacementandthedailyamountsofsolution drained.Thefiguresareusedtojudgetherelativesuctionperformanceofthelysimeters.Allfour lysimetersof column1showsimilarperformance(Fig.

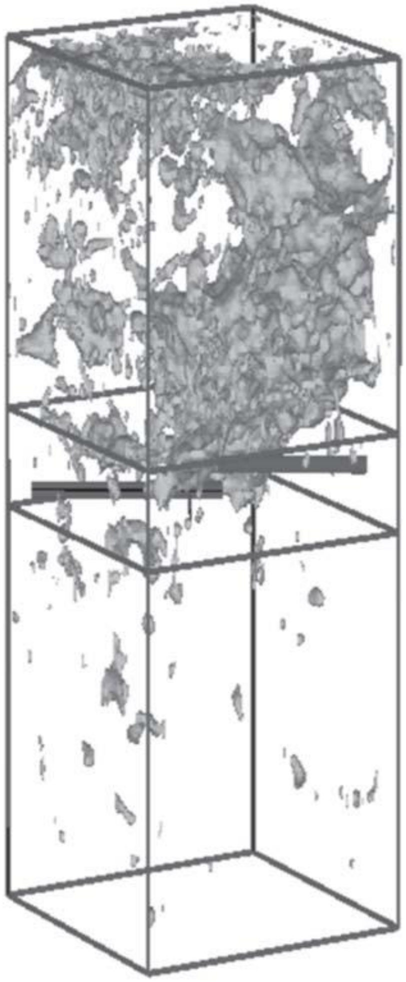

Fig.2a,Column1,withsection

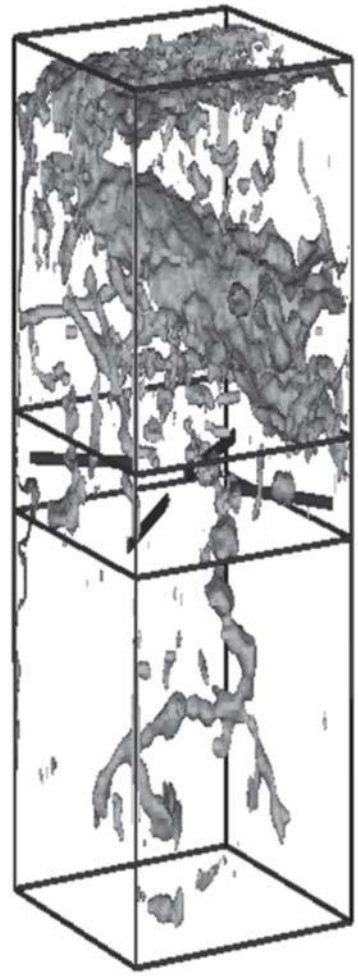

Fig.3a,Column5,withsection

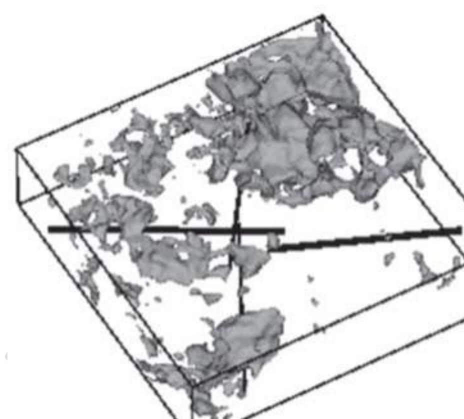

Fig.2b,Column1,section,40degree

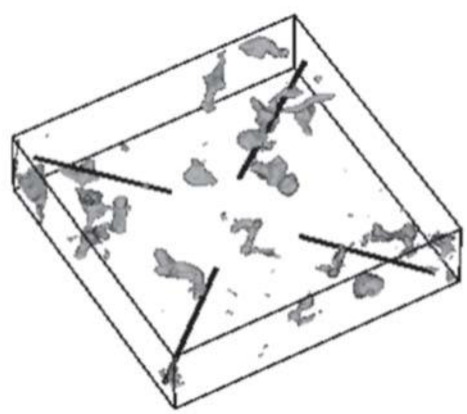

Fig.3b,Column5,section,40degree

Fig.2.3-Dreconstructionofcolumn1(experimentalvariant 1)withinstalledmicro-lysimeters.Inthecoreofthe column,thescaledattenuationvaluesfrom0to30are presented.Forabetterview,thesectionwiththelysim-etersispresentedina40degreelook-angle.Thecore ofthecolumnhasacross-sectionalareaof10cm×10cm

Fig.3.3-Dreconstructionofcolumn5(experimentalvariant 2)withinstalledmicro-lysimeters.Inthecoreofthe columnthescaledattenuationvaluesfrom0to30are presented.Forabetterview,thesectionwiththelysim-etersispresentedina40degreelook-angle.Thecore ofthecolumnhasacross-sectionalareaof10cm×10cm

