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UPTAKE POTENTIAL OF NON-REGULARLY DISTRIBUTED ROOTS

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ABSTRACT

Traditionally, models on transport of nutrients through the soil and uptake by the root assume regular distribution of roots. In this paper some consequences of non-regular root distribution are discussed. Three aspects of non-regular distributions are evaluated: The distribution of the size of the region of influence around the roots; the eccentricity of the root's position in the region; and the form of the region.

INTRODUCTION

Existing models on uptake of nutrients by root systems implicitly or explicitly assume a regular root distribution (2, 8). Then an equal volume of soil can be attributed to each root and the uptake by a crop can be studied by considering one root, as representative of the root system.

Barley (3) proposed to construct around each root polygon, the locus of points in the soil nearer to that root than to any other. This construction - called the Dirichlet tesselation (7) - seems as a first approximation an acceptable way to define the region of influence of each root. The polygons obtained are usually called Thiessen polygons. Barley substituted for each polygon a circle with the same area, and calculated the uptake of the collection of cylinders obtained in this way. He found that depletion rate differed only slightly between his most regular and his most irregular distribution. Thus in this approach only the distribution of area size, as acquired by the Dirichlet tesselation is retained. The position of the root and the particular form of the polygon is ignored.

In this paper we will explore some aspects of the Dirichlet tesselation with respect to uptake. The influence of the distribution of the areas, the location of the root and the form of the area will be discussed.

TESSELATION

The transport of a nutrient subject to linear adsorption and diffusive transport can be described by

$$\frac{\partial C}{\partial T} = D\nabla^2 C = \frac{D'}{K+\Theta}\nabla^2 C \qquad \text{Eq. 1}$$

where C is the concentration of the nutrient in mg/ml, T is time in days, D is the effective diffusion coefficient of the nutrient in the soil in cm^2/day, K is the adsorption constant in ml/cm^3, Θ is the water content in ml/cm^3, D' is the diffusion coefficient of the nutrient in soil, and ∇^2 the Laplacian operator in cm^{-2}. In order to solve Eq. 1 boundary and initial conditions have to be formulated. The first boundary condition considered is that at the root surface. For many crops the uptake rate under optimum conditions is almost constant, and accordingly, if it can be assumed that all roots are equally active, at the root surface:

$$\vec{\nabla} C = \text{constant} \qquad \text{Eq. 2}$$

If the root is to take up the nutrient from a confined region, then at the boundary of this region:

$$\vec{\nabla} C = 0. \qquad \text{Eq. 3}$$

A necessary condition for the Dirichlet tesselation to be concordant with diffusive flow, is that on the boundary of these regions condition (Eq. 3) is satisfied, which implies that isoconcentration lines are perpendicular to these boundaries. This was examined in the following way. Carslaw and Jaegar (4 page 261, eq (5) present the solution of diffusive flow in an infinite region to a line sink of constant strength. As Eq. 1 is linear the solution for N roots can be found by superposition.

With this solution isoconcentration lines were constructed, together with a Dirichlet tesselation, for a randomly distributed root system. This is shown in Fig. 1; generally isoconcentration lines cross the boundaries of the polygons perpendicularly, except

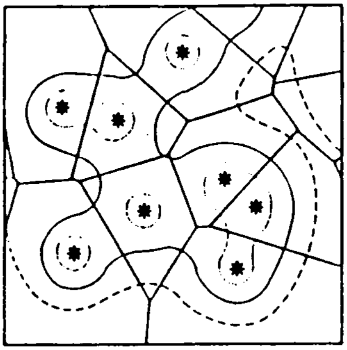

FIG. 1. Isoconcentration lines and the Dirichlet tesselation, associated with 8 roots.

sometimes near sharp vertices. Based on this and other similar calculations, it can be concluded that a Dirichlet tesselation gives an acceptable subdivision of the soil around roots, and such a tesselation will be the basis of the discussions presented here.

DISTRIBUTION OF THE AREAS OF THE THIESSEN POLYGONS

From root maps made in the field in arable soils, coordinates of the roots were read, and with these Thiessen polygons were constructed. An example is shown in Fig. 2, giving the appearance of roots of winter wheat in the plow layer. Clearly the roots are not regularly distributed, they are not even dispersed according to a random uniform distribution, but are more clustered, as can be tested by various methods (6). When the soil is homogeneous as far as soil fertility is concerned, the uneven distribution of roots - which may be due to growing of plants in rows, inhomogeneities in a physical sense etc. - has an adverse effect on uptake. To illustrate the disadvantages of the uneven distribution, it was calculated in what way, with the given distribution of areas, the total demand of the crop should be distributed optimally over the roots.

The uptake potential of a root system can be characterized by a characteristic time: the period of unconstrained uptake (T_c), during which uptake is in accordance with plant demand.

Fig. 3 shows the optimum T_c as a function of the adsorption constant K for the measured distribution of Fig. 3, and the results for a regular and a random uniform distribution.

