CHAPTER 7

Trench Profile Techniques and Core Break Methods

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A.L. Smit et al. (Eds.), Root Methods

7.1 Introduction

This chapter describes methods for root observations based on mapping or counting root intersections with planes of observation in the soil. Normally these planes of observation are either vertical or horizontal. Compared with the methods based on washed root samples discussed in Chapter 6, these "profile wall" methods have advantages as well as disadvantages. A major disadvantage of the profile wall methods is that only a small part of a root is visible on such an intersection and it is not easy to distinguish between roots of different species, or between live or dead roots. Even the question of whether a whitish thread-like object sticking out of a plane is a root and not an enchytraeid (pot worm) or other soil organism may take some experience to answer (potworms move when touched). Creating access to planes of observation via trenches can be a rather destructive activity which is not welcome on small experimental plots, especially those intended for long-term experiments. On the positive side, however, profile wall methods can give a quick estimate of overall root distribution and can give detailed information on spatial patterns of roots in their interaction with physical, chemical and biological characteristics of the soil profile. If maps are made of root occurrence as well as any other readily observable feature, the toolbox of geographical information systems and quantitative map analysis can be used to analyze patterns, be it in only two dimensions.

In this chapter we will describe practical aspects of preparing profile walls for observations and various methods for recording data (Sect. 7.2). In Section 7.3 we will focus on the analysis of data obtained, especially for root maps, and discuss the inferences which can be made about three-dimensional reality on the basis of two-dimensional observations.

7.2 Practical Aspects

7.2.1 Preparing Profile Walls for Root Observations

Field methods for root mapping include the following steps: a plane of observation must be chosen, and an access trench dug (Fig. 7.1A, B). The number of profile walls observed per treatment is usually one but further observation planes can be obtained from the same trench, a few centimeters (depending on plant space in the row) beyond the previous profile wall. The surface of the plane is then prepared and root locations recorded on plastic overlays or as tabulated data (Fig. 7.1C, D). We will consider these steps in turn, as there is a range of options for each of these.

Choosing an Observation Plane. Usually maps are made on vertical planes of observation, perpendicular to crop rows and near the base of a plant, where

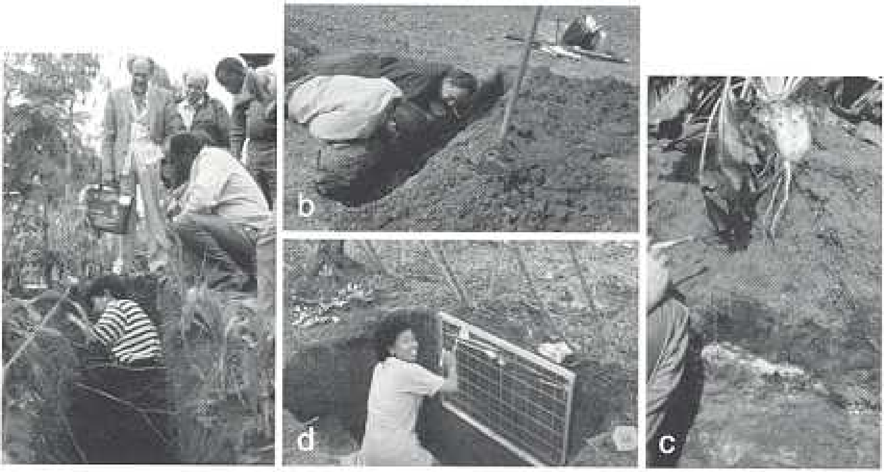

Fig. 7.1. Direct root observations on trenches and profile walls. **a** Direct observations in a deep trench perpendicular to hedgerows, **b** direct observations in a plough layer of an arable system, with minimum disturbance to the soil profile, **c** brushing away soil from a sugarbeet root system to observe its interactions with different layers in the soil profile, **d** mapping root intersections on a polythene sheet, with a grid system as a guide. (Photographs: courtesy of Meine van Noordwijk)

applicable. Horizontal planes give additional information on root orientation, but this makes removing the last layers of soil difficult.

Preparing Access. For "plough layer" observations a trench 0.3 m wide and 0.3 m deep may be enough, as the observations can be made without the observer having to get into the trench. Otherwise, a trench about 1 m across is needed for access by the observer, with a depth and width depending on the size of the maps to be made. To reduce damage to long-term experimental plots, sampling locations are normally chosen close to the border of plots; this may compromise on the representativeness of the sample. The soil from the soil pit or trench should be put on the outer side, so as not to influence the observations. If topsoil and subsoil are separated by canvas sheets during excavation, disturbance to the soil profile can be reduced, but the sampling sites should be marked and avoided in future.

Smoothing the Observation Plane. A long knife blade is normally used to obtain a flat and smooth plane of observation. No further preparations are necessary if the soil and root have very good contrast in colour, provided that the observer examines the profile closely.

Removing Last Layers of Soil. On most soils it is advisable to wash a few millimetres of soil from the prepared surface to facilitate observations. This can be done with a knapsack sprayer, working from the top of the profile downwards; a disadvantage of spraying is that in a wet soil 'smearing' of surfaces can easily cover fine roots. On heavy clay soils washing can be facilitated by covering the profile with a cloth soaked in sodium pyrophosphate (see Chap. 6) to disperse the clay. As an alternative one can carefully blow away fine soil with a "vacuum cleaner" (used in reverse) – live roots are remarkably resilient to this and will generally remain visible.

Recording Roots and Profile Features. The number of root intersections can be counted using a sampling grid, or the positions of the roots can be mapped on polythene (plastic) overlays. This latter method gives most flexibility in subsequent analysis of the data. Appropriate light conditions should be created for observation. Avoid direct sun-light, as it dries out roots quickly and gives too sharp a contrast and will lead to water condensation if plastic overlays are used for mapping. An umbrella or screen can be used to shade the plane of observation and give diffuse light.

