Conceptual modelling of the dynamics of soil macroporosity based on an*in situ* and direct observation of major soil structuring agents during early stage of pedogenesis

Abstract

Many factors affect soil porosity but major of them are soil fauna, plantroots and the climate. Many studies attempted to investigate the effect ofthese factors on the evolution of soil porosity separately. The objective ofthis study is, based on an in situ experiment including three major porosityfactors,proposeaconceptualmodelofsoilmacroporosityevolution.Insituobservationand quantification of the evolution of macroporosity under the influence ofeach agent separately and the three agents combined allow to propose amodelforeachcase.Results show that the evolution of microporosity due to plant roots linear and reach its maximum at the end of the plant cycle. Earthworms create and destruct macroporosity during the up and down movement for food searching. At long term, the consequence of earthworm action results to an increase of macroporosity. Wetting and drying cycle has the same effect as earthworm. At the beginning, when soil shrinks, it leads to a creation of macroporosity that could be disturbed by swelling during soil humectation. Some soil particles migrate in the shrink and reduce the surface of microporosity. When faced to many wetting drying cycle, the surface of macropores increase during time.Mathematicalalgorithmsandcomputingarenecessaryto formalise this model and long-term experiment is needed to validate thismodel.

*Keywords:*Differential equations, Soil structure, Earthworms, Castsproduction,SwellingShrinkage,Plantroots

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1.Introduction

Soil,duetoitsimportanceinfurnishingecosystemservices,attractedthe attentionofmanysoilscientistsformanyyears.Manyprocessesoccurringin soilaredefinedandcharacterizedbuttobetterunderstandthefateofimpor-tantfactors,modellingapproachhasbeendeveloped.Sincethen,avarious modelsconcerningsoilprocessesweredevelopedandahistoricalpointof viewofthismodellingisgivenbyVereecken*etal.*(2016).Amongthese processessoilstructure,definedastherearrangementofsolidsoilparticles gotagreatinterest.Theconsequenceofthisarrangementistheformation ofaggregatesandvoids.Manystudieshighlightthemainfactorsthatinfluencesoilstructureandthefivemajorofthemarei)soilfauna,ii)plant roots,iii)environmentalfactors,iv)inorganicbindingagentsandv)soilmicroorganisms(Six*etal.*,2004).Researchhavebeenleadedtoinvestigate theroleofdifferentagentsontheevolutionofstructure.Plantrootsinfluencesoilstructureindifferentwaysbutthemoststudiedisbyintroducing organicmatter.Thisprocessinwidelyinvestigatedandsomemodelshave beenproposed.Forexample,Roth-Cstudythesoilorganicmatterturnover innon-waterloggedsoils(ColemanandJinkinson,1999)andhowthisprocessisinvolvedinsoilstructure(aggregationformation).BasedonRoth-C, Malamoud*etal*.(2009)proposedanewmodelwhichstudiesthedynamics ofsoilstructure(aggregationandporosity)namedStructure-C.Thismodel writteninMathlabconsistsofthreesubmodels.Anaggregationsubmodel, organicmattersubmodelandporositysubmodel. Theporositysubmodel predictstheevolutionofporosityduringtimeunderspecificconditionsof soilorganicmatterturnover.

Apartfromitsactionincreatingstructurebyintroducingorganicmatter insoil,plantrootsalsoenmeshsoilparticlesandcreatesaggregatesbetween whatporesarecreated.Thisaspectofresearchisnotwidelyexplored.Nevertheless,theprocessisdetailedbyJangorzo*etal.*(2015).Amorecomplex modellingplatformhasbeendevelopedtohelpunderstandingandsimulate majorprocessesgoverningsoilevolution.ThisplatformnamedVirtualSoil orVsoil(Lafolie*etal*.,2015)isdesignedtofacilitatemodellingchemical, physicalandbiologicalinteractionsoccurringinsoilsandimprovethesimulationofanthropicactivitiesandclimatechangeimpactonthesoilecosystem services.Differentcontributorsmayworktogetherinordertodevelopmodulesthatcanbeincorporatedintheplatform.Sincethen,moduleoforganic matterturnover,waterdynamicsaredeveloped.Animportantmoduletodevelopwillbethatwhichconcernthedynamicofsoilstructure(porosityand aggregation).Suchamoduleexists,exampleStructure-Cdevelopedbased onRoth-C.Itdescribestheevolutionofsoilstructureundertheinfluence ofsoilorganicmatterdynamicsandtheagentsthatconditionthisevolution (Malamoud*etal.*,2009).Thismodeldoesnottakeintoaccountthefact thatsoilporosityevolvesaccordingtotheinfluenceofothermajorprocesses likeearthworm activities aswell asthe physical processoccurring in soillike swellingandshrinkage.Theroleofearthwormsinsoilstructureisalsowidely studiedandanattempttomodelthisprocesshasbeenundertaken.