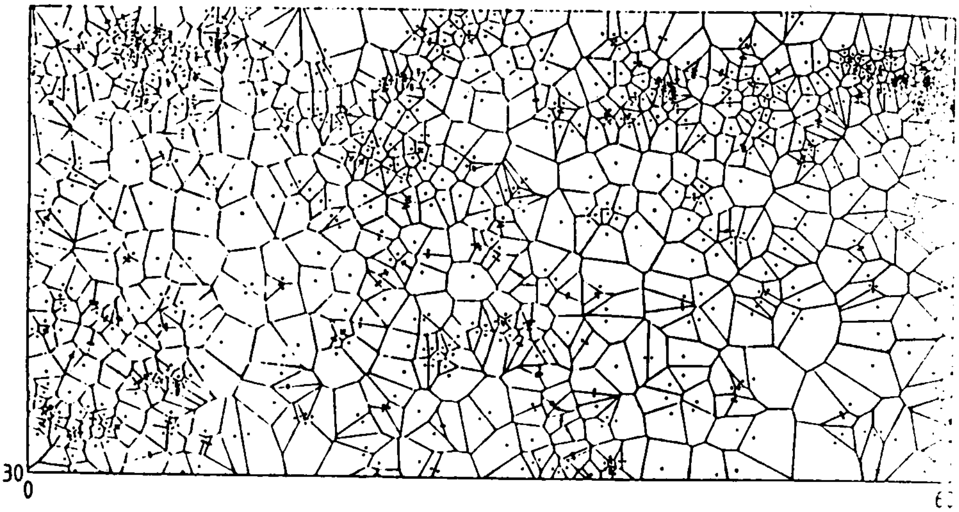

FIG. 2. Root map and corresponding Dirichlet tesselation of the plow layer under a wheat crop.

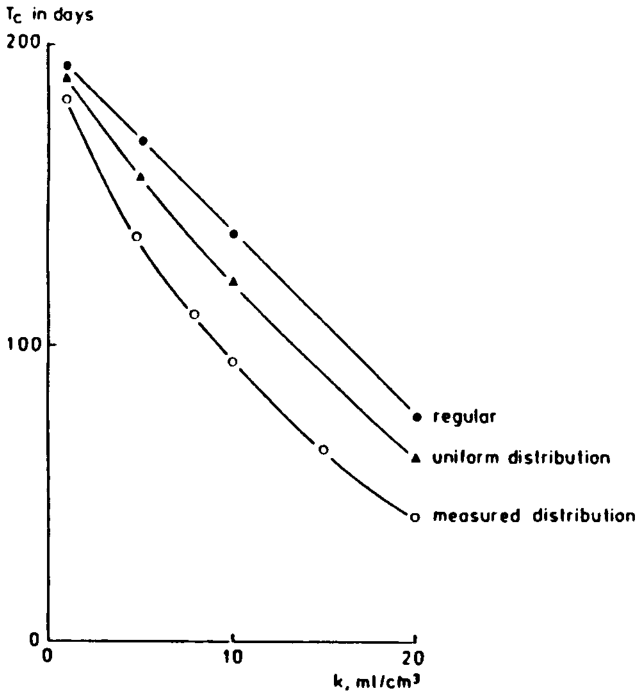

FIG. 3. Optimal period of unconstrained uptake as a function of adsorption constant K, for three root distributions.

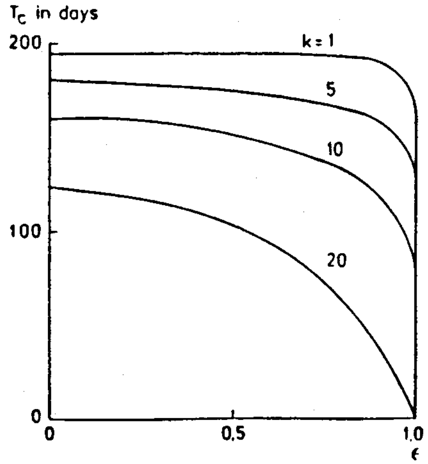

FIG. 4. Period of unconstrained uptake as a function of the eccentricity of the position of the root. The eccentricity is defined as the distance of the centre of the root to the midpoint of the soil cylinder, relative to the radius of the soil cylinder, in which the root is contained.

ECCENTRIC POSITION OF THE ROOT

The treatment above assumed that the Thiessen polygons could be approximated by circles where the root was located in the midpoint, precisely as Barley (3) has done. But as was remarked earlier the position of the root in the area, i.e. its degree of deviation from the barycentre, can be expected to have considerable effect on the possibilities for uptake. In order to analyze the influence of the root's position, we started from the steady-rate situation in a cylindrical geometry (5). Then an analytical solution of the problem can be found. With this solution the period of unconstrained uptake T_c can be calculated. Fig. 4 shows T_c in days as function of the relative position of the soil cylinder midpoint with respect to the root's centre, for some values of the adsorption constant. For a mobile nutrient like nitrate, eccentricity of the root has little effect on the potential uptake period, while for a strongly adsorbed nutrient like phosphate, with an adsorption coefficient of 100 or more (9) the period of unrestricted uptake is seriously affected by the location of the root. In Fig. 5 the cumulative frequency of the distance of the root to the barycentre, relative to the radius of the equivalent circle, of the root distribution of Fig. 2 is given. About 50% of the roots has an eccentricity of

