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Behaviour of roots in cracks between soil peds

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Summary Experimental methods are described for observing the behaviour of roots growing over the surfaces of undisturbed soil clods and for roots growing along narrow cracks between two clods. Seminal roots of pea, rape and safflower were compared for a range of soil strengths and angles of inclination of the clod surfaces. For all three plant species, the ability of the roots to penetrate ped surfaces decreased with increasing soil strength and increasing angle of the surface relative to the horizontal. However, there was considerable variability of behaviour between roots. Roots were able to elongate more rapidly in cracks narrower than the root diameter than through undisturbed clods without cracks, provided that the crack was not orientated at an oblique angle to the preferred geotropic growth direction.

Introduction

Whenever a soil contains cracks or planes of weakness between macroscopic structural units or peds, it is common to find a preferential growth of roots on the ped surfaces rather than within the structural units. Russell[12] described this as a situation where roots are growing *around* rather than *through* the soil. Any such tendency for roots to be influenced by the soil macrostructure will have important implications, not only for the mechanical resistance to root elongation, but also for the degree of contact at the soil-root interface and the efficiency with which the roots can explore the total soil volume for the uptake of non-mobile nutrients[9].

In order to study the behaviour of roots when growing over ped surfaces, measurements were made of root elongation rates in cracks and of the abilities of roots to penetrate the adjacent ped surfaces for three types of vertically geotropic seminal tap-roots over a range of crack orientations and soil strengths. A treatment was included with cracks wider than the root diameter where there was no contact between the roots and an upper crack surface. This was compared with a second treatment where the root growing along the crack was likely to be at all times in contact with both sides of the crack.

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Root behaviour in soil cracks

There are numerous reports in the literature of root growth in the field being confined to the planes of weakness between soil structural units[2,4,11,16]. However, the behaviour of individual roots under these conditions has not been thoroughly investigated.

Bradford[3] measured the rate of root elongation through a blocky structured soil and found that the mean elongation rates increased with decreasing penetrometer resistance but, because of the variable distributions of growing roots and macropores, the effects on individual roots were extremely variable. It is thought that seminal roots growing down vertical cracks experience great difficulty in entering the crack walls but that lateral roots, because of their orientation, are better able to penetrate the walls[13].

In the field, variabilities in the structure and strength of individual peds, and the ped surfaces may influence root distribution[7,10].

It is not known how the resistance to penetration of roots growing along planes of weakness narrower than their own diameter would differ from the resistance in the bulk of the soil. Greacen *et al.*[8] found that the rate of elongation of pea radicles in compacted Young sand was greatly increased when following previously formed channels much narrower than the root diameter. Displacement of soil particles ahead of the root tips was greatly reduced when the channels were present and thus a major advantage of structural features smaller than the root diameter is that they can be enlarged by purely cylindrical expansion. In laboratory studies with soil cores, increasing confining pressure has been found to restrict root growth to the planes of weakness with a resultant flattening of roots and other morphological changes[14].

The effects of orientation

In order to model the behaviour of roots in tilled soil, it has been proposed that once a root has been deflected over the surface of an aggregate it will continue to grow over the surface of the aggregate until it can resume its preferred geotropic growth direction[5]. This may be a reasonable assumption for small rounded aggregates where the angle of the surface from the horizontal, θ, continues to increase with increasing distance from the point of deflection on the upper surface of the aggregate. However, this would not be the case for the cracks and channels found in non-tilled soil or below the depth of tillage. Here, the significance of an initial deflection event when a root tip first encounters a crack depends on the ease with which the root tip can penetrate the adjacent ped surface under the influence of geotropy while it is growing parallel to and adjacent to the ped surface. It is this latter mode of surface penetration which is examined in this paper.