7.2.2 Root Counts on a Grid

The simplest way of recording root occurrences is by overlaying the plane of observation with a grid and counting the number of roots crossing the plane. The size of the grid then depends on the purpose of the study and the level of detail needed. Fine grids require more work, but allow data to be converted to those of coarser grids (multiples of the fine grid), while the reverse process is not possible. French researchers in particular (Tardieu and Manichon 1986; Tardieu 1988) score the presence/absence of roots on a fine grid, rather than counts of root sections seen on the plane. A frame of strings can be used as a grid, either prepared in advance, or created on-site with pins, string, and pieces of lead as weight. It is usually worth distinguishing between root diameter classes in the counts.

Two types of criterion have been used for including roots in the counts. In the "Reymerink method" all roots exposed after removing a specified layer of soil are counted (Schuurman and Goedewaagen 1971; Böhm 1976). More recently, roots are only counted at the point where they emerge from the soil in the plane of observation. The latter can be more easily related to root length density per unit volume of soil (see below), but may not be as visually rewarding as drawings of roots hanging on the profile wall recorded with the first method.

7.2.3 Root Maps on a Plastic Overlay

Maps on plastic overlays can be made with permanent marker pen; roots are represented as 'dots', with different colours used for diameter classes or roots of different species where these are recognizable. Other features can be included such as soil horizons, cracks or finer soil structural features, or local accumulations of organic residues (Fig. 7.2). By spraying suitable dyes onto the excavated soil surface, spatial patterns in other features of the profile wall such as soil pH or redox status may be recorded. Water infiltration patterns via macropores can be visualized with dyes such as methylene blue or fluorescein (the latter requires UV light for observations and may be poorly visisble when adsorbed to the soil). Macropores can also be made visible by infiltrating an iodine solution and covering the soil surface with a fine layer of starch powder; a blue colour will appear where the iodine has reacted. Root maps should be wrapped in paper on a roll, rather than being folded to avoid a "printing" process during storage.

As a special case of profile wall observations, resin-impregnated blocks can be prepared and used for more detailed observations. This is similar to the "thin sections" used in soil micromorphology (Kooistra and Van Noordwijk 1996; Ringrose-Voase 1996).

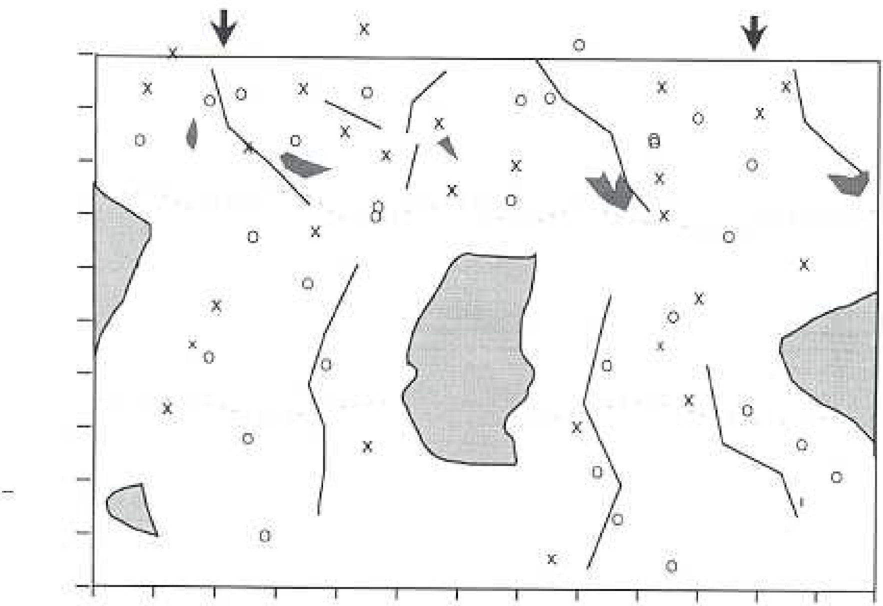

Fig. 7.2. Example of a root map with a number of features: *x* and *o* indicate two types of roots (different species or diameter), the *continuous lines* indicate major structural features of the soil, the *broken lines* profile layers, the *hatched areas* recognizable plant residues ploughed into the topsoil, and the *shaded areas* reflect anaerobic areas (bluish-grey)

7.2.4 Calibration Samples

The number of root intersections per unit area of observation plane can be calibrated against the root length density per unit volume in the soil directly behind the plane of observation by taking shallow sample boxes from well-marked places in the profile (Fig. 7.3). The box size should correspond with (a multiple of) the grids used for direct counts; where root maps are made, the size of the sample box is arbitrary, but it should be marked on the root map. Shallow sample boxes (about 2 cm deep) are better where large gradients of root length density are expected. In very shallow samples, however, the root segments obtained may be so small that washing losses increase; variability in actual sample size may also increase when the boxes are made shallow. The calibration samples can be washed and treated as described for other washed samples in Chapter 6. Oliveira-Carvalheiro and Nepstad (1996) made profile wall observations and empirically calibrated these against small block samples up to a depth of 9 m.