Anotherphenomenonthatinfluencesoilporosityisthewetting-drying cyclerelatedtopropertyofswellingandcrackingofthesoil. Manystud- ieshavebeenundertakentostudytheprocessofsoilcracking(Konradand Ayad,1997;Greco,2002;BraudeauandMohtar,2006;PengandHorn,2007; Chertkov,2012b,a)anditsimpactonsoilporosity(Coppola*etal.*,2012, 2015).Inarecentwork,Stewart*etal*.(2016)showedthatmostofmod- elsdevelopeddonotconsidertheprocessinitswhole.However,thetotal porosityproducedduringsoilcrackinginaswellingsoilcouldbeapportioned inthreeparts:aggregatesporosity,shrinkagecracksandverticalsubsidence andthenproposedaunifiedmodel.Thereisanongoingdebateconcerning theverticalsubsidenceaspartofsoilporosityinaswellingsoil.However,we assumethattheverticalsubsidenceistakenintoaccountwhenconsidering thedecreaseofaggregatesporosityduringsoilcompaction. Moreover,the modelofStewartdidnotconsidertherepeatingwetting-dryingprocessora successiveswelling-shrinkagewhichnaturallyhappenedinaVertisol.This whyheassumedthatthemassmovementanderosionwereinsignificant. But,inawetting-dryingcycle,massmovementisthemajordriverofcracks dynamic(Jangorzo*etal.*,2015).Nevertheless,apartofthismodelcouldbe integratedinanewmodeldevelopmentbyconsideringitasthestateofthe porosityinthefirstswelling-shrinkageprocess.

Twomechanismsdrivetheswelling-shrinkagecycleinsoil. Mechanical loadingmechanismandthesecondassociatedwiththechangeinsuction knownashydraulicloadingmechanism(WangandWei,2014). Mecha- nismofreversibleswelling-shrinkagestrainandtheMechanismofirreversible swelling-shrinkagestrain(WangandWei,2014)showsthebehaviourofsoil volumeduringswelling-shrinkagecycle.Thisvolumeisassumedtobeirre- versible(Tessier,1984;Jangorzo*etal.,*2015)innaturalconditions.Morethe dryingisimportantlessthesoiluptakewaterduringwettingwhichmeans thatthesoilwillswellless(volumedecrease)(CroneyandColeman,1954). Earthworm,consideredasecosystemengineer(Jones*etal.*,1994)havebeen widelystudiedinthecontextoftheirroleinsoilstructure. Theefficiency oftheseengineers(activity),particularlyearthwormsdependsonthreefac- tors(Kretzschmar,1991).However,earthwormsaremoreactiveinarange ofwaterpotential,whensoilislooseanddependingontheperiodofyear. Thisactivityconditionedtheeffectofthisengineeronsoilstructureasthe latterdependsontheintensityofburrowing(Jangorzo*etal*.,2015).Ac- tivityofearthwormisalsoconditionedbysoiltemperatureandindividual massoftheorganism(Kaneda*etal.*,2016).Basedonlaboratoryandfield experiments,manymodelshavebeendevelopedtopredicttheroleofsome earthwormspeciesinsoilaggregation(e.g.Kaneda*etal.*,2016)orinsoil carbonsequestration(e.g.Komarov*etal*.,2017).Butthesemodelsneither theydidnotpredicttheevolutionofsoilporosity~~nor~~theydidnotconsider thesynergythatexistbetweenplantrootsandearthworminsoilstructure (Zangerlé*etal*.,2011;Jangorzo*etal.*,2015).Oneofthefactorthatmost incitesearthwormburrowingisthefoodseeking.However,earthwormmoves intodifferentlayerofsoiltofindfreshorganicmatterthattheydecompose andtranslocatesometimesdeeperinthesoil(Jangorzo,2013).Wecould thenassumethatmorefoodisavailable,greateristheburrowingactivity. ThisassumptionismodelledbyDaniel(1991)whenhestudiedtheeffectof foodconsumptiononaggregatesformation.Thedegreeofsoilorganicmat-tertransformationbyearthwormisconceptualizedandmodelledbyChertov *etal.*(2017)andKomarov*etal*.(2017). Ifthesoilaggregateformationis known,itisnotthecasefortheporosityexistinginandbetweenaggre-gates.Theaimofthisworkistodevelopamathematicalintegratedmodel describingtheporositydynamicsinmodelsoils“constructedTechnosols”. Thismulti-agentsmodeltakesintoaccounttheeffectofthreerankedfactors -wetting-dryingcycle,plantrootsandsoilfauna-(Jangorzo*etal*;2017,data notpublished)intheevolutionofsoilstructure.

2.Modeltheory

2.1.Generalmodelofsoilporositydynamics

Wehypothesisthatthechangesofmacroporosity$P$withtime$t$,$\frac{dP}{dt}$, depends on the variation of macroporosity due to i) soil moisture $f(\Theta)$, ii)thepopulationdynamicsofroots$f$(r),andiii)theearthwormactivity$f$(w)respectively,aswellasaporositydisappearancetermD_P:

$$\frac{dP}{dt}=f(\Theta)+f(r)+f(w)-D_P. \quad (1)$$

2.2. Changes in porosity due to variations in soil humidity (wetting and dry-ingcycles)

In clayey soils like Vertisols or in Technosols made of swelling materialslike paper or iron industry sludges, there are changes in soil porosity withthe variations of soil humidity (Peng and Horn,2007;Huot*et al.*,2014).Thisshrinkageandswellingbehaviourcreates macroporosity in soil when shrinks and decreases soil porosity during swelling processes.