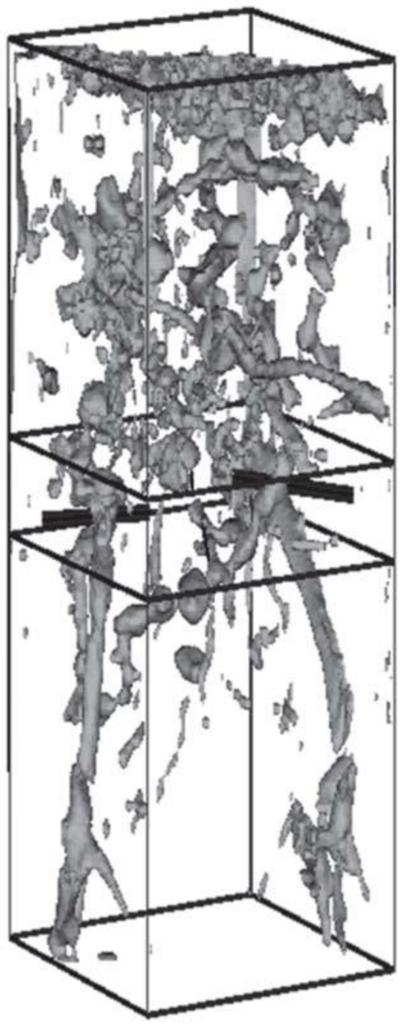

Fig.4a,Column12,withsection

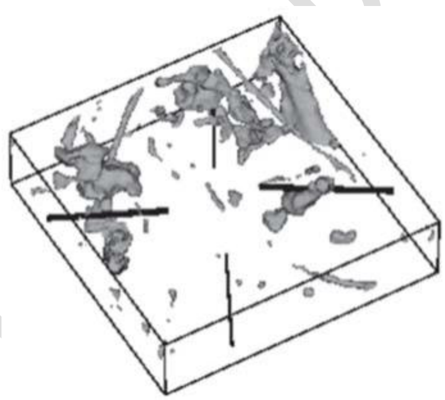

Fig.4b,Column12,section,40degree

Fig.4.3-Dreconstructionofcolumn12(experimentalvariant 3)withinstalledmicro-lysimeters.Inthecoreofthe columnthescaledattenuationvaluesfrom0to30are presented.Forabetterview,thesectionwiththelysim-etersispresentedina40degreelook-angle.Thecore ofthecolumnhasacross-sectionalareaof10cm×10cm

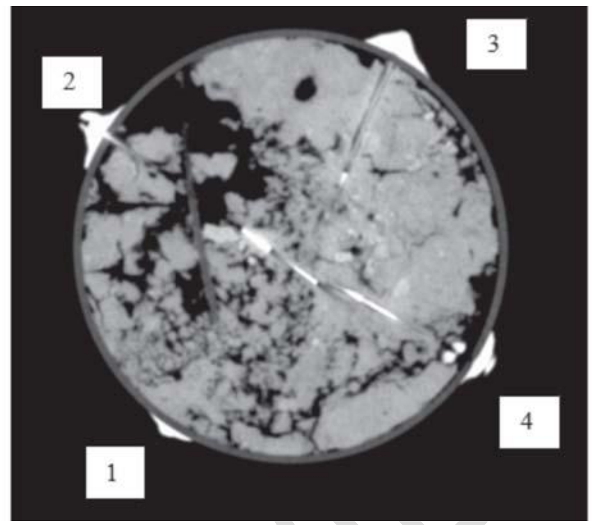

Figure5a,cross-sectionofcolumn1withmicro-lysimeters(topleft:no2;topright:no3;bottomleft:no1;bottomright: no4)andtheirnumbering

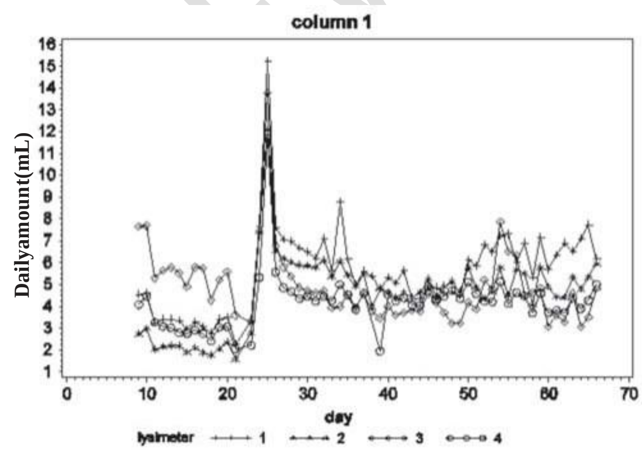

Fig.5bSamplevolumes(ml)ofcolumn1

Fig.5. Cross-sectionimageofcolumn1withmicro-lysim-etersandtheirnumbering(5a)aswellasmicro-lysim-eters'respectivemeasuredsamplevolumes(mL),col-umn1(5b)