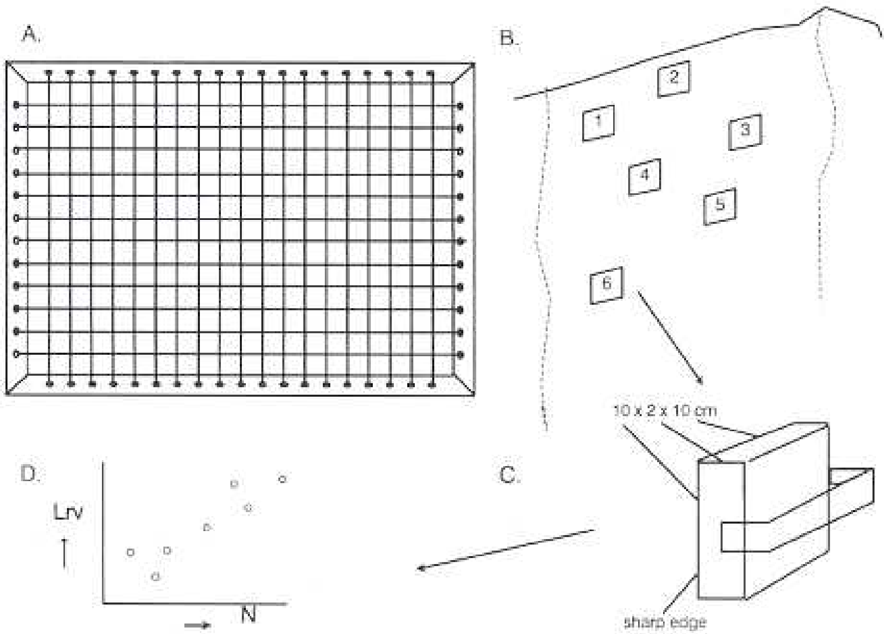

Fig. 7.3. Root maps can be combined with small blocks from which roots are washed (see Chap. 6) to derive an empirical relationship between root length density (cm per cm^3) and intersection point density on the map (cm cm^{-2})

7.2.5 Core-Break Method

The core-break method (Schuurman and Knot 1957; Schuurman and Goedewaagen 1971; Böhm 1979; Drew and Saker 1980) is a rapid and simple method of observing and recording the presence of roots as a function of depth; the method is treated here rather than in Chapter 6, as the basic observation of number of root intersections per specified area of observation is the same as in the profile wall methods. Cylindrical soil cores (see Chapter 6 for auger design) are broken in half and the number of roots sticking out of both soil surfaces is recorded (Fig. 7.4). The two results should be added together, as the same root cannot be exposed on both sides after breakage; usually roots will break some distance from the plane of observation and only show on one side. If root branches are observed these should be ignored, as the count refers to a 'plane of observation' and not to a volume.

Advantages of the core-break method are that samples are small, allowing many replicates to be taken. Direct counts are faster than for washing the roots from a whole sample, and a higher sample variability (the coefficient of variation for root counts may be 50–100% higher than for root length in washed auger samples) can be compensated for by larger sample numbers; the time needed per sample is considerably less. A selection of the samples can be

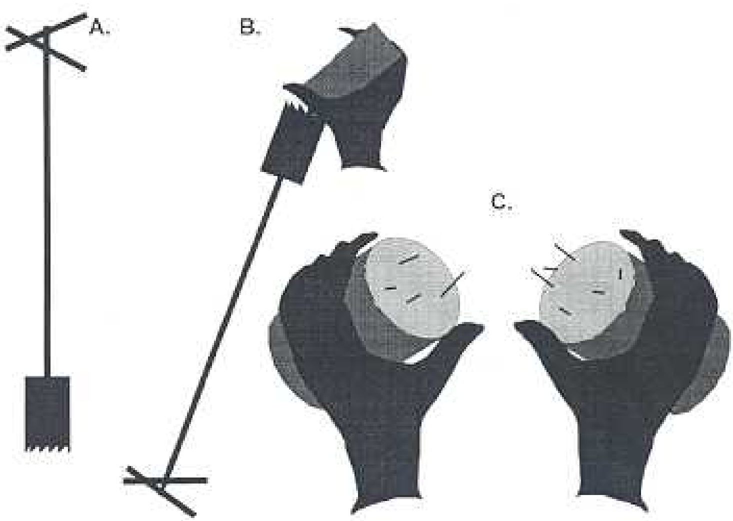

Fig. 7.4. Core-break method for estimating density of roots intersecting with a horizontal plane of observation

washed to obtain a direct calibration of root length versus counts. Schuurman and Goedewaagen (1971) gave a series of standardized dot maps with logarithmic increase in density which can be used for rapid assessment ("Knot method"), especially in grasslands where point densities will be high in the upper layers.

Disadvantages of the core-break method are that, similar to washed auger samples, no correlation can be made between local root density and other features of the soil, as recorded in the profile wall method. Bland (1989, 1991) discussed a number of sources of error: effects of preferential root orientation (see below), systematic gradients of root length density within a core making the break in the middle non-representative (this can be ignored unless there are very steep gradients in root length density), random variation of number of roots intersecting the plane of observation, and counting errors. Between different people scoring core-break results, however, systematic differences can be reduced or avoided by mutual cross-checking during a learning period.

7.2.6 Time and Labour Requirements of the Methods

A rough estimate of the time involved is given in Table 7.1. The number of replicates to be used, especially for the calibration of samples depends on

Table 7.1. Estimated time involved in profile wall and core-break method; estimates are based on an experienced crew and soils which are easy to work; they serve as a first approximation only

	Person-days per sample	Suggested number of replicates per treatment/ observation period	Total time per treatment in person-days
Profile wall			
Fieldwork to make maps of $1 \times 1\,m^2$	0.25	4	7
Digitizing and analysis	1.5		
Washed calibration samples: processing	0.15	16	2.5
Core break			
Fieldwork	0.08	25	2
Calibration of samples: processing	0.25	10	2.5

the number of treatments or situations to be compared, as data may be pooled for analysis. The estimates given refer to three to five treatment comparisons. Time for processing data in the lab exceeds (as usual) the amount of time spent in the field. With efficient organization of digitizing and standard software for data processing, the total time required can be reduced.