Whenasoilissetupandwatered,thefirstprocessthataffectsitsporosity iswaterloss. Thebehaviourofwatermovementinsoilhasbeenlargelystud- ied,particularlytheprocessofswelling-shrinkage(Smiles,2000).According toitstexture,soilswellswhenitiswettedwhichcausesanincreaseofvol- ume,adecreaseofbulkdensity,andanincreaseinmacroporosity(Smiles, 2000).Conversely,whenthesoildries,itshrinksanditsvolumedecreases whichleadstoanincreaseofsoilbulkdensity(PengandHorn,2007),ade- creaseofaggregatesporosity(microporosity),andanincreaseofshrinkage cracks(macroporosity)(Stewart*etal.,*2016).But,asthevolumeofcracks isimportant,weassumethatthetotalporosityofthesoilincreasesassoon asthewaterpotentialincreases.

Stewart*etal.*(2016)haveproposedandvalidatedaunifiedmodelto representthevariationsofthedifferenttypesofporositywiththechangesin soilhumidity.Theyconsiderthreetypesofporosity: -

Inabsenceofanyotheragents,hereweassumethattheeffectofmicro- organismsisnegligible,themainprocessthatgovernporosityformationis waterflowexpressedbytheswelling-shrinkagephenomenon.Weusedthe equationofStewart*etal.*(2016)tomodelthevariationofporositydueto onewetting-drying cycleforcracksporosity:

$$\phi_{\text{crack}} = (\phi_{\text{pedon}} - \phi_{\text{min}}) \left(\frac{1 - U^q}{1 - \varepsilon U^q} \right), \tag{2}$$

with$U$=Θ/Θ_{max}andotherparametersinStewartetal.(2016).

LinkingStewartetal.(2016)equationwithourframework:

$$f(\Theta)=\frac{\partial \phi_{crack}}{\partial t}. \tag{3}$$

Wethusneedtoderivateϕ_{crack}withtime$t$:

$$f(\Theta) = \frac{[-qU(t)^{q-1}U'(t)(1+\varepsilon U(t)^q)] - [q\varepsilon U(t)^{q-1}U'(t)(1-U(t)^q)]}{(1-\varepsilon U(t)^q)^2} \tag{4}$$

and $U'(t) = \partial\Theta/\partial t$

$$f(\Theta) = (1-\varepsilon)\frac{[-qU(t)^{q-1}] - [2q\varepsilon U(t)^{2q-1}]}{(1-\varepsilon U(t)^q)^2}\frac{\partial\Theta}{\partial t}, \tag{5}$$

where$\varepsilon$and$q$arefittingparameters.

2.3. Changes in porosity due to the dynamics of roots population

Roots have three different impacts on porosity:

- firstly, they fill some available porosity while they are appearing and growing and then free up some pores when ageing and dying (by narrowing) and disappearing (by degrading); this affects macroporosity;

- secondly, when they are growing, they compact the neighbouring soil (rhizosphere) leading to a decrease of what Malamoud *et al.* (2009) called aggregates porosity or the soil microporosity. The intensity of compaction depends on either cracks exist before the appearance of roots or not; however, Jangorzo *et al.* (2015) showed that roots preferentially used existing pores like cracks when growing.

- third, when roots are degraded, they enter into the soil organic matter turnover which also has another impact of soil porosity as demonstrated by many authors (e.g. Coleman and Jinkinson, 1999; Malamoud *et al.*, 2009).

In this model we only consider the effect of roots on the dynamics of macroporosity by infilling.

Jangorzo (2013) and Jangorzo *et al.* (2015) have shown that the impact of roots on macroporosity depends on the age category of the roots. When young roots appear and then mature, they are growing thus leading to a decrease in porosity. During ageing and degradation after death, they are freeing some space which, by consequence lead to an increase in porosity. Thus when roots age and become old roots the porosity increases. Thus, if we consider the total surface fill by roots we can distinguish three different age categories:

- surface with young root $R_y(t)$,
- surface with mature root $R_m(t)$,
- surface with old root $R_o(t)$,

The relationship between those three categories of the root population can be modelled as shown in Figure 1. Here we consider there is no death of young and mature roots. The computation of the root surface dynamics is

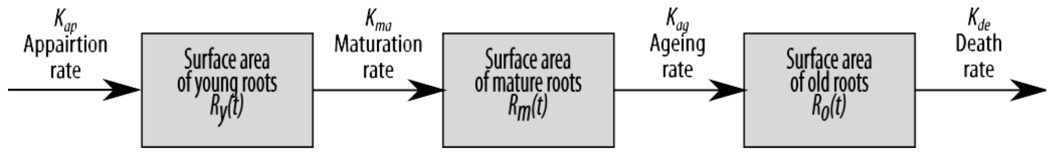

Figure1:Conceptualmodelofthedynamicofrootsurface.
Possibilitytoconsideronlytwocategoriesfortherootpopulation.κfunctionoftime?

givenbythefollowingequations,with$R_y(t)$,$R_m(t)$and$R_o(t)$,thesurface areasoccupiedbyyoung,mature,andoldroots,respectively:

$$\frac{\partial R_y}{\partial t} = \kappa_{ap}(t) - \kappa_{ma}(t) \quad (6)$$

$$\frac{\partial R_m}{\partial t} = \kappa_{ma}(t) - \kappa_{ag}(t) \quad (7)$$

$$\frac{\partial R_o}{\partial t} = \kappa_{ag}(t) - \kappa_{de}(t), \quad (8)$$

with$\kappa_{ap}(t)$theapparitionrateofyoungroots,$\kappa_{ma}(t)$thematuringrateofyoung roots,$\kappa_{ag}(t)$ theageing rateof matureroots,and $\kappa_{de}(t)$the death rateof old roots.No death of young and mature roots is considered.Thus thechangesinthetotalsurfaceoccupiedbyrootsis:

$$\frac{\partial R}{\partial t} = \kappa_{ap}(t) - \kappa_{de}(t) \quad (9)$$

Thegeneralequationforthechangesinporosityduetothepopulationdynamicsofroots isfunctionof$\kappa_{ap}(t)$,$\kappa_{ma}(t)$,$\kappa_{ag}(t)$,and$\kappa_{de}(t)$:

$$f(\mathrm{r}) = -\kappa_{ap}(t) - \kappa_{ma}(t) + C_{ag}\kappa_{ag}(t) + \kappa_{de}(t). \quad (10)$$

