

## MODELLING NATURAL BURROW SYSTEMS IN SOIL BY FIBRE PROCESS: MONTE-CARLO TEST ON INDEPENDENCE OF FIBRE CHARACTERISTICS

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### ABSTRACT

The presence of earthworm burrows in soil has been shown to increase gas diffusion in the soil depth (Kretzschmar and Monestiez, 1992). One of the suspected effects of burrow arrangement on gas diffusion is addressed by the estimation of weighted distances in the burrow system assuming much quicker diffusion through the burrows than in the surrounding soil. The simulations used in previous papers (Monestiez and Kretzschmar, 1989; 1992) were based on Poisson distribution of fibres and on a hypothesis of independence between length and orientation. The present paper focuses on applicability of these assumptions to natural burrow systems. Considering a burrow system as a three-dimensional fibre process, independence assumption of positions of the uppermost points of the fibres was tested using a Monte-Carlo procedure. The latter has been performed conditionally to the empirical distribution of fibre length and orientation. The criterion was based on the weighted distance distribution that is sensitive enough local interactions between fibres. The tests were applied to several natural burrow systems which were described through geometrical characteristics (Kretzschmar, 1988; Kretzschmar and Monestiez, 1987) and showed seasonal variations due to earthworm activities.

Keywords: fibre process, Monte-Carlo test, pore system, second-order statistics, soil burrows.

### INTRODUCTION

The porosity created by earthworm activity in soil represents a small part of the total porosity but plays an important role in soil and plant respiration and leads to significantly increased gas transfer in soils. The pores resulting from the earthworm activity look like thin cylinders and are usually not connected.

However, even if the pores are not connected, the pore system functions as a network. This property leads us to model it as a network and to define preferential paths inside the soil using the pores. A weighted distance along these paths was defined and found to be in quantitative agreement with diffusion measurements (Kretzschmar and Monestiez, 1992).

The previous simulations experiments utilizing this distance and the related geometrical patterns (Monestiez and Kretzschmar, 1989; 1992) were based on Poisson boolean processes of fibres, i. e., on a hypothesis of independence between length, orientation and location of individual fibres.

This paper focuses on the applicability of these assumptions to natural burrow systems. The test will be based on the weighted distance distribution which characterizes the network from the viewpoint of the global gas transfer properties.

MATERIAL, MODEL AND METHOD

**The natural burrow systems:** The systems described below were collected from a permanent pasture near Dijon (France). The total soil volume described was 10 x 10 x 100 cm, and the coordinates of each burrow, i.e., extremities and points where the direction changed, were recorded in three dimensions. These observations were replicated three times (June, December and February).

Figure 1 shows vertical projections of these natural burrow systems.