7.3 Data Analysis

Data from trenchwall observations can be analyzed in a number of ways to derive information on spatial distribution of roots in the plane of observation, as well as to make inferences on the three-dimensional reality from which samples were obtained. The first step in any data analysis is digitizing the root maps at an appropriate level of precision for further analysis. The theoretical relation between point density on a map and the three-dimensional density and distribution of cylinders has been well studied, but empirical correlations make clear that often considerable "errors" are involved in the observation process. After describing these, we will discuss a range of techniques for describing root distribution with depth and horizontal distance from the plant, and spatial correlations between roots and other mapped features.

7.3.1 Digitizing Root Maps and Overlays

The purpose of digitizing is to derive a list of x,y coordinates of roots intersecting the plane of observation; this corresponds with grid counts with an infinitely small grid size. A range of technical options exist, from digitizing tablets where every point has to be touched with a pen to record its position, to "scanners" which read a section of a map and can be linked with an image analysis routine which returns the "centres of gravity" to retain a single-pixel representation of root occurrence. Overlays can be scanned separately to digitize other mapped features as lines or areas. The list of x,y coordinates can be analyzed in various ways.

The points can be grouped into any grid size and shape for the types of analysis discussed in section 7.3.2. Dividing the x,y coordinates by a grid size and taking integer values classifies the roots into a grid cell; a subsequent tabulation can yield point densities in a grid. Similarly, classification in circular sections can be obtained by transforming the rectangular coordinates to circle coordinates around plant rows or single trees as the point of origin.

7.3.2 Relation Between Intersection Point Density and Root Length Density

For a set of randomly oriented line pieces, the basic relationship between length density per unit volume L_v and the point density of intersections with any plane of observation N, was derived as $L_v = 2N$ by Lang and Melhuish (1970) and Melhuish and Lang (1968). The derivation has its origin in the 18th Century and is known as Buffon's problem (Marriot 1972). The derivation considers the probability that a randomly positioned and randomly oriented line section (of unit length) with its centre within a specified volume of space will intersect with a given plane of observation (any plane or a plane bordering the volume), and then integrates over all possible positions and orientations, to obtain an average probability of being observed per unit root length. For a population of line pieces, the expected number of intersections per unit area of observation plane can then be related to the total length of line. Taking the inverse of this equation, the length can be derived from the number of intersections. The fact that root systems in a unit volume of soil are not independent little sections of line, but tend to be interconnected may cause some doubt on the applicability of the $L_v = 2N$ result, but the connections will increase the variance rather than affecting the expected value and mean.

Random orientation can, however, not be taken for granted in root systems and a modified form of the equation is $L_v = 2XN$, where the factor X depends on root orientation (see Box 7.1). If the N in the equation represents the average for three mutually perpendicular planes of observation ($N_m = (N_{x1} + N_{x2} + N_y)/3$), the deviations of X from 1.0 are relatively small (Lang and Melhuish 1970; Baldwin et al. 1971, 1972). In practice, however, one wants to estimate L_v from observations in one (or maximum two) plane(s) of observation.

Information on root orientation, or at least on the N_z/N_x ratio (e) is obviously needed to convert intersection point density measurements on profile walls or core-break planes into estimates of L_v. Counting root intersections in both vertical and horizontal planes may give the most direct approach. Available estimates show that this ratio will at least vary in the 0.5–4 range, and may thus cause substantial deviations from the $L_v = 2N$ equation.

Theoretically, one can reconstruct root angles from observations of the elliptical shapes of root intersections, e.g. on resin-imbedded soil thin sections. In practice, however, slight deviations of root shapes from a cylinder shape and errors in measurement make this approach unreliable (Van Noordwijk et al. 1992).

A number of authors (Bengough et al. 1992; Pagès and Pellerin 1996; Pellerin and Pagès 1996; Jourdan and Rey 1997; Pagès and Bengough 1997; Lynch et al. 1997; Grabarnik et al. 1998) have used three-dimensional root distribution models (cf. Chap. 4) to predict root intersections with any plane of

BOX 7.1. Effects of Preferential Root Orientation (Anisotropy)

In the following we denote the point density of intersections of roots with three mutually perpendicular planes of observations as N_x, N_y and N_z, respectively, with N_m as their mean. If we can assume the two vertical planes of observation to yield equal results, we may write $N_x = N_y = \lambda N_z$, and hence $N_m = N_z(2\lambda + 1)/3$. Van Noordwijk (1987) normalized the anisotropy factor defined by Melhuish and Lang (1968), to obtain:

$$a_n = \sqrt{\frac{(1-N_x/N_m)^2+(1-N_y/N_m)^2+(1-N_z/N_m)^2}{6}}$$
$$= \frac{|1-\lambda|}{2\lambda+1}, \qquad (7.1.1)$$

(this means that $a_n = 0$ for $N_x = N_y = N_z = N_m$ ($\lambda = 1$), $a_n = 1$ if two of the three observation planes have no roots at all, $\lambda = 0$) and a_n approaches 0.5 if one of the planes has virtually no roots ($\lambda \rightarrow \omega$).