This equation means that for each surface increase of young and matureroots there is a direct proportional loss of porosity.Reversibly, for eachsurface decrease of old roots by death,there is a direct proportional increaseofporosity.Whenmaturerootsareageingandbecomeold,theconsequenceis the increase of porosity. dt_1 is the time elapsed between the moment thefirstrootappearsandthemomentitstartsnarrowing.dt_2isthetimeelapsedbetween dt_1 and the lifetime of the plant or roots.dt_3 is the time elapsedbetween dt_2 and the moment all dead roots disappeared or are degraded.Thistimeissoilmoistureandbiologicalactivitydependent. Asyoungand matureroots have the same effect on soil porosity, we include the youngroots andmature by extending the time. The previous equation then becomes:

$$f(\mathrm{r}) = -K_{ma}(dt_1) + K_{ag}(dt_2) + R_{de}(dt_3) \quad (11)$$

From equations 10, 6, 7, 8, **??**, we can deduce:

$$f(\mathrm{r}) = kR_{\mathrm{o}}(t) - \kappa_{\mathrm{ap}}(t) - \frac{\partial R_{\mathrm{m}}}{\partial t}. \quad (12)$$

$R_{\mathrm{y}}(t)$, $R_{\mathrm{m}}(t)$ and $R_{\mathrm{o}}(t)$ and their time derivatives can be obtained from the experimental data at each time step. If no experimental data are available general forms for $\kappa_{\mathrm{ap}}(t)$, $\kappa_{\mathrm{ma}}(t)$, and $\kappa_{\mathrm{ag}}(t)$ must be proposed.

*2.4. **Changes in porosity due to earthworms activity***

Jangorzo et al.(2013) showed that the intensity of earthworm activity increase soil porosity. This activity is function of i) the number of earthworm, ii) the quantity of organic matter and iii) the soil moisture. Many authorshave described the soil organic matter turnover and models were developed. Among these models we can announce the RothC (Coleman and Jinkinson, 1999), StructureC (Malamoud *et al.* 2009) and a module in Vsoil (Lafolie *et al.*, 2015). The general equation of porosity evolution according to the intensity of activity is as follows:

$$F(w) = k_{I_w} \times I_w \quad (13)$$

$$I_w = f(I_w^{\max}, \mathrm{nb}_w, \Theta, \mathrm{MO}) \quad (14)$$

Where $F(w)$ is the rate of porosity changes due to worm activity; I_w is the total intensity of worm activity; $I_w max$ is the maximal intensity of wormactivity; ki_w is the conversion rate between the intensity of worm activityand the proportion of pore surface; nb_w is the number of earthworm; Θ is the soil moisture or water potential and MO is the soil organic matter.

2.4.1. Worm activity in relation with soil humidity

In relation to earthworm development and activity, soil humidity is better expressed as water potential due to the physiological characteristics of these organisms (Kretzschmar, 1991; Kretzschmarand Bruchou, 1991; Holmstrup, 2001; Moreau-Valancogne *et al.*, 2013). Some studies showed the influence ofwaterpotentialonearthwormdevelopment(KretzschmarandBruchou, 1991;Holmstrup,2001;Eriksen-HamelandWhalen,2006)andactivityof earthworm(Kretzschmar,1991;Hindell*etal*.,1994;Daniel*etal.,*1996).All thosearticlesassessthedevelopmentortheactivityof*Aporrectodeaspp.*, whichareendogeicoraneciceearthworms.Otherfactorscanbetestedin parallel(compaction,temperature).The earthworms activityisassessed via theircastproduction.Kretzschmar(1991);Hindell*etal.*(1994);Daniel *etal.* (1996)showthesamepatternfortherelationshipbetweencastproduction andwaterpotential:nooranegligiblecastproductionforwaterpotentials morenegativethanabasepotential$\Psi_b$andthenalinearincreaseofcast productionwithincreasingwaterpotentialuntilΨ=0.Theestimatedvalues of$\Psi_b$varywithspeciesbutindicateanarrowmoisturetolerancerange(Table2.4.1).$\Psi_b$seemtovarywiththeecologicaltype:around-20–-40kPa foranecicandaround-10kPaforendogeic.

Reference	**Species**	**Ecological type**	**Ψ_b (kPa)**
Kretzschmar(1991)	*Aporrectodealonga*	anecic	-40
Hindell*etal.*(1994)	*Aporrectodearosea*	endogeic	-10
id.	*Aporrectodeacaliginosa*	endogeic	-10
id.	*Aporrectodeacaliginosaf.trapezoides*	endogeic	-5
Daniel*etal.*(1996)	*Aporrectodeanocturna*	anecic	-20

Table1:Valueofthebasewaterpotential,Ψ_b,measuredbydifferentauthors.