Materials and methods

The soil used was from the A horizon of Urrbrae fine sandy loam from the Waite Agricultural Research Institute (34°58′S, 138°38′E). A site was chosen where the soil had not been tilled for several years. Large undisturbed field clods were taken when the water content was $< 10\%$ to minimize disturbance of their internal structure. A large soil volume was loosened so that approximately equidimensional clods of between 80 and 100 mm could be selected for use in the experiments. The clods were air-dried at room temperature. Tensile stress was applied to the clods by hand until they cracked. Clods which ruptured with a uniform crack close to the centre of the clods were kept and all others rejected. For very narrow cracks (Fig. 1A) the two parts of the block were refitted together and the upper and lower surfaces of the block were trimmed so that the principal angle of the crack, θ, was approximately 0, 45 or 90° to the horizontal. This produced narrow cracks with a mean separation between blocks of 0.194 mm with a standard deviation of 0.018 mm. This crack width was measured with a travelling microscope on sawn sections through impregnated blocks[15]. The prepared soil blocks were set in plaster-of-paris, E, fitted into the sintered class funnels and wetted to the desired water matric potential. Fine adjustment of the crack angles relative to the true horizontal direction was obtained by rotation of the sintered funnels. Good contact between the sintered glass plate, C, and the soil block was made by means of a layer of remoulded soil, D. The root tips of pregerminated seeds were inserted into preformed grooves at the upper edge of the crack, and held in position by packing firmly with added soil, G. For different blocks, A was removed after 1, 2 or 3 days and a record made of (i) whether or not the root penetrated B, (ii) the length of root in the crack to the top or to the point of penetration, and (iii) root diameter. General observations were made of root behaviour and morphology. Penetrometer resistance was measured with a stainless steel, conical penetrometer of 1.00 mm diameter and 30° semi-angle, penetrating at a speed of 3 mm min^{-1}. The shaft of the penetrometer was relieved to a diameter of 0.80 mm behind the tip to eliminate friction between the shaft and the soil. Penetrometer resistance was recorded at a depth of penetration of 4 mm. Measurements were done in triplicate on each clod surface.

For wide cracks, the same procedure was followed except that block A was absent (Fig. 1B). A was replaced by a black filter paper cover, F, to shield the roots from light. The cover was positioned 3–4 mm above the open crack surface and kept moist by contact with G and E to maintain a humid environment next to the crack. The funnels were covered with polythene film during the experiments to reduce evaporation losses.

Two additional treatments were done: (i) roots were grown through soil blocks without cracks and root lengths measured after 2 to 3 days, and (ii) roots were grown through loosely-packed soil prepared as follows. Soil blocks were equilibrated to the desired water potential, were passed through a 5.3-mm sieve, and the loose soil was packed into funnels by hand. Pre-germinated seedlings were then planted on the surface of this and covered with G as above. Root lengths were measured after 2 to 3 days. With all root lengths, the times of planting and measurement were recorded to the nearest hour so that measurements taken at different times could be compared directly. For all treatments 20 replicate roots were measured.

Results and discussion

The relationships between gravimetric water content, %w, and penetrometer resistance, P_p, of the soil for the 4 water potential treatments used in all the experiments are given in Fig. 2. There is a significant difference in P_p between all four treatments.

