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Comparison of Fixed-Wall and Pressurized-Wall Minirhizotrons for Fine Root Growth Measurements in Eight Crop Species

Stephen D. Merrill,* Donald L. Tanaka, and Jonathan D. Hanson

ABSTRACT

Study of root growth is important for understanding C flow through plants to the soil and for modeling plant–soil interactions. Fine root growth can be observed through minirhizotrons (MRs), tubes installed in the field. We compared the use