Therelationshipbetweentheactivityof*Lumbricuscastaneus*(epi-anecic worm,testedinJangorzo(2013))andthewaterpotentialshowsthesame patternasidentifiedforaneciceearthwormsintheliterature.Sowehypothesisedthatequations13 and 14canbeinferredfor*L.castaneus*.Weassume thatthenormalisedearthwormactivityisproportionaltothenormalisedcast production.Manyequationswereusedtomodeltheevolutionofearthworms activityasfunctionofwaterpotentialbutweareinterestedinthatissuing thecastproduction.Forexample*Danieletal.*(1996)usedanexponential equationtopredicttheevolutionofcastproductionby*Aporectodeanocturna*.

$$C^*(P)=he^{(Pi)} \quad \text{for} \quad -0.06\text{MPa}\le P\le 0\text{MPa} \qquad (15)$$

where$C^*(P)$isthetransformedrateofcatproductionasafunctionofwaterpotentialinMPaand$h$and$i$areconstants. Theyassumedthatcast

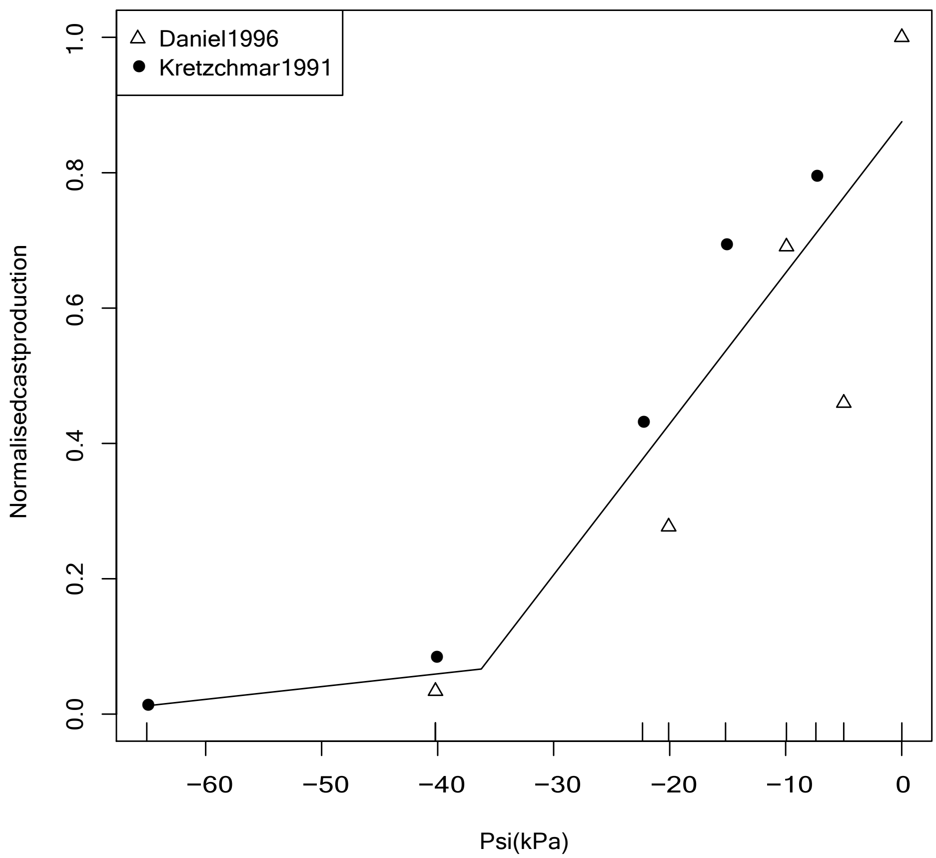

Figure 2:Model of the normalised cast production as a function of water potential foranecic earthworms.The data were extracted from Kretzschmar(1991) and Daniel *et al.*(1996).Thefittedvaluesareshownaspoints.

increasedexponentiallywiththeincreaseofwaterpotential.Kaneda*etal*. (2016)ontheotherhandusedthemodifiedGompertzfunctionexpressedas follows:

$$f(\Psi)=\zeta\exp^{-(\exp^{(-(\Psi+\eta)/\vartheta)})} \quad \text{for} \quad -90.6\text{kPa}<P<-2\text{kPa} \tag{16}$$

where$f(P)$standsforthesoilaggregateformationrate-modifyingfactorfor soilmoistureasafunctionofwaterpotentialΨ,inkilopascalζ,$\eta$and$\vartheta$are constantexperimentalcoefficientsdeterminingslopeofthecurve.Theyuse thisfunctionratherthanDaniel'sbecausetheirdatashowedalevelling-off nearthewaterpotential0kPa. Incontrary,experimentaldataobtained byimageanalysisshowedtheincreaseofearthwormactivitywhenwater potentialincreases(Jangorzo,2013;Jangorzo*etal.*,2015). Wetherefore usedtheDaniel'sexponentialequationtopredicttheevolutionofearthworm activity.Thisrelationcouldbeformalizedbythenormalizedcastproduction equation:

$$I_w(\Psi)=he^{(\Psi i)} \tag{17}$$

Hereweconsiderthecastsproductionasaresultoftheintenseactivityof earthwormandthisisproportionaltotheporosityproduction. However, whenearthwormsburrow,theydig,ingestsoilparticlesmixedwithorganic matterthattheyexcretelikecasts.So,thecastproducedareproportionalto thevoidcreatedinthesoil.Sayk_{I_w}thecoefficientindicatingtheconversion between $I_w$andporosity.We assumethat$0<k_{I_w}<1$asit isa ratiobetween the$I_w$andtheI_w^{max}.Itmeansthatnotallthecastsproducedareequivalent totheporositycreated.