Marriot (1972) derived estimates of the factor X (in $L_v = 2\,X\,N_m$) as function of a_n. The functions for X can be adequately approximated (Van Noordwijk 1987) by

$$X = 0.5a_n^2 + 1, \quad \text{and} \quad X = 0.8a_n^2 + 1, \qquad (7.1.2)$$

where the first equation applies to a 'linear' and the second to a 'planar' situation with (0,0,1) and (1,1,0) roots in the extreme cases, and $\lambda < 1$ and $\lambda\,\Omega\,1$, respectively. Root anisotropy will have a relatively mild effect on the calculated L_v values based on this X, provided that the average point density N_m is used. For the core-break method we are, however, mainly interested in the L_v/N_z relationship and for the profile wall observations in L_v/N_x, or L_v/N_y. In these ratios we find much stronger effects of anisotropy, as λ also influences N_m/N_z or N_m/N_x. Van Noordwijk (1987) derived from the above equations that for preferentially vertical root orientations with $0 \le \lambda \le 1$:

$$\frac{L_v}{N_z} = \frac{3\lambda^2+2\lambda+1}{2\lambda+1} \quad \text{and} \quad \frac{L_v}{N_x} = \frac{3\lambda^2+2\lambda+1}{2\lambda^2+\lambda}, \qquad (7.1.3)$$

and for roots with a preferentially horizontal orientation and $\lambda > 1$:

$$\frac{L_v}{N_z} = \frac{16\lambda^2+8\lambda+6}{10\lambda+5} \quad \text{and} \quad \frac{L_v}{N_x} = \frac{16\lambda^2+8\lambda+6}{10\lambda^2+5\lambda}. \qquad (7.1.4)$$

One can see that for $\lambda = 1$ the equations return to the $L_v = 2\,N$ form; for $\lambda = 0$ we obtain $L_v = N_z$ (and L_v/N_x is infinite), which may represent the parallel, vertically oriented cylinders of many root uptake models.

The equations for L_v/N_x (profile wall) show a sharp decrease in the trajectory up to $\lambda = 0.5$, stabilize around 2.0 for $0.5 < \lambda < 2$ and show a mild decrease for $\lambda > 2$ (Fig. 7.5). The equations for L_v/N_z (core-break) are monotonously increasing functions of λ starting at 1.0 for $\lambda = 0$.

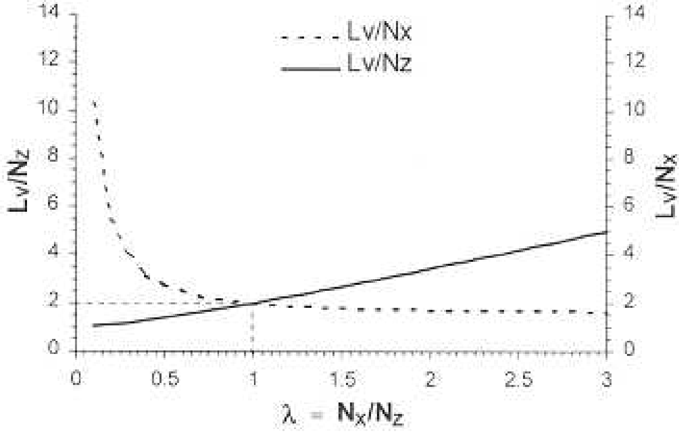

Fig. 7.5. Theoretical relationship between root length density per unit volume (L_v) (cm cm^{-3}) and intersection point density N on the map (cm cm^{-2}) of horizontal and vertical planes of observation for cases where the densities in the two possible mutually perpendicular vertical planes of observation are equal

observation. This has provided a valuable tool for exploring the effect of the type of deviations from random root orientation to be expected for real-world root systems.

7.3.3 Empirical Correlation for Core-Break and Profile Wall Observations

Real world calibrations of the method contain observation errors (in both profile wall and washed samples) and may deviate from the theoretical values which primarily depend on root orientation. Table 7.2 presents a selection of published data on empirical calibration factors. Schuurman and Goedewaagen (1971) gave calibration results for "root coverage" (related to N) versus root dry weight for grassland roots.

A point of warning may be that not all these studies have corrected for trends of root length density and comparisons may be based on intersection density on a plane external to the volume for which L_v data are obtained rather than for a plane halfway through this volume (Bengough et al. 1992).

Table 7.2. Examples of published values of calibration factor X in $L_v = 2\,X\,N$ relation between root intersection section N and root length density L_v. (Extended from Bengough et al. 1992)

Method	Crop	X for Nv	X for Nh	Comments	Reference
Profile wall	Maize/ soybean	8			Logsdon and Allmaras (1991)
	Maize	1.9			Vepraskas and Hoyt (1988)
	Tobacco	4.1			Vepraskas and Hoyt (1988)
	Mixed vegetation	0.41		Profile walls up to depth of 9 m	Oliveira-Carvalheiro and Nepstad (1996)
	Potato	1.0–4.5			Parker et al. (1991)
	Maize	3.0			Van Noordwijk et al. (1995)
Core-break	Oats		2.25		Bragg et al. (1983)
	Wheat		3.3–4.4		Drew and Saker (1980)
	Cotton/ sorghum		0.7–1.2		Bennie et al. (1987)
	Maize	0.8–1.1		X increases with depth	Van Noordwijk et al. (1995)
Impregnated soil blocks	Cotton	1.0			Melhuish and Lang (1968)
	Maize	1.0			Van Noordwijk et al. (1992)

7.3.4 Root Counts as Function of Depth and Horizontal Distance

Grid counts can be made from root maps in the laboratory by using a plastic sheet overlay. Grid size can be adjusted, and more flexibility is retained than with field grid counts. Non-rectangular grids, e.g. following soil horizons, can be used, as long as the surface area of each section is measured so that results can be expressed as number of points per area mapped. Point densities of root intersections can be converted to estimates of root length density L_v on the basis of empirical correlations or estimates of root anisotropy (Table 7.2).

Recording the x and y coordinates of each root is equivalent to a very fine grid, where the data get a presence-absence character rather than a number of points per grid. When x,y coordinates are recorded one can easily derive a grid classification (by taking the integer part of the coordinates divided by grid size). It usually is best to use grid sizes in which inter-row distances are multiples.