5c).Micro-lysimeters2and4showidenticalcurves, evenbeforeandafterthebreakincontinuityof leaching.Theirtipslieclosetoeachother(Fig.5a and5b),soweassume,thesesuctionlysimetersshowedr eciprocalinfluence.Modelingofthe breakthroughcurvesdidn'tmakesense.Incolumns5 and12,bothpreviouslydried,atleastonemicro-lysimeterhaddirectcontacttoamacropore(Fig.6a, micro-lysimeterno4andFig.7amicro-lysimeterno 15).Thesemicro-lysimetersshowedthelowestsuction performancewithintheircolumn.Thus,contacttoa macropore(>0.5cm)appearstohaveaclear influenceonthesuctionperformanceofamicro-

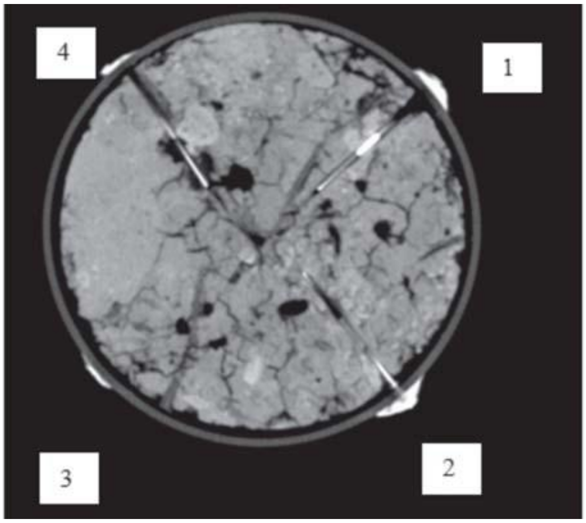

Fig.6across-sectionofcolumn5withmicro-lysimeters(top left:no4;topright:no1;bottomleft:no3;bottomright:no2) andtheirnumbering

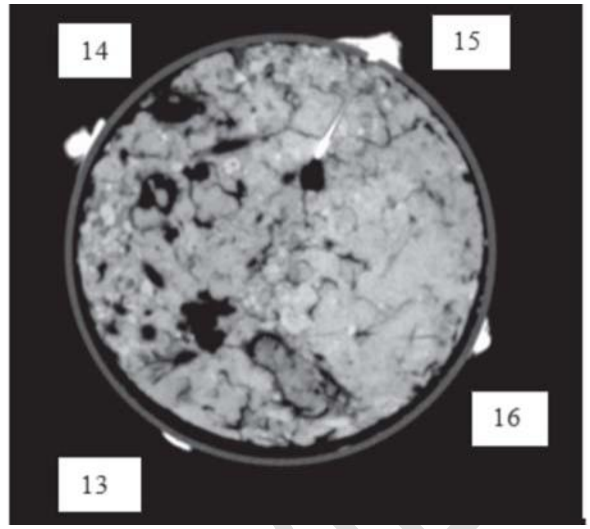

Fig.7aCross-sectionofcolumn12withmicro-lysimeters(top left:no14;topright:no15;bottomleft:no13;bottomright: no16)andtheirnumbering