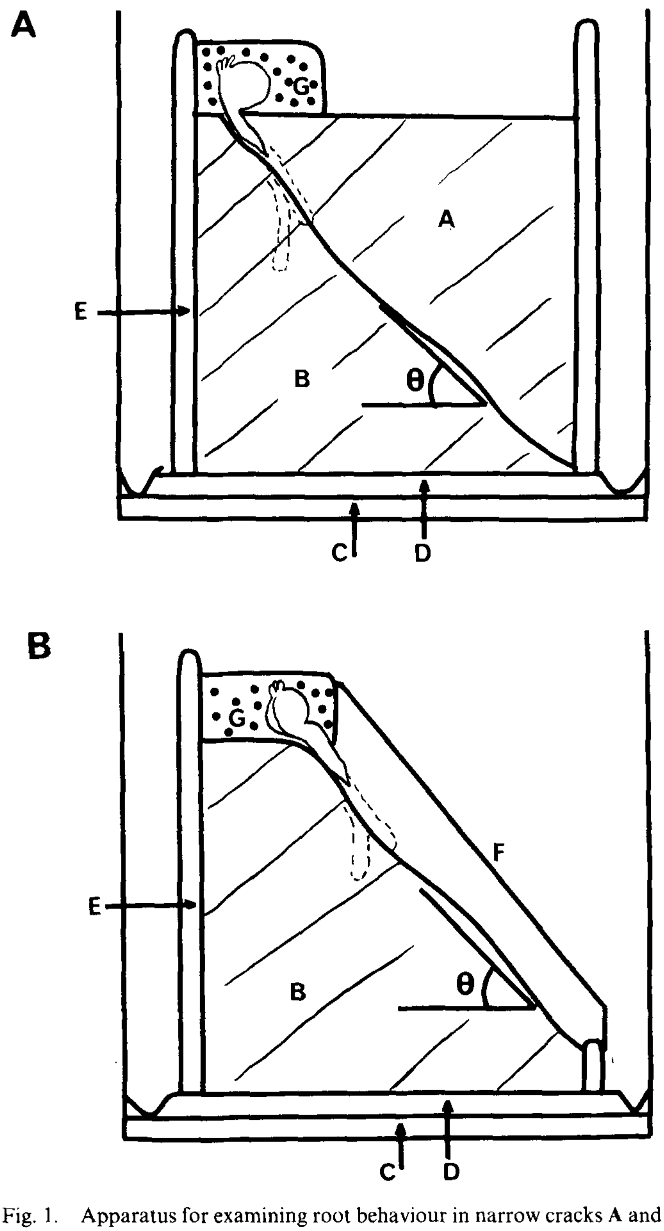

Fig. 1. Apparatus for examining root behaviour in narrow cracks **A** and in wide cracks **B** between two soil blocks A and B. Other components are described in the text.

Penetration of ped surfaces

The results of the mean length, l_s, to the point of soil penetration are shown for all treatments in Fig. 3A, B and C for pea, rape and safflower seminal roots respectively. Here, l_s, is the length of root on the clod surface before the root penetrates the clod.

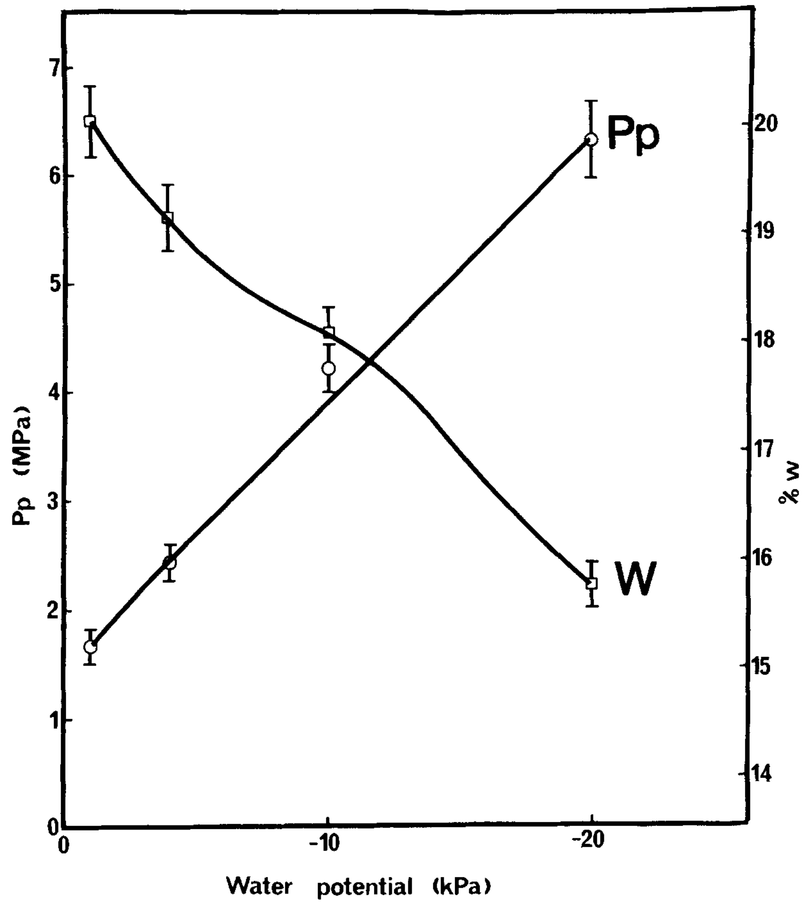

Fig. 2. Penetrometer resistance ○, and gravimetric water content □, of undisturbed field clods of Urrbrae sandy loam when wetted to different matric water potentials. Error bars are 2 × standard error.