2.4.2. ***Wormactivityinrelationwithnumberofearthworms***

Mostofexperimentswereundertakenwithasingleindividualofearth-worm.Theeffectofmanyindividualsisnotarithmeticbutithasbeenshown thatmorethenumberofearthwormishigh,greateristheintensityandso theporositycreated(Jangorzo*etal.,*2015).However,equation 17couldberearrangedasfollows:

$$I_w(\Psi)=nb_w\times he^{(\Psi i)} \tag{18}$$

Wherenb_wisthenumberofearthworms

2.4.3. ***Wormactivityinrelationwithorganicmattercontent***

Organicmatterisusedbyearthwormsforfeedingandtheyburrowin ordertofindfood.Inthismodel,weassumethattheorganicmattercontent isconstantasthequantityintroducedinthesystemdoesnotvary.However, thevariationofearthwormactivityasfunctionoforganicmatterisequalto zeroaswellasthatofsoiltemperature.

Combiningtheequations13,14and18wecanwritethegeneralequation ofporosityevolutionasfunctionofearthwormsactivityasfollows:

$$F(w)=k_l\times n_w b_w\times he^{(\Psi i)} \qquad (19)$$

2.5. ***Porositydisappearance***

Wesuggestthataproportionofthetotalporositydisappearedateach timestep: Twoprocessesinduceporositydisappearanceaccordingtoour assumption: i)waterloadingchargeduringwettingorwateringandsoil fauna(earthworms)whenburrowing.

$$D_P=f(\Theta,I_w) \qquad (20)$$

2.5.1. ***Porositydisappearanceduetowatering***

Whenwaterisaddedinastructuredsoil,accordingtothestabilityof thesoil,thiswaterinduceextinctionofsomeaggregates.Duringwaterflow, theseparticlesaretransportdeepinthesoilthroughporosity.Atthelimitof waterinfiltration,these particlesaredeposited creatingfilings.Thisprocess leadtothedecreaseofporosity. Howeverasuccessivewateringwithout bioturbationleadundoubtedlytoadisappearanceofsoilmacropores. Say P_0theporosityofthesystematT_0. Afterthefirstwatering,theporosity decreaseintoP_1atT_1.After$n$seriesofwateringwehaveaporosityofP_n. Thetotalporositythatdisappearsis:

$$\Delta(P_\Theta)=\sum_{1}^{n}(P_{n+1}-P_n) \qquad (21)$$

Where$P$istheporosity,$n$thenumberofwateringseriesandthe$_\Theta$meansthatthede creaseisduetowatering.

2.5.2. ***Porositydisappearanceduetoearthwormsactivity***

Inpresenceofearthworms,weassumethatthedecreaseofporositydue towateringisnullasduringburrowingearthwormarewillingtoextractthe filings.Theonlyactionthatdecreasesporosityisthedepositofcastsin burrows.Thisactiondependsonhowmanytimesanearthwormspassesin aburrow.SayP_0theporosityofthesystematT_0. Afterthefirstpassage (burrowing),theporositydecreasesintoP_1atT_1.After$n$seriesofburrowing wehaveaporosityofP_n.Thetotalporositythatdisappearsis:

$$\Delta(P_w) = \sum_{1}^{n}(P_{n+1} - P_n) \qquad (22)$$

Where$P$istheporosity,$n$thenumberofearthwormactivity(burrowing) andthe$_w$meansthatthedecreaseisduetoburrowing.

Thesolutionsofequations21and22couldbeobtainedusingtheleastmean squaremethodsasexperiencedbyDaniel(1991);Daniel*etal*.(1996).The principleofleastmeansquaremethodisformalizedby(Stocker*etal.*,2002) whichstipulatesthat: Givenafunction$y(x)=y(x;a)$dependantonapa- rameter$a$and$n$couplesofvalues$(x_i;y_i)$,theoptimalparameter$a$isdefined bytheGaussfunctionasfollows:

$$\sum_{i}^{n}(y_i - y(x_i;a))^2 = Min_a \qquad (23)$$

The idea behind this function is that it minimise the variable *a* and tends to aresidual.In the case of our study, it means that the disappearance of porositydue to watering and earthworm activity is minimised.However the porositydecreases at each time step and at each watering, but due to the action ofplants roots or burrowing, the decrease is compensate latter particularly byearthworms.This is why, unless this temporary decrease, the surface area ofporosityincreaseswithtime.

*2.6.**Submodelsintegration***

Inourapproach,weassumedthatdifferentfactorsactedsuccessivelyin soilstructuring.Beginningbythesoilmoisturewhichisthelimitingfactor tobiologicalactivity.Secondplantsfindidealconditionstodevelopandthen soilfaunalikeearthworms.Tomaintainanequilibrium,aproportionofsoil structuredisappearsduetothesamestructuringagents,primarilywater.