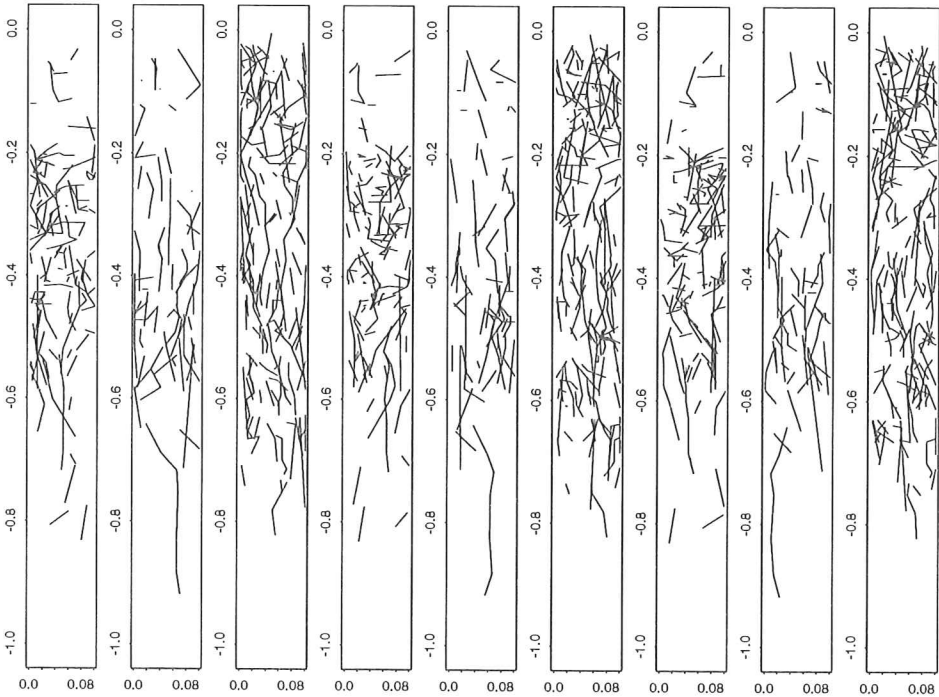


Figure 1. Projection of pore systems onto a vertical plane (units in metres). From left to right: actual systems 3 (June), 4 (December), 5 (February), then two sequences of simulations of the conditional boolean Poisson process conditioned by the systems 3, 4, 5.

The three observed systems do represent seasonal variation. This is mainly marked by the fact that the top 20 cm in systems 3 and 4 are almost empty of burrows, because the earthworms destroy burrows at the beginning of summer and dig again near the surface quite late in winter. System 5 represents the highest density of a burrow system.

**The random pore model:** Based on observations of natural burrow systems, a boolean Poisson fibre process is used to generate similar spatial networks.

Let  $\Phi = \sum l_i$  denote a boolean fibre process in  $R^3$ . Each fibre  $l_i$  has a length  $\nu(l_i)$  and is a sequence of  $N_i$  segments. Let  $x_i^1$  be the upper point of the first segment of  $l_i$ ,  $y_i^1$

its lower point which is the upper point of the second segment (if  $N_i > 1$ ), till the last extremity  $y_i^{N_i}$ .

Let  $(\psi_i^k, \theta_i^k, k \in [1, N_i])$  be the sequence of angular orientations of  $\vec{x_i^k y_i^k}$ : where  $\theta_i^k$  is the angle between  $x_i^k y_i^k$  and the vertical axis, and  $\psi_i^k$  is the angle between the projection of the segment on a horizontal plane and an arbitrary horizontal axis.

We suppose in the following that the point process of the upper points  $x_i^1$  of fibres is a Poisson point process whose intensity  $\lambda$  depends only of the vertical coordinate. We suppose also that the distribution of lengths and angles  $\theta_i^k$  of the segments does not depend upon  $\psi_i^k$ ,

Let  $B$  be a cubic observation window, with one of its faces horizontal. Let  $P_z(x_i^k)$  be the projection of  $x_i^k$  on the vertical axis. We consider  $\Phi'$ , the process  $\Phi$  conditioned by :

- the empirical distribution of  $(P_z(x_i^k), \nu(l_i), \theta_i^k)$  of the fibres not intersecting  $\partial B$ ,
- the empirical distribution of  $(x_i^k, \nu(l_i \cap B), \theta_i^k)$  of the fibres intersecting  $\partial B$  where  $x_i^k$  denotes now the point of  $l_i \cap \partial B$ ;

$\partial B$  is the boundary of  $B$  not including the upper and lower bases of  $B$ .

Due to the boolean Poisson assumption, the segments belonging to different fibres of  $\Phi'$  are independent. The upper points of the fibres are independent with a non-stationary density. Realizations of  $\Phi'$  are presented in Figure 1 and may be compared to the actual systems.

**The Monte-Carlo test:** The test was performed using a Monte-Carlo approach (Diggle 1983, Barnard 1963).

Let  $T(\phi_i)$  be a statistic measured on a realization  $\phi_i$  of  $\Phi'$ . Let  $n$  be the number of realizations of  $\Phi'$  and let  $\phi_0$  be the observation. Under the null hypothesis,

$$P(T(\phi_0) \in [\inf(T(\phi_i), 1 \leq i \leq n), \sup(T(\phi_i), 1 \leq i \leq n)]) = n/(n + 1) \tag{1}$$

The proposed method allows to test the boolean assumption without modelling the distribution of  $(P_z(x_i^k), \nu(l_i), \theta_i^k)$ .

With nineteen realizations of the conditional process  $\Phi'$ , we get a 5% test and with ninety realizations a 1% test.