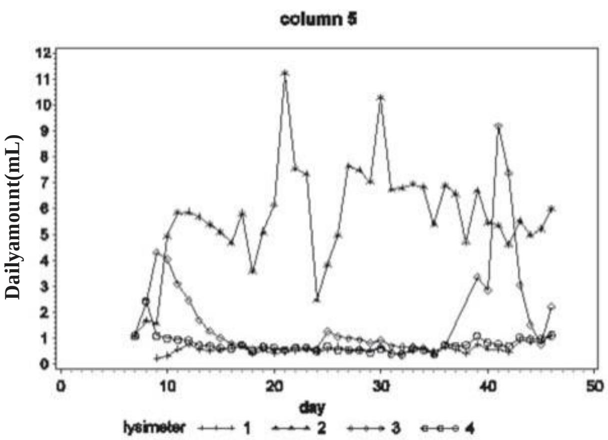

Fig.6bSamplevolumes(ml)ofcolumn5

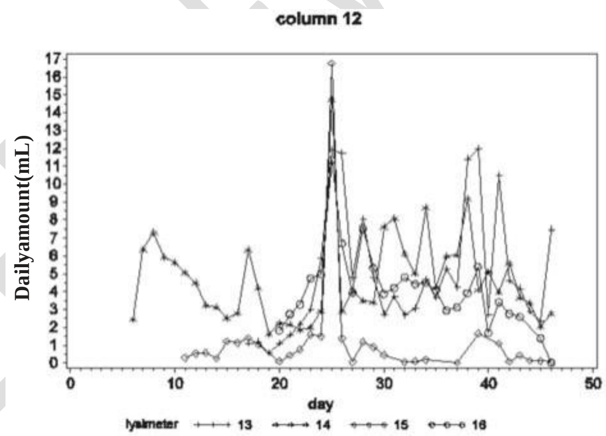

Fig.7bSamplevolumes(ml)ofcolumn12

Fig.6. Cross-sectionimageofcolumn5withmicro-lysim-etersandtheirnumbering(6a)aswellasmicro-lysim-eters'respectivemeasuredsamplevolumes(mL),col-umn5(6b)

Fig.7. Cross-sectionimageofcolumn12withmicro-lysim-etersandtheirnumbering(7a)aswellasmicro-lysim-eters'respectivemeasuredsamplevolumes(mL),col-umn5(7b)

lysimeter.Underunsaturatedconditions,onlyathin filmofwaterispresentonthewallsofporesofthis diameter.Becauseofthis,thesesuctionlysimeters drainednosolutionmostofthetime,andhencelowvolume ofleachate.Transferringthisresulttonatural conditionswherethemicro-lysimeterswouldrepresent therootingzoneofforesttreesitcanbeassumedthat alreadyunderthesesimulateddroughtconditions waterstresswouldhavebegun.

Micro-lysimetersinacompactsoilmatrixalso showedlowsuctionperformance.Aplacement avoidingtheseextremesresultedinsatisfactoryfunctioning.Ifenoughfineporesarepresentinthe vicinityofthemicro-lysimeters,thecapillary contributionofwateroutweighstheairfilledporosity, andthevolumeoftheleachatecollectedwillbehigher (Fig.8).Themediandailyamountofleachateafter theinitialphaseoftheexperimentisshownonthe abscissa.Ontheordinate,thecontentofthesolidsin thesoilinanellipsoidalregionaroundthetipofthe micro-lysimeter(ca.12cm^3)isshown.Interestingly, thesuctionperformanceofthemicro-lysimeterwithhighporevolumewasaspoorasforlysimeterswith almost100%compactsoilaroundit(column3).Most lysimetersshowbestperformancewithmoderately compactsoil.Inadditiontothetotalquantityofporesandsolidvolume,theporesizedistributionandtheir connectivitytotheimmediatevicinityofthelysimeter

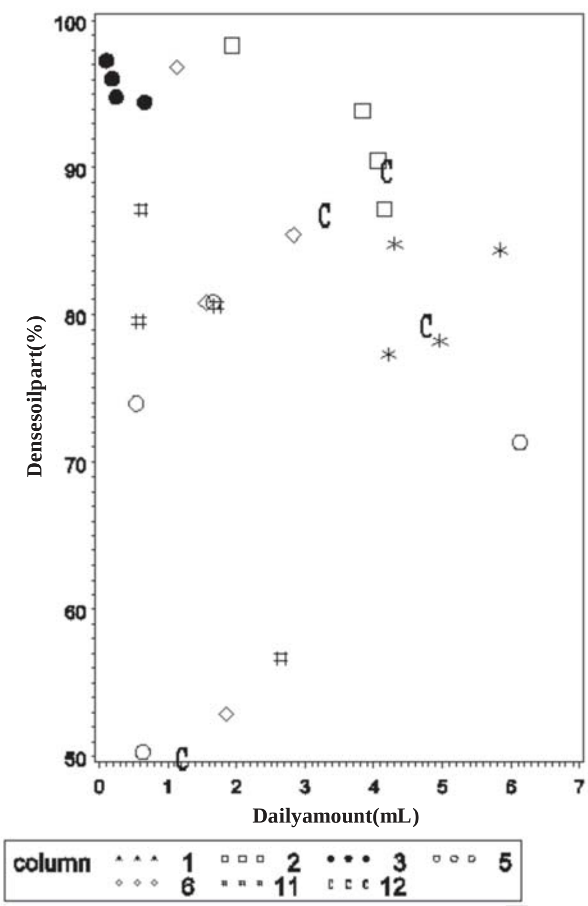

Fig.8. Percentagesoilsolidsaroundthelysimeterinrelation tothesuctionperformanceofthelysimeterfor28lysim-etersin7columns.ThesoilsolidcontentwasobtainedfromtheCTattenuationdata

isimportant.Allthesefactorsappeartoberesponsible fortheotherwiseunexplainedsuctioneffectiveness ofthelysimeters.Eightofthe28lysimetershaveto beconsideredtobeineffective,sincetheydrainless than1mLd^{-1}(Fig.8).About70%oftheinstalled micro-lysimetersarecapableofdraining,andabout halfofthemaredistinctlyuseful(>3mLd^{-1})underthegivenconditions.