In many treatments some roots grew over the 60–80 mm of the prepared crack surfaces without penetrating the surface. This made it impossible to calculate the mean length to penetration, l_s, from a summation of the individual roots in each treatment. The results in Fig. 3 were calculated by dividing the total root length over the surface for all 20 roots in each treatment by the number of penetrations (but excluding penetration at the edges of the soil block).

For all three root types in Figs. 3A, B and C, there is a tendency for l_s to increase with increasing soil strength. However, there is considerable random variability between individual treatments. Values of $l_s > 300$ mm are not shown. With a sample size of 20, values of $l_s > 300$ would be calculated from samples where less than 4 or 5 roots had penetrated the surface. The calculated values would therefore be greatly affected by one or two chance penetrations.

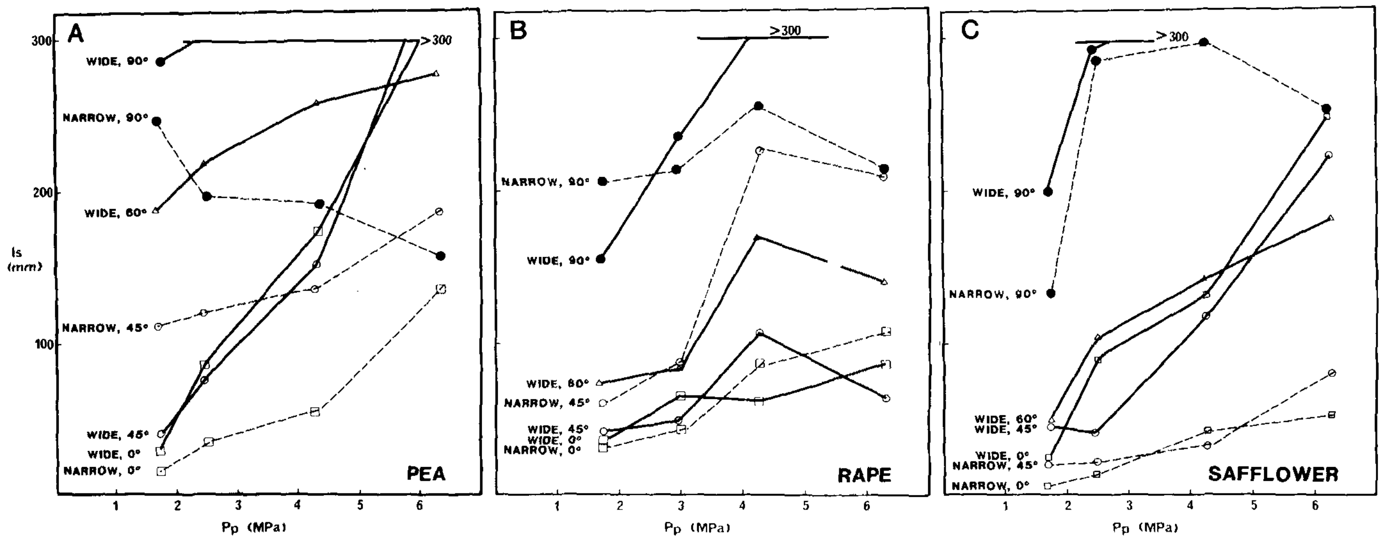

Fig. 3. Mean length of travel l_s, of roots from their initial point of contact with a crack surface to the point of penetration of the lower soil block B shown in Fig. 1. l_s is shown as functions of penetrometer pressure P_p, and crack angle from the horizontal θ (90° ●; 60° △; 45° ○; and 0° □). *Solid lines* are for wide cracks and *broken lines* are for narrow (0.194 mm) cracks.