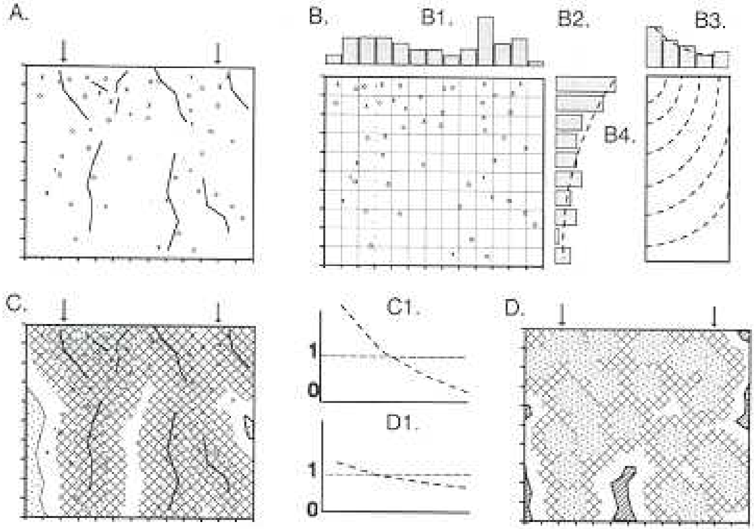

Fig. 7.6. Methods for analyzing root maps obtained in a vertical plane (A). **B** By overlaying the map with a grid, we can obtain histograms of intersection point density (number of intersections per unit area) as a function of horizontal distance (**B1**), vertical depth (**B2**) and distance to the nearest plant (**B3**). **C** By classifying the map by distance to cracks (or any other mapped feature) one can test the homogeneity of the relative point density for the strata so obtained (**C1**). **D** If two types of roots were mapped (*x* and *o* in this example) the point density of *x* can be sampled by strata differing in distance to the nearest *o* to test their spatial correlation (**D1**)

When a specified layer of soil is washed away from the profile wall, the number of points per grid or soil depth can also be converted into root length per unit of soil surface area (Böhm 1976). This can be achieved for a known length of profile wall by assuming that each root has the same length in the removed layer. Calibration of this technique with washed samples (blocks or cores) is very desirable.

Various root distribution functions can be fitted to the data (see Chap. 4), once grid counts are made. The grids are classified by their depth z below the soil surface and radial distance r to the nearest plant and root intersection. Densities are converted to root length densities on the basis of the conversion factor $X(z,r)$, which may depend on depth z and distance r. In soils without major restrictions to root growth an exponential decrease of root density with increasing distance from the plant may be expected. Van Noordwijk et al. (1996) expanded on the one-dimensional form of Gerwitz and Page (1974) and obtained:

$$L_v(z,r) = L_a|_{r=0}\,\alpha e^{-\alpha\sqrt{z^2+\beta r^2}} . \qquad (7.1)$$

This function has three parameters: $L_a|_{r=0}$ is the total root length per unit area ($cm\,cm^{-2}$) at a distance $r = 0$ from the tree stem, α is the parameter (m^{-1}) governing the decrease with depth of root length density (for $r = 0$, at a depth of $0.699/\alpha$ the root length density has half of its value at the soil surface), and β is the dimensionless parameter governing the shape of the root system; values less than 1 indicate shallow-but-wide root systems, values of 1 give a circular symmetry, and values >1 indicate deep-but-narrow root systems.

If β does not differ significantly from 1 and we ignore possible variation in $X(z,r)$ with distance r, the equation may be simplified to a one-dimensional distribution of root length density with depth:

$$L_v(z) = L_a \alpha e^{-\alpha z}.$$

7.3.5 Root Distribution Pattern Within a Zone: Nearest Neighbour Distances

Root maps in the horizontal and vertical plane (trench method) not only yield information on average root length density per soil layer, but also allow quantification of the distribution pattern within each layer (Barley 1970; Diggle 1983). The 'null model' of root distribution, against which one would usually want to test, is of independent roots with a homogeneous probability of occurrence within (a section of) the plane of observation. A Poisson distribution in the observation grid thus gives the appropriate comparison. A number of tests have been proposed, especially in plant ecological literature (Pielou 1969). Several of these use the fact that in Poisson distributions the mean of the number of points per cell equals the variance; the ration of mean and variance in a sample can thus be compared with the confidence intervals for finite samples. A variance/mean ratio above 1 indicates clustering, a ratio below 1 regularity (Fig. 7.7).

A different category of test is based on a comparison of "point-root" and "root-root" distances, where "points" are chosen randomly in the plane of observation. If roots behave as mutually independent points, the two distributions should be essentially identical. Where roots tend to cluster, root-root distances tend to decrease while point-root distances increase. Where root patterns tend towards regularity, the point-root and root-root curves will change in an opposite direction. The difference between these two distributions thus gives a sensitive test (Pielou 1969).

To derive the frequency distribution of nearest neighbour distances, two basic approaches are:

1. Start with a "source" point of measurement, calculate the distance to all neighbours and select the shortest distance (nearest neighbour);

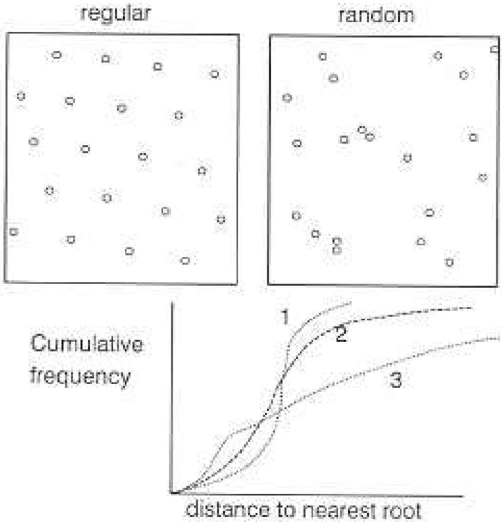

Fig. 7.7. Basic terminology for spatial point patterns and a nearest neighbour distance frequency diagram which can be used to test randomness of the pattern; if the lines for random points to the nearest root are not essentially different from those for roots-to-roots, the root pattern may be called random itself

2. Start with all target points and classify the area surrounding them by distance – this is the equivalent of drawing circles of increasing diameter around all "target points".