Forthefirsttime,CTanalysiswasabletovisualizea ndrevealcause-effectrelationshipsofmicro-lysimeterporecontactsandtheirsuctionability. TheX-rayCTimagesofcrosssectionsofthesoil columnsdidnotshownoticeabledisturbanceinsoilstructu reofthecolumnsduetoinstallationofthe micro-lysimeters(Figs.5a,6aand7a).Incontrastto this,Beckmann*etal*.(1992)foundnoticeable disturbancesinsoilstructureduetoinstallationofstandardl ysimetercupsinthefield,resultinginan alterationoftheporesystem.Formostofthedried columns(columns5and12;Figs.10and11)the micro-lysimetershavemissedthemainbreakthrough astheyhadnoinitialsoilcontactbecauseofthedry stateofthesoil,orthefirstfastbreakthroughbypassed them.

Localizationofthemicro-lysimetersanditsrelation totracerbreakthroughcurves

GiventhatnoCDEmodelcouldbefitforthe micro-lysimeterdata,itsbreakthroughcurvesin relationtoporestructurecanonlybediscussedina qualitativeway.Asexamplesthe3-Dreconstructionsofcolumns1,5and12withinstalledmicro-lysimetersarepresentedinfigures2,3and4,respectively.

Thebreakthroughcurvesofallmicro-lysimetersareavailableaswellasall3-Dreconstructionsofthe scannedsoilcolumns.Thebreakthroughsofthe micro-lysimetersofcolumn1(thewetvariantofthe experiment)alongwiththebreakthroughofthewhole columnarepresented(Fig.9).Inthiscolumn,the maximumvaluesofthemicro-lysimeterbreakthrough curveswerelowerthanthecolumnoutput.Obviously, thereitwasafastbreakthrough,whichbypassedthe micro-lysimetersandaslowbreakthroughthatwasseizedbythelysimeter.Thesimilarityofthemicro-lysimeterbreakthroughsisexplainedbythefactthat all4micro-lysimetersliedclosetoandinfluenced eachother(Figs.2and5a).Incolumns2and3the micro-lysimeters,toagreatextent,attainhigher bromidevaluesearlierthanthecolumnoutflow

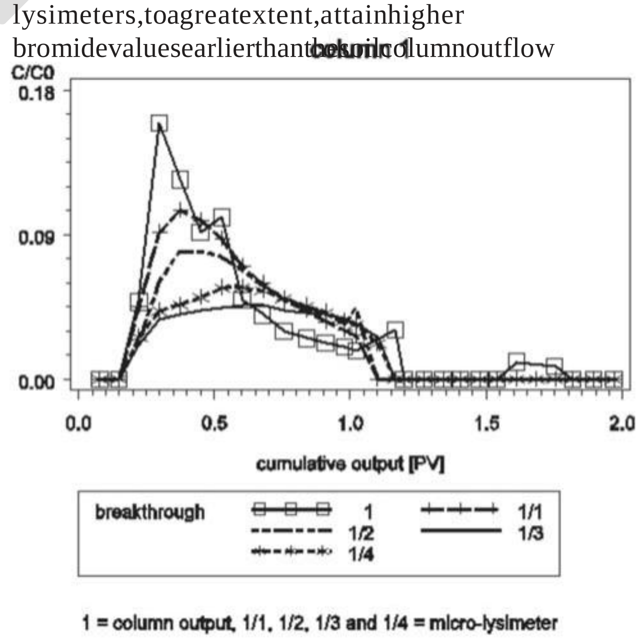

Fig.9. Breakthroughcurvesofcolumn1(experimentalvariant 1)inunitsoftheporevolume.C=measuredconcen-tration,Co=concentrationoftheBrpulses

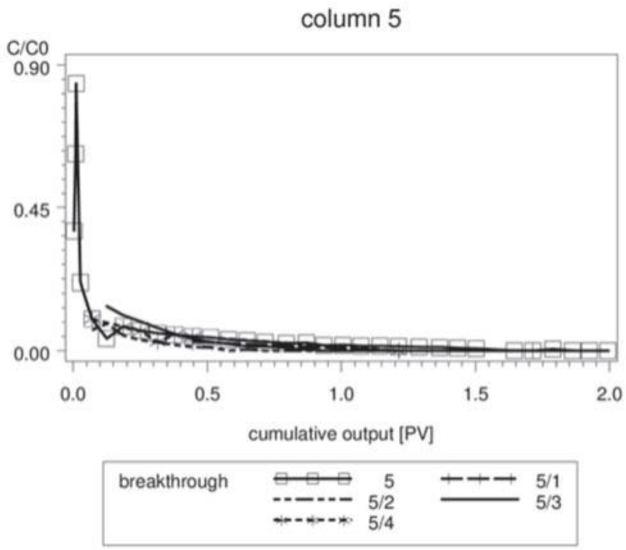

Fig.10. Breakthroughcurvesofcolumn5(experimentalvari-ant2)inunitsoftheporevolume.C=measured concentration,Co=concentrationoftheBrpulses