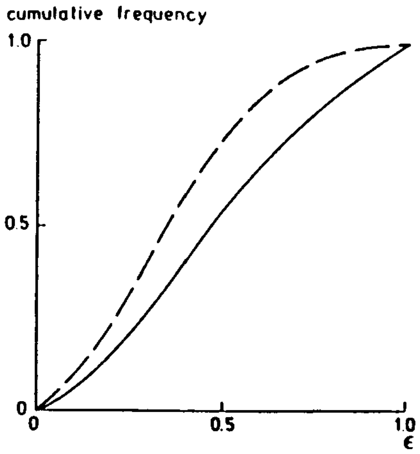

FIG. 5. Cumulative frequency of the eccentricity of the root for a random uniform distribution (__ __) and the distribution given in Fig. 2.

more than 0.5, and about 10% an eccentricity of more than 90%. The corresponding figures for roots, randomly distributed are 30% and 1%, considerably more favourable.

FORM OF THE POLYGON

Up to now it has been assumed that the constructed polygons could be replaced by equivalent circles. Shape itself will play an important role where it deviates significantly from more regular forms like a square, or hexagon. To illustrate its influence, for the sake of simplicity it was decided to use a rectangle as the base for our calculations. Roots were assumed to be distributed such that the Thiessen polygons were identical rectangles, with the roots located in their centre. It was calculated how T_c depends on λ, the ratio of the short side of the rectangle to the long side, while keeping the area of the rectangle, and so the root density, constant. Results are displayed in Fig. 6; a considerable interaction between the buffer capacity of the soil, and the shape factor λ is apparent: deviations from a regular form are more important the higher the adsorption constant.

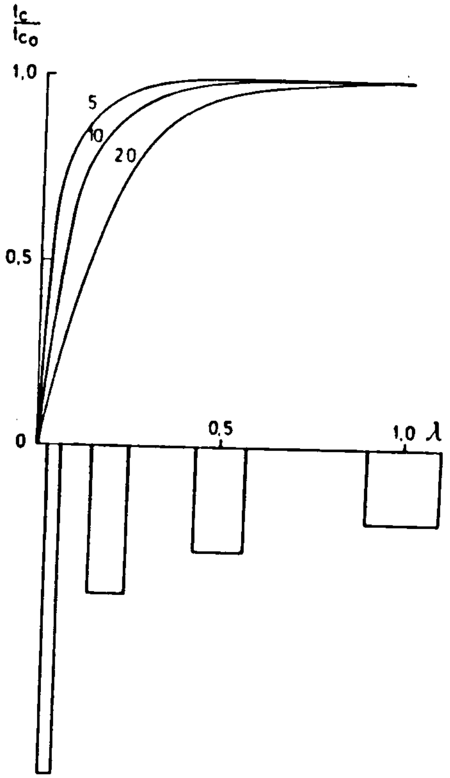

FIG. 6. Relative value of the period of unconstrained uptake as a function of the shape factor λ. The root is assumed to be located in the centre of a rectangular area. The shape factor is the ratio of the short side of the rectangle to the long side. The numbers of the curves refer to the value of the adsorption constant.

DISCUSSION

Contrary to Barley (3), Baldwin et al. (1), using analog simulation, found a large difference between regular and clustered distributions. The effect of the position of the root and the shape of the region, both neglected by Barley, may explain this difference. We intend to use the theory for evaluation of the influence of soil structure and tillage on uptake potential of roots.

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REFERENCES

1. Baldwin, J. P., P. H. Nye and P. B. Tinker. 1972. Uptake of solutes by multiple root systems from soil. II. The theoretical effects of root density and pattern on uptake of nutrients from soil. Plant Soil 36:693-708.

2. Barber, S. A. 1984. Soil nutrient bioavailability, Wiley, New York etc., 398 pp.

3. Barley, K. P. 1970. The configuration of the root system in relation to nutrient uptake. Adv. Agron. 22:159-201.

4. Carslaw, H. S. and J. C. Jaeger. 1959. Conduction of heat in solids. Second Edn., Clarendon Press, Oxford, 510 pp.

5. De Willigen, P. 1981. Mathematical analysis of diffusion and mass flow of solutes to a root assuming constant uptake. Inst. Bodemvruchtbaarheid, Rapp. 6-81, 56 pp.

6. Diggle, P. J. 1983. Statistical analysis of spatial point patterns. Academic Press, London etc., 148 pp.

7. Green, P. J. and R. Sibson. 1978. Computing Dirichlet tesselations in the plane. Comput. J. 21:168-173.

8. Nye, P. H. and P. B. Tinker. 1977. Solute movement in the soil-root system. Blackwell, Oxford etc., 342 pp.

9. Van Noordwijk, M. and De Willigen, P. 1978. Calculation of the root density required for growth in soils of different P-status. In: Harley, J.L. and R. Scott Russell (Eds.), The soil root interface, 381-391. Academic Press, London etc.