Rearranging1weobtained:

$$\frac{dP}{dt} = [(I_w^{max} \times nb_w)^{-zv} \times \left\{ \begin{array}{l} 0,0224\psi + 0,8764, \text{for } \psi \; < \; \Psi_\text{b} \\ 0,0019\psi + 0,1379, \text{for } \psi \; > \; \Psi_\text{b} \end{array} \right] \tag{24}$$

$$+[(3+\eta_{ar}) - \frac{(D_b yr + D_b ar + D_b or)}{D_s}] \tag{25}$$

$$+[\int_1^n (\frac{\varepsilon + 1}{\varepsilon + \Theta^{-q}},)] - D_P \tag{26}$$

3.Modelimplementation

Anexperimentwassetupinaclimatechamberwheretheeffectof wetting-dryingcycle,plantrootsandearthwormactivityonsoilstructure hasbeenstudied.Thisexperimentwasrunduring14months;imageswere recordedusingSoilinsight(INRA,2015),adispositiveof*insitu*monitoring ofsoilstructuredevelopedbyJangorzo(2013)andsoilstructureparameters werequantifiedbyimageanalysis(Jangorzo*etal.*,2013,2014,2015).Three replicatesofeachfactorwererealized.Theexperimentaldesignwasfullyde- scribedinJangorzo(2013).

3.1.Initialconditions

Atthebeginningoftheexperiment$t$=0,thesurfaceareasofporosity andaggregateswerequantifiedbutthesurfaceareaofrootswasnullaswell astheearthwormactivity.

$$P(t=0)=P_0 \tag{27}$$

$$r(t=0)=0 \tag{28}$$

$$I_w(t=0)=0 \tag{29}$$

3.2.Swelling-Shrinkageparameters

Themesocosmusedinthisexperimentwerefilledwithaconstructed Technosol 500µmsieved.The soilwasmadeby amixtureof TreatedIndus- trial Soil (TIS) and Paper mill-Sludge (PS). At the top of the cosm a thin layerofcompostwaslayedout. Cosmswerefirstmoistenedbycapillarity uptakeuntilsaturationandgravimetricwatercontentatfieldcapacitywas measuredbyweighing.Thenfourwetting-dryingcycleswhereapplied.After saturation,thesystemwasletfordryinguntil20%. Thenitiswettedun- tilsaturationandtheexcesswaterwascollectedasleachate.Regularlythe cosmswereweighedtodeterminethewatercontent.Basedontheseinfor-mationtherelationbetweenmatricpotentialandgravimetricwatercontent wasestablishusinghydrus. Imageswereanalysedandcracksparameters werequantified.

3.3.Plantrootsparameters

Inothercosms,fourseedsof*Lupinusalbus*weresownandrootdevel-opmentismonitoredasdescribedbyJangorzo*etal.*(2015). Fourdays afterthebeginningoftheexperiment,thefirstrootsappeared.SayD_1this date. Rootscontinuegrowingduringtimeandthesurfaceiscalculatedby imageanalysis. Bycomparingdifferentimagesgenerated,weidentifythe timewhenrootsstopgrowing.SayD_2thisday.Thenthedt_1isdeducedas follows:$dt_1=D_2-D1$. Thevariationofrootssurfaceaccordingtotime $\frac{\partial R_m}{\partial t}$ iscalculated.Theexperimentcontinuedrunningandat amomentplant rootsweredeadunlessthesystemwaswatered.SayD_3thisdate.Thetime elapsedduringrootsnarrowing$dt_2=D_3-D_2$isdetermined.Knowingthat thetotalsurfaceofdeadrootsisquantified,thenthevariationrate $\frac{\partial R_o}{\partial t}$ is calculated.Therateofdeadrootsdegradationisdeterminedassoonasroots disappeared.Thiscoefficientcanalsobedeterminedusingtheequationof LafolieusedinVsoil.

3.4.Earthwormsactivityparameters

Incosmscontainingplantroots,wereintroducedsixindividuals(nb_w)of *Lumbricuscastaneus*.Thesoilmoisturewasmaintainedinarangebetween 60%fieldcapacityand80%filedcapacity.Usinghydrus,thismoisturecon-tentisequivalenttoacorrespondingsuctionΨ.Asinthepreviousystems, imagesweregeneratedeachtwohourswhatallowsustomonitortheearth-wormactivity.Thedifferentoperationsrecordedarethenumberofvisible actionsmadebyaworm: i)creatingaburrow,ii)filingaburrow,iii)en-largingburrow;iv)unchangedburrow((Jangorzo*etal.*,2015).Thenthe intensityofearthwormsactivity$I_w$wasdeterminedknowingthenumberof individualsandthetimeelapsed.Moreover,imagewereanalysedtoquantify theevolutionofsoilporosity.

4.Conclusionandperspectives

Basedonaninnovativeexperimentalset-upofsoilobservationandquan-tification,weproposedaconceptualmodelofsoilporositydynamicsunder theinfluenceofthreeaggregationfactors.Forthis,threeagentswereexperimented:wetting-dryingcycleforenvironmentalfactor,*Lupunusalbus*for plantrootsand*Lumbricuscastaneus*forsoilfauna.Tovalidatethismodel, itisimportanttosetupanewexperimentandresolvethedifferentequations bycomputingthem.

Appendix A.Variabledefinitions

AllthevariablesusedinthemodelaresummarisedinTableA.1.