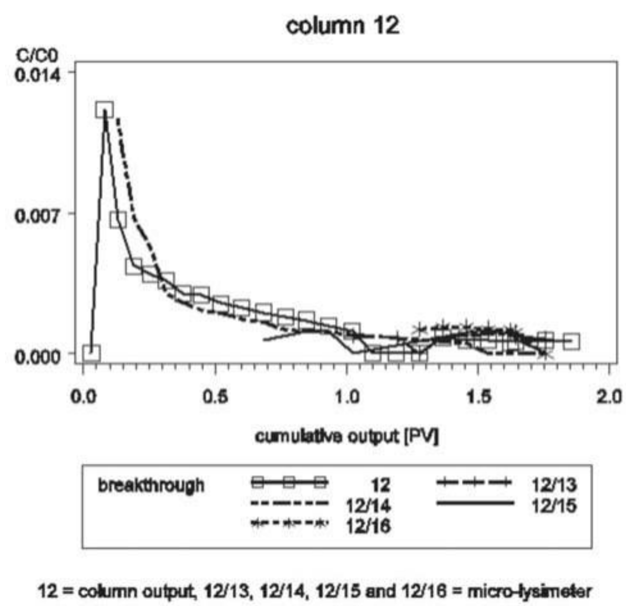

Fig.11. Breakthroughcurvesofcolumn12(experimentalvari-ant3)inunitsoftheporevolume.C=measuredcon-centrationsCo=concentrationoftheBr-pulses

(notshown).Theselysimetershaveparticipatedin thefastbreakthroughviathecoarsepores,*e.g.*column 2(notshown,lysimeters5and7).

Atleastonemicro-lysimeterofcolumn5(Figs. 3,6aand10)hadveryclearcontacttothemiddleof acoarsepore,whichtraversedthroughthesoil column,andwhichpossiblycontributedtothefast transport.Becauseofthedeficientinitialsoilcontact ortoolowsuctioncapacity,thislysimeterdidnot showthefastbreakthrough.Asinglelysimeterofthe drycolumns,lysimeter14ofcolumn12(Figs.4,7a and11),showedanalmostcompletefast breakthrough.Ofallthelysimetersofthiscolumn, thiswasthefirsttoleadtosoilsolutionleaching,and waspresentinthesoilmatrixwithindirectcontactto coarseporespace.Thisconstellation,amixingof indirectcontacttocoarse-porestransportspaceand directcontacttothefine-porematrix,appearstohave thebestpre-conditionforaquickfunctioningofthe lysimeters,aboveall,indriedsoilsubstance.

Poreconnectivityinthecolumnsandtheirimpor-tancefortracertransport

Forabetterunderstandingofthetotaltransport throughthecolumns,thetransportintopsoilandin subsoilwasconsidered.Thesetwowerecharacterized byadifferentsoilstructureandporestructure.The topsoilhadamoreorlessstronglyexpressedcrumb structurewithhighporosity,whereas,theporosityin thesubsoilwaslow,becauseoftheclaycontent. Hence,itsstructurewasstronglyinfluencedbyroots, faunalburrows,andshrinkagecracksthroughdrying, therefore,containsmacropores.Bothsoilregions, accordingtotheirexpressionoftheirmain characteristics,differentlyinfluencedtracertransport inacolumn.

Luo*etal*.(2010)investigatedquantitative relationshipsbetweenmacroporecharacteristicsand twomajorflowandtransportparameters(K_{sat}andλ). Macroporesplayedanimportantrole.Thetraditional CDEmodeledtheBTCswell.Correlationbetweenλ ofthe wholesoilcolumnandK_{sat}valuesoftheB$_t$horizon(notA)im pliedthatthedispersivitywasmainlycontrolledbythehori zonwiththelowestK_{sat}inthesoilcolumn.Themostuseful macropore parametersforpredictingflowandtransportunder saturatedconditionsinthestructuredsoilsincluded macroporosity,numberofpaths,hydraulicradiusand macroporeangle.Thepresenceoftraversingpores(notnec essarilymacroporesintheclassicalsense)in thesubsoilinfluencethevelocityandconcentration ofthetracerstransportinthispart.Thereconstruction oftheflowpatternisdifficult,althoughtheparametersarecl earlydefined.Thisisbecauseoftheinterplayof allfactors,withinitialandboundaryconditionaswatercon tentcanbedifferenteveninasmallspace buthaveagreatinfluence.Further,theproblemexiststhato nlyverticaltransportmechanismwasconsidered.Asis knownfromdye-experiments,the horizontaltransportalsospreadstoagoodextent (GhodratiandJury1990),thatiswhy,thevertically connectedporesdonotleadtopreferentialflow.