**The distance distribution:** As the statistic  $T(\phi_i)$ , we computed the empirical distribution function of the weighted distance between the soil surface and a horizontal section in soil, with the burrows behaving as direct paths. This distance, introduced in Monestiez and Kretzschmar (1989), is defined by

$$d(x, S) = \text{Min}_{\forall \mathcal{P}_{x \rightarrow S}} \left[ \sum_{i=1}^n w(p_i) \nu(p_i) \right] \tag{2}$$

where  $\mathcal{P}_{x \rightarrow S}$  is any continuous path from  $x$  to the surface  $S$ , the sequence  $\{p_i, i = 1, \dots, n\}$  denotes a decomposition of  $\mathcal{P}_{x \rightarrow S}$  into elementary sub-paths  $p_i$  either inside a pore with  $w(p_i) = 0$  or outside the pores with  $w(p_i) = 1$ . The length of  $p_i$  is denoted by  $\nu(p_i)$ . This distance is in fact a cumulated sum of inter-burrow minimal distances (or inter-fibre distances), minimizing the diffusion path between any point in the soil and the soil surface. The empirical distributions of distances were computed for three levels (10, 30 and 50 cm deep) in the soil with burrow systems.

## RESULTS

For example, let us consider the system 5 (February) at the 30-cm-deep level. Figure 2 (left) shows in thick solid line the distribution of distances for the actual burrow system. The nineteen other solid lines issued from nineteen realizations of the process  $\Phi'$  conditioned by the corresponding actual system. The actual distribution looks quite different from the simulated ones, but to perform tests, one classically works with the cumulated distribution functions (Figure 2, right). From the nineteen simulated sigmoid curves, we traced the hull according to Eq. (1), denoted by dotted lines. The actual distribution curve (thick line) is clearly outside and the 5% test is then significant.

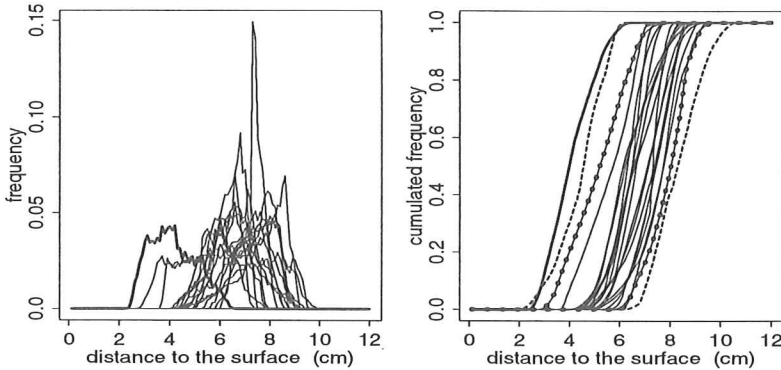


Figure 2. (left) Empirical distribution of the distance  $d(x, S)$  for  $x$  belonging to the 30-cm-deep level; thick solid line is used for the actual system 5, and the 19 other distributions are from realizations of  $\Phi'$  conditioned by the same actual burrow system; (right) corresponding cumulated distributions. Dotted line is for the nineteen-simulated-curve hull, and dash line for the ninety-simulated-curve hull.

On the same graph, the hull of ninety simulated distributions (not individually represented) are traced by dash lines. The actual system curve is also partly outside the ninety-curve hull so that the test is also significant at 1% level.

Figure 3 shows the results for all three levels and the three natural burrow systems. The boolean assumption is clearly rejected at the level 1% for the burrow system 5 at any depth. For the burrow system 3, the test is not significant even at level 5% at any depth and the boolean assumption seems relevant. For the burrow system 4, the results are not so clear and the test is significant at level 5% only for the 30-cm depth.

## DISCUSSION

With the method applied here, we wanted to test if spatial independence between burrows may be assumed, or if a significant spatial interaction occurs between burrows.

Burrows are collections of linked segments with different directions but only few ones feature long series. One must remind that a burrow system, as a collection of individual burrows of various lengths, derives from the continuous trajectories dug by the earthworm population (no assumption is made of the possibility that several animals use permanently or temporarily the same burrow); latter on, the continuity of trajectories is disrupted by deposition of casts inside the burrows.