Var.	Definition	Units	Source
a_{r_y}	Apparitionrate of young roots	$mm^2 \times 10^{-2}$ $mm^{-2} \times h^{-1}$	
$A(t)$	Surfaceareaofthesoilaggregatesinproportiontothe total surface of the pic-ture	$mm^2 \times 10^{-2}$ mm^{-2}	Obtained by imageanalysison experimentaldata (Jangorzo, 2013)
d_{r_d}	Degradationrate of dead roots	$mm^2 \times 10^{-2}$ $mm^{-2} \times h^{-1}$	
D_P	Destruction rate of the porosity	$mm^2 \times 10^{-2}$ $mm^{-2} \times h^{-1}$	Literature review on soilcompaction and collapse, experimental framework
ϑ	Rateof porosity changes duetosoilhumidity(wettinganddryingcycles)	$mm^2 \times 10^{-2}$ $mm^{-2} \times h^{-1}$	
$f(\mathrm{w})$	Rateof porosity changes duetowormactivity	$mm^2 \times 10^{-2}$ $mm^{-2} \times h^{-1}$	
$f(\mathrm{r})$	Rateof porosity changes duetorootdynamics	$mm^2 \times 10^{-2}$ $mm^{-2} \times h^{-1}$	
I_w	Totalintensityofwormactivity	Numberofworm actionsperhour	Computed by image analysis fromexperimen-

			taldata

TableA.1–continuedfrompreviouspage

Var.	Definition	Units	Source
I_w^{max}	Maximalintensityofworm activity	Numberofworm actions per hourandperindivid-ual	Computed by imageanalysisfromexperi-mental data Jangorzo(2013)
k	Factorofporositydestruc-tion(collapseduetohumid-ity)	Dimensionless	Calibration or literaturereview
k_{I_w}	Conversion rate between theintensity of worm activ-ityandporesurfacepropor-tion	$mm^2 \times 10^{-2}$ mm^{-2}per wormaction	
k_{r_d}	Conversion rate between the surface of degradedrootsandtheporesurface	Dimensionless	Calibration or computationfrom experi-mental data Jangorzo(2013)
k_{r_y}	Conversion rate between thesurfaceareaofnewyoungrootsandtheporesurfacearea(proportionofporosity occupied by the surfaceareaofnewyoungroots)	Dimensionless	Calibration or computationfrom experi-mental dataJangorzo(2013)
$k_{r_{y\to o}}$	Conversion rate between the surface area of new oldrootsandtheporesurfacearea	Dimensionless	Calibration or computationfrom experi-mental data Jangorzo(2013)
$k_{r_{o\to d}}$	Conversion rate between thesurfaceareaofnewdeadrootsandtheporesurfacearea	Dimensionless	Calibration or computationfrom experi-mental data Jangorzo(2013)

TableA.1–continuedfrompreviouspage

Var.	Definition	Units	Source
k_{Θ}	Conversion rate between humidity variations andporesurface proportion	$mm^2 \times 10^{-2}$ mm^{-2} per soilhumi dityunit	Literature review on shrinking, ex-perimental framework
m_{r_d}	Deathrate/mortalityofold roots	$mm^2 \times 10^{-2}$ $mm^{-2} \times h^{-1}$	
MO	Soilorganicmattercontent	$g.g^{-1}$	Literature re-view
nb_w	Numberofearthworms	Individuals	
$P(t)$	Surfaceareaoftheporosity (>50 μm) in proportion tothe total surface of the pic-ture	$mm^2 \times 10^{-2}$ mm^{-2}	Obtained by image analysis onexperimental data(Jangorzo,2013)
P_0	Surfaceareaoftheporosity (>50 μm) in proportion tothe total surface of the pic-tureattheinitialtime$t$=0	$mm^2 \times 10^{-2}$ mm^{-2}	Obtained by imageanalysison experimentaldata (Jangorzo, 2013)
$R(t)$	Totalsurfaceareaoccupied byrootsinproportiontothe total surface of the pic-ture	$mm^2 \times 10^{-2}$ mm^{-2}	Obtained by imageanalysison experimentaldata (Jangorzo, 2013)
$R_o(t)$	Surfaceareawitholdroots inproportiontothetotalsurface ofthepicture	$mm^2 \times 10^{-2}$ mm^{-2}	Obtained by imageanalysison experimentaldata (Jangorzo, 2013)
$R_m(t)$	Surfacearea with mature rootsinproportiontothetotalsurfaceofthepicture	$mm^2 \times 10^{-2}$ mm^{-2}	Obtained by imageanalysison experimentaldata (Jangorzo, 2013)

TableA.1–continuedfrompreviouspage

Var.	Definition	Units	Source
$R_y(t)$	Surfaceareawithyoungrootsinproportiontothetotalsurfaceofthepicture	$mm^2 \times 10^{-2}$ mm^{-2}	Obtainedbyimageanalysison experimentaldata(Jangorzo, 2013)
t	Time	Hour(h)	Experimentaltime step is 2hforatotallengthoftheexperimentof14 months
v_{r_y}	Ageingrateofyoungroots (conversioninoldroots)	$mm^2 \times 10^{-2}$ $mm^{-2} \times h^{-1}$	
$\kappa_{d_{r_d}}$	Coefficientofrootdegra-dation(proportionofrootdegradationinrelationtothepopulationofdead roots)	h^{-1}	Calibration or literaturereview
Θ	Soilhumidityormatricpo-tential(Ψ)	Unitsinrelationwiththechosen variables	Literature re-view

TableA.1:Descriptionoftheusedvariables.Var. :Variables.

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