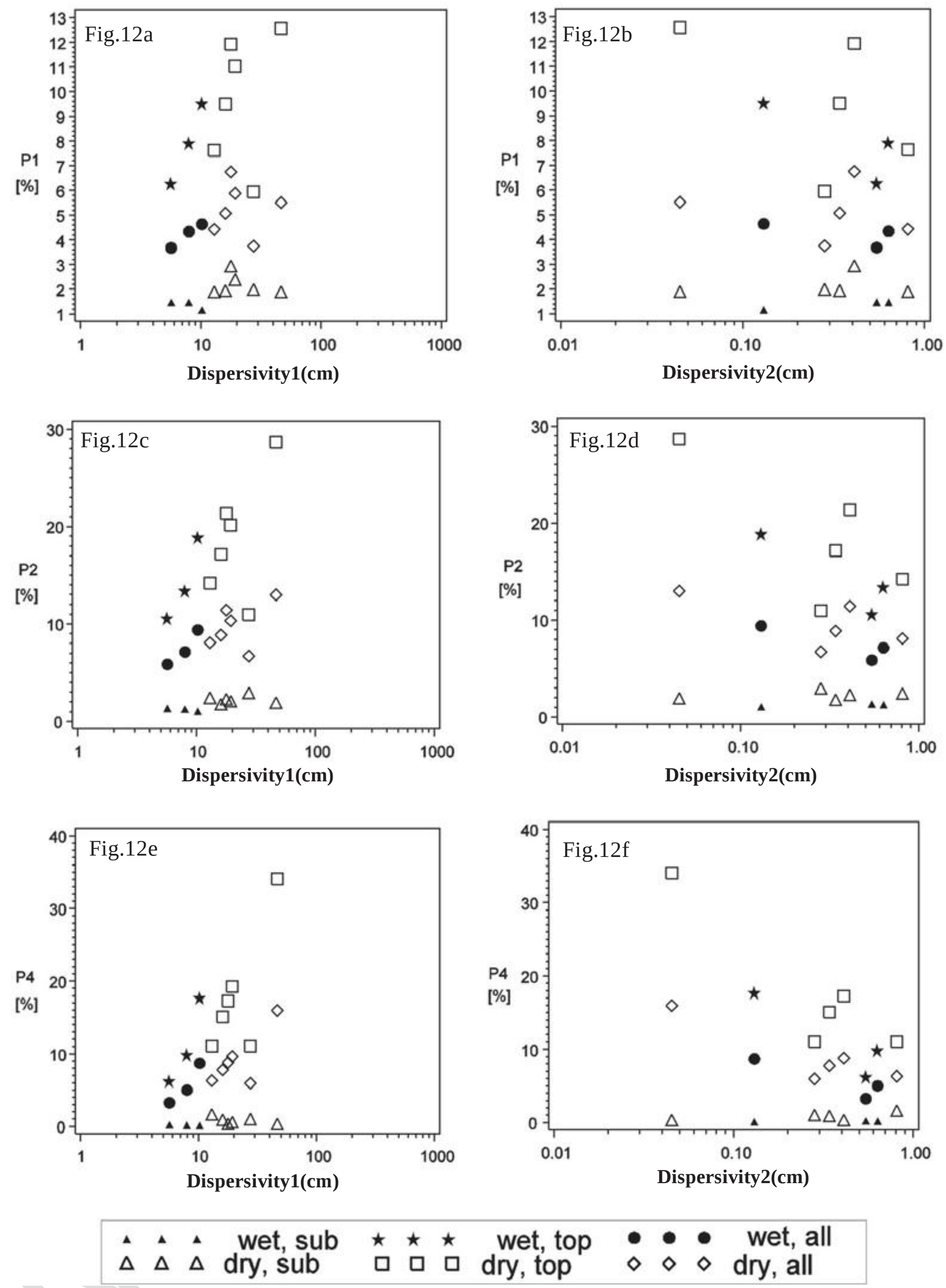

Fig.12. Dispersivityofthebimodalapproachinrelationtoporestructureatthreedifferentscales(P1,P2,P4);threevaluesfor therespectivecolumn.Dispersivity1=D1/*v*1=fastbreakthrough,dispersivity2=*D*2/*v*2=slowbreakthrough(Table2). “Bottom”meanssubsoilofthecolumn;“top”meanstopsoiland“comp.”meanscompletecolumn.