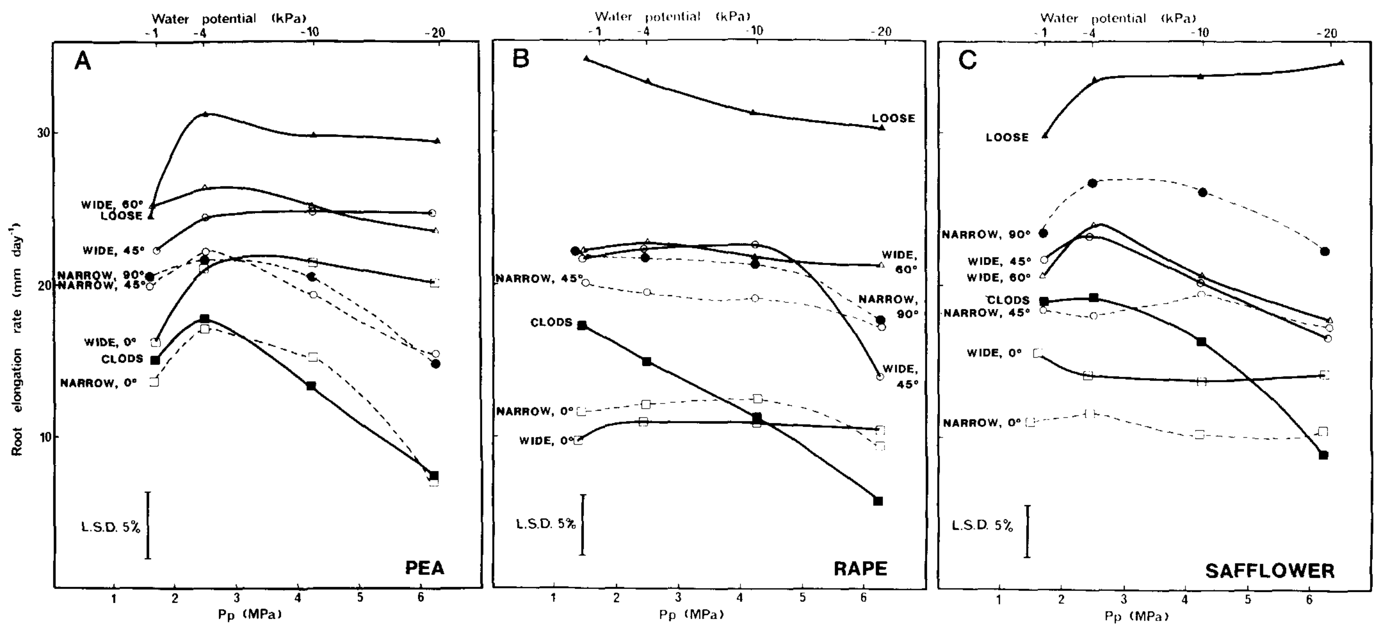

Fig. 4. Rates of elongation of seminal roots in cracks compared with the rates through soil clods ■, and loosely tilled soil ▲, as functions of penetrometer pressure P_p. *Solid lines* are for wide cracks, soil clods and loosely tilled soil. *Broken lines* are for narrow (0.194 mm) cracks. Crack angles to the horizontal (θ) are, 90° ●; 60° △; 45° ○; and 0° □.

In some but not all cases, the presence of the upper crack surface reduced l_s. This might be expected since the upper surface could enable a reaction force to be applied by a root when penetrating the lower surface. With the wide cracks, the roots would have to rely on anchorage to the lower surface. When root tips encountered obstructions on the rough crack surfaces, the zone behind the tip often arched upwards and this commonly effected penetration. It is difficult to draw any conclusion about differences between root types from these results. With the wide cracks, the length of root hairs extended outwards from the root surface to mean distances of 0.8 mm for pea, 1.1 mm for safflower and 3.1 mm for rape (when fully developed). Also, the zone of active root hair development began at a mean distance from the root tip of 5.7 mm for pea, 6.2 mm for safflower and 2.5 mm for rape. For rape (Fig. 3B) the l_s values for the wide cracks were generally lower in comparison to l_s values for the narrow cracks than for pea or safflower. This may be due to improved anchorage to the surface by root hairs for rape in comparison to pea or safflower.