In the past, method 1 was most used, as it can be defined as a straightforward algorithm combining logical steps and a distance equation. Within this approach there is the option of calculating the distance from each source to all targets and select the shortest one, or use some prior sorting of target points which directly helps to select a subset of target points to be considered for a given source point. The choice between these approaches depends on the size of the data set (Diggle 1983). With the progress made in image analysis techniques, the approach based on drawing circles around all target points, lines or polygons can now be easily implemented. Image analysis or GIS software may have a built-in "distance transform" which can be used, or a distance-like operation can be based on a sequence of 'filters' using four or eight-neighbour expansion steps (Van Noordwijk et al. 1993a,c). With the latter one can evaluate the effects of 'barriers' on distance measurements. With some GIS software one can, similarly, incorporate information on 'resistance' in distance measurements (similar to the use of roads of different qualities).

If statistical tests indicate that observed patterns differ from "random", the question is what alternative distribution should be used. Diggle (1983) discusses the use of 'stratified Poisson' processes, which may be useful in root research.

Essentially, these distributions assume a random set of "mother" points, with an increased probability of finding 'daughters' in a local neighbourhood. Two parameters of such a process are then the average number of daughters per mother, and the distance around the mother point in which daughters are to be found. By modifying these two parameters the spectrum from highly clustered to truly random patterns can be generated.

Two interpretations of these parameters are: (1) that the area was a priori heterogeneous in its attractiveness to root development, and (2) that branch roots develop necessarily close to the axes from which they originate. The pattern as such does not allow us to distinguish between these two reasons for clustering.

7.3.6 Spatial Correlation of Mapped Features

Spatial correlation can be tested by implementing a stratified sampling of roots with strata chosen with increasing distance to mapped features such as cracks (Fig. 7.6C; Van Noordwijk et al. 1993b,c).

The following steps can be taken in the analysis:

1. Digitize root (X,Y) coordinates and map other features of interest (here indicated as focal phenomena),
2. Determine the point density of roots coinciding with the focal phenomena, by counting the number of roots and measuring the area,
3. "Expand" the image of the focal phenomena by including all the area within one unit distance of the previous map of focal phenomena,
4. Determine the point density of roots for the previous distance increment,
5. Repeat steps 3 and 4 until the whole map is covered,
6. Transfer the data to a statistics package and test for spatial correlation; the null hypothesis of independent random events, is equivalent to the absence of a significant trend in local point density with distance to other features. A model of point density as a function of distance can be fitted and used to test the null hypothesis. When fitting a distance function, one should acknowledge that the data will have a Poisson rather than normal distribution (an example, using the Genstat statistical package is provided by Van Noordwijk et al. 1993c)

7.3.7 Root Position Effectivity Ratio, R_{per}

The frequency distribution of nearest-neighbour distances of random points to the nearest root on such a map indicates the possibilities for transport by diffusion of all soil resources (Van Noordwijk 1987; Rappoldt, 1990).

BOX 7.2. Steps in the Derivation of the Root Position Effectivity Ratio, R_{per} (Van Noordwijk et al. 1993c):

1. Digitize a map of root distribution in a horizontal or vertical plane to derive a list of *X*,*Y* coordinates and estimate the corresponding root length density L_v,
2. If desired, introduce 'barriers' in the root map, e.g. representing incomplete root-soil contact or cracks in the soil,
3. Derive a cumulative frequency distribution (Fig. 7.8A, B) of distances from points in the soil to the nearest neighbour root, taking into account the existence of barriers (this can be done by 'expanding' the area taking roots as starting points and measuring surface area after each distance increment),
4. Derive an 'annulus fraction' representation (Fig. 7.8C) of these nearest neighbour distances by dividing the fraction of soil in each distance increment by that for an equivalent annulus,
5. Transfer the annulus fractions into fractions f_i of complete circle models with radius R_i ('cutting the pie'; Fig. 7.8C).
6. Calculate the total transport capacity to a sum of cylinders with radius R_i for a given uptake model; since the zero-sink uptake of water as well as nutrients is proportional to a G-function (De Willigen and Van Noordwijk 1987a; cf. Chap. 15):

$$Gsum = \frac{\sum_i f_i G(R_i) R_i^2}{\sum_i f_i R_i^2}, \qquad (7.2.1)$$

with:

$$G(Ri) = 0.5\left[\frac{1-3\rho^2}{4} + \frac{\rho^4 \ln \rho^2}{\rho^2 - 1}\right] \quad \text{and} \quad \rho = \frac{2R_i}{D_r} = \frac{2}{D_r\sqrt{\pi L_v}}, \qquad (7.2.2)$$

where D_r is the assumed root diameter,

7. Find the R^* for which $G(R^*) = Gsum$, and the corresponding L_v^*,
8. $R_{per} = L_v^*/L_v$.

The R_{per} factor (root position effectivity ratio) was introduced (Van Noordwijk et al. 1993a; Van Noordwijk and Brouwer 1997) to derive a correction factor, such that when L_v is multiplied with this factor an equivalent root length density L_v^* is obtained for a simple model geometry (regularly spaced, parallel cylinders), with the same opportunities for transport towards the root surface. The method (Box 7.2; Fig. 7.8) can potentially be applied to any root distribution pattern, but it assumes that the soil resources themselves are homogeneously distributed (initially). For homogeneous resource distributions, a regular root spacing maximizes uptake, so R_{per} will be less than 1.0 for non-regular root distribution. If resources are non-homogeneous, non-regular root distributions may be superior if roots and recources tend to coincide.

$$L_v^* = R_{per}\, L_v. \quad (7.3)$$

Van Noordwijk and Brouwer (1997) reported values of R_{per} in the range of 0.3 for winter wheat and sugar beet in the plough layer of arable land. Haberle et al. (1994) explored how R_{per} varies with the plane of observation based on three-dimensional root branching models (See Chap. 4).