Inthesameway,Flury*etal*.(1994)reported thatamajorpartofthewaterflowedpastthesoil matrix.Asaresult,anunexpectedlysmallportionofthesoil, possibletookpartinthetransport.Booltinkand Bouma (1991) observed discontinuous macropores,so-calledinternalcatchments,which shouldbeintegratedinwaterflowmodeling.From studiesonsoilstructureusingx-rayCT,itwasreportedbyLuo*etal*.(2008)thatnomacropor eswere continuousfromthetoptothebottomofthesoil column,andsomemacroporesbecameineffective becauseofair-entrapment.Theyconcludedthat

Table2. Resultsofbimodalparameterevaluation.Retarda-tionfactorR=1,coefficientofdispersivity(cm^2Day^{-1}),v=averageporewatervelocity($cmDay^{-1}$), D_v/v_v=dispersivity(cm),Br=Bromidequantityof theimpulses(mg).

Column	*D*1/*v*1 (cm)(cm)(mg)	*D*2/*v*2	Br
1	9.0	0.18	14.3
2	8.0	0.63	16.0
3	5.7	0.54	15.0
4	14.5	0.3	15.7
5	19.3	0.0	32.4
6	38.1	0.08	34.5
8	16.0	0.34	14.3
10	24.4	0.49	16.4
11	23.1	0.26	16.8
12	12.9	0.81	11.5

macroporenetworkbyitselfcannotsimplybeequated toapreferentialflownetwork.Accordingly,inthe descriptionofflowprocess,aseriesofcomplex processesneedtobeconsidered.

Inordertodescribetherelationshipbetweenthe BTCandthesoilporecharacteristics,weopposedfit parametersoftheCDEandsoilporeindices.As explainedearlier,theindexes(P_1,P_2andP_4)werecomputedf ortheporestructureofacolumn.P_1isan indexforporestructureinsmallerscale.TheP_4on theotherhand,isanindexforcoarseporestructure (Fig.1).Therespectiveindices,P_1,P_2andP_4areshown ontheordinate,Ontheabscissa,eitherthedispersivityofthe slow(D_1/v_1)orfast(D_2/v_2)areshown(Fig.12, Table2).Thesymbolrepresentsthevariantofthe experiment(dry,wet)andtheareaofthecolumnthe indexappliesto(top=top-soil,bottom=sub-soil, comp.=completecolumn).

Infigures12b,12dand12f,correspondingfast dispersivityvalues(D_2/v_2)inrelationtoindexesforfine(P_1),middle(P_2),orcoarse(P_4)poreswere presented.Atallthethreescalesthesefiguresshowed anegativerelationshiptodispersivity,whichincreased withdecreasingaircontent.Thisrelationshipwas strongerforcoarserporeindexesintopsoil.The transportpathwayappeardtobeshortenedbyhigheraircon tent,whichloweredfastdispersivity.When coarseporeswerepresentinthecolumns(P_4),then withfastbreakthrough,uniformflowwastobe expected,withoutheterogeneityofpathwayofwaterandch emicalmovement.Nearlylinearlydecreasing linescouldbeobserved(Fig.12f)fortopsoiland wholecolumnindexes.Thishappenedtoalesserextentev enwithmorefinelydividedporespace (Fig.12d).Theslowdispersivityvalueshadapositive relationshiptotheporeindicesforallscales(Fig. 12a,12cand12e)andsoilareas,whichwasnearly linearinallscales.Withgrowingporecontentthe heterogeneityofthepathwaysincreased.Again,thisrelati onshipwasmoreapparentintopsoil.

Allresultshavetobeconsideredwithabitof caution,astheCDEfitwasusingamodel,whichfor thedrycolumnsmightbequestionable.Asa mathematicalmodelitreachedplausibledispersityvalu es,though.Itexplainswhywecouldnotdetect differencesamongthesoilcolumnsjustby visualizing.Itcanbeassumedthatallcolumnsshowed macroporetransport,whichwasnotlinkedto dispersivityofthesub-soils.

Conclusions

The3Dreconstructionoftheporoussystemcan beusedtodiscussthesuctionperformanceof individualmicro-lysimetersandforexplainingthe breakthroughcurvesofmicro-lysimetersAnumeric poreindexrepresentingavolume'sporecontentataspecific scalecanbecomputedfromCTdata,and doeshavearelationtoflowparameters.Thepore indexhasgenerallyanegativelenearrelationshipwith thefastdispersivity,andapositivelenearrelationship withtheslowdispersivity.Theserelationssuggest thatwithincreasingporosity,theheterogeneityofthe pathwaysincreases.WeconcludethattheCTimageslikecr oss-sectionsand3Dre-constructionsprovide aninterestingandquiteuniqueinsightintothesoilporesyst emaftermoderatedrying.Cross-sectionsvisualizingtheporecontactofmicro-lysimeters'tipsmayhelptointerpretsoilwatermonitoringi nabetter way.

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