Even at the lowest P_p, l_s varied from 10–20 mm at $\theta = 0°$ to the horizontal up to 167–200 mm at $\theta = 90°$ to the horizontal. Therefore, for roots growing in beds of small aggregates whose diameters are smaller than l_s, penetration of the aggregates by roots growing along the aggregate surfaces will hardly ever occur. Penetration of ped surfaces by roots following cracks or channels longer than l_s, on the other hand, will occur and will have important effects on root distribution.

The rate of root elongation in soil cracks

All three root types in Figs. 4A, B and C show the expected reduction in elongation rate with increasing soil strength when growing through the clods. The reduction in elongation shown by pea and to a lesser extent safflower at −1 kPa was probably a result of reduced aeration. At 20% gravimetric water content, the clods were close to saturation.

On the ped surfaces with wide cracks when $\theta = 45°$ the rates of elongation for all three root types were consistently higher than within the soil clods. Also, the effect of reduced elongation rate with increasing soil strength is either reduced or not apparent within the range of soil strengths used in these experiments. For safflower and rape (Figs. 4B and C) the rate of elongation on both the wide and narrow horizontal cracks is consistently low and independent of soil strength (or water potential within the experimental range). This reflects the interference with the normal growth processes when the roots are forced to grow at angles very different from their preferred geotropic growth direction.

For the narrow cracks at $\theta = 45°$ and $\theta = 90°$, the rates of elongation for all three root types are consistently higher than the corresponding rates of elongation within the soil clods. For rape and safflower but not for pea, the dependence of the elongation rate on soil strength is also greatly reduced. This difference may be due to the diameter of pea roots being larger than the width of the cracks.

When the soil blocks were broken into a loose aggregated condition, Fig. 4, the resultant rates of elongation were consistently greater than any of the elongation rates in cracks. It is not possible from these experiments to establish an explanation for this observation.

Greacen *et al.*[8] argued that the major advantage of narrow cracks is that they can be enlarged by purely cylindrical expansion. This view is supported by morphological observations made during these experiments which showed that root tips in narrow cracks were often uniformly tapered over a distance up to 10 mm from the tip. This elongated cone shape contrasted with the radially enlarged zone immediately behind the tip which commonly accompanied the penetration of the soil surface by the root. The latter morphological response is the normal response to axial resistance[1].

It was also observed that the roots were usually flattened in the plane of the crack.

Conclusions

It has been shown that even when the soil is near to saturation with a relatively low penetrometer resistance, ped surfaces still represent a significant barrier to root penetration. Penetration ability of the roots is influenced by plant species, soil strength and crack orientation.

Application of the values found in these experiments to other situations will be limited because the specific properties of the surfaces used in these experiments are likely to have influenced the results. Since the roots have grown over the prepared surfaces for long distances, heterogeneity of the surface is likely to be an important factor in determining the actual points of penetration and a major source of the observed variability.

The results presented here for the behaviour of roots in cracks can be compared with the results of Dexter and Hewitt[6] and Whiteley[15], for the behaviour of roots encountering cracks in soil. These results can be summarized as follows.

When the soil strength is higher, the angle of the surface is closer to the preferred geotropic growth direction of the roots, or the crack is wider, a larger proportion of roots encountering a crack are deflected along the crack. The roots which are deflected tend to grow along the surface for relatively long distances. At the opposite extreme, when the soil strength is smaller, the angle of the surface is nearer to 90° from the preferred geotropic growth direction of the roots, or the crack is narrower, a smaller proportion of roots encountering a crack are deflected along it. Further, the roots which are deflected tend to penetrate the surface along which they had been deflected after a relatively short distance. The conclusion is that the behaviour of roots elongating in cracks tends to amplify the behaviour of roots encountering cracks.

It can also be concluded that roots are able to elongate more rapidly in cracks narrower than the root diameter than through clods of naturally compacted Urrbrae sandy loam provided that the crack is not orientated at an oblique angle to the preferred geotropic growth direction. Narrow cracks also reduce the dependence of elongation rate on soil strength.

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