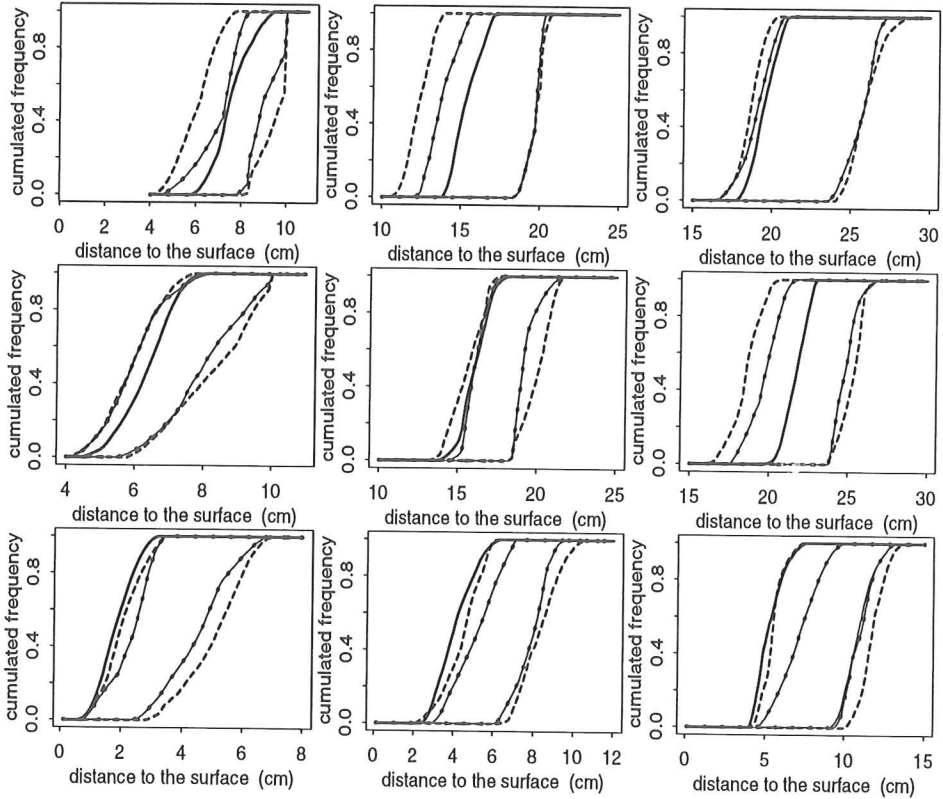


Figure 3. Empirical distributions of the distance  $d(x, S)$  for  $x$  belonging to different levels in the soil; from top to bottom, burrow system 3, 4 and 5 and, from left to right, 10-cm-deep level, 30-cm-deep and 50-cm-deep level. Solid lines represent the actual burrow system, dotted lines are the nineteen-simulated-curve hull and the dash lines stand for the ninety-simulated-curve hull.

Schematically, the spatial interaction between the burrows may be:

- vertical: the concealed continuity which pre-exists within the system, but is not apparent, due to the cast deposition or other disruptive mechanisms.
- horizontal: due to inhomogeneous spatial density of the pores, which is probably of a lesser importance.

It is generally accepted that vertical movements of earthworms are related to the search of expansion to the surface or to the depth, as the way to increase vital space; horizontal movements are rather linked to foraging activities (Lee, 1985)

As the population density increases (in winter), the burrow system becomes denser and the casts deposited in the pores are less abundant. Consequently, the burrows are disrupted with shorter filled intervals and the vertical interaction appears.

On the contrary, when foraging horizontally, the earthworm deposits many casts. If it is foraging during a sufficient time, then its successive vertical burrows will appear independent.

## CONCLUSION

The study of spatial interaction between the burrows, tested on their ability to shorten the minimum pathways from the depth to the soil surface, leads to the conclusion that :

- the dependence patterns can be neglected when earthworms density or activity is low. Even if long vertical burrows occur, they work exactly as if they were independent.
- when the burrows are dense all along the soil profile, from surface to depth, they feature some dependence pattern. This interaction shortens further the pathways, compared to the independent set of burrows. The extent of interaction is burrow length density dependent.
- the observation of interactions fits the known behaviour of these animals. Behavioural considerations must therefore serve as a basis for the next simulation model.

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