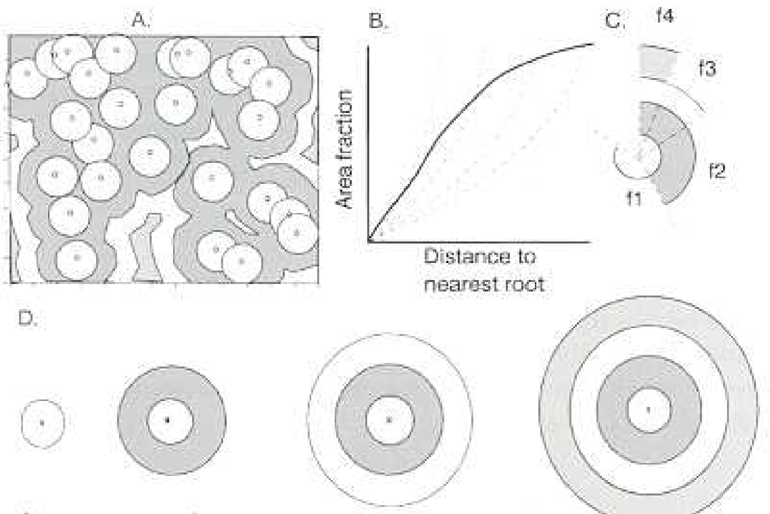

Fig. 7.8. Analysis of root distribution pattern. By applying a 'distance transform' to the map on the basis of all roots mapped; measurement of the nearest neighbour distances (B) can be used to derive the area in each distance class for an 'average' root (C); by 'cutting the pie' we can derive the relative frequency of cylindrical models with 1 . . . x layers which together may represent the possibilities for uptake by the root pattern (D); for a given root uptake function, we can finally derive the equivalent homogeneous root density which would allow the same uptake to occur and express the ratio of this hypothetical and the measured point density as the root position effectivity ratio, R_{per} (Van Noordwijk et al. 1993a,c)

A major assumption in this approach is that a classification of soil according to the nearest root (i.e. a Dirichlet tessellation) is acceptable. If all roots start to function at the same time, this assumption leads to only small errors (De Willigen and Van Noordwijk 1987b). In the model representation, the cumulative frequency distribution of transport distances should be conserved. For any frequency distribution of distances to a spatial point pattern, a frequency distribution of cylinders can be derived which fulfills this criterion (Van Noordwijk 1987; Rappoldt 1990; Van Noordwijk et al. 1993a).

7.3.8 Transition from 2-D to 3-D Distance

A partly unresolved problem in interpreting root maps is the fact that the real three-dimensional distances are smaller (except for roots growing perpendicular to the mapped plane) than the two-dimensional distances measured on the map. For randomly orientated roots, the frequency distribution of three-dimensional distances coincides with that for 0.71 times the two-dimensional distances (Van Noordwijk 1987). For non-random root orientation the problem is unresolved; a serious complication is the fact that a plane represents a biased sample of roots, as roots growing almost perpendicular to the plane are over-represented and roots growing almost parallel to the plane are under-represented. For a 2-dimensional map of the Z-plane, the frequency distribution of point-root distances in case of a random distribution of roots can be derived from a Poisson distribution (Pielou 1969; Marriott 1972):

$$P[d < D_2] = 1 - e^{-\pi N_z D_2^2}, \tag{7.4}$$

where D_2 is the two-dimensional distance and d is the distance of a point on the map to the nearest root.

For three-dimensional distances of points to randomly oriented and spaced cylinders (lines with density L_v per unit volume and radius R_0) Ogston (1958) and Barley (1970) derived that:

$$P[d < D_3] = 1 - \pi L_v R_0^2 - e^{-\pi L_v (D_3^2 + 4/3 \Lambda D_3^3)}, \tag{7.5}$$

where D_3 is three-dimensional distance, and Λ is the number of root tips per unit root length.

The term L_v R_0^2 refers to the volume of the cylinders themselves and is normally negligible. The last term in the equation (4/3 Λ D_3^3) refers to a half sphere around the root tip for 'end-contacts' and has a considerable modifying effect on the curve, which is mainly determined by the tangential contacts of the middle term. For $\Lambda = 0$ the 3-D equation becomes comparable to the 2-D one if:

$$D_3 = \frac{D_2}{\sqrt{2}} = 0.71D_2. \tag{7.6}$$

This result strictly depends on random orientation of the roots with regard to the plane in which two-dimensional distances were measured. If D_2 is measured in a plane perpendicular to a parallel set of cylinders, D_3 will equal D_2.

7.4 Conclusions and Perspectives

The profile wall methods discussed in this chapter for observing roots span a wide range of applications: from "quick and not-too-dirty" impressions of overall spatial patterns, which can be much faster than methods based on washed samples, to methods aimed at extracting specific spatial information which cannot be obtained from washed samples at all.

The geometrical relations between three-dimensional root systems and observations on any two-dimensional plane of observation are far from trivial and further progress is to be expected from links between root architectural models, and predicted and observed point patterns on a range of planes of observation. For several root ecological questions analysis of "spatial correlation" of roots and other phenomena (roots and cracks and/or anaerobic spots, roots of species A and those of species B, roots and concentrations of organic inputs, roots and decaying root channels formed by a previous vegetation) is crucial, but refined observation techniques may be needed and the standard "root map" may be too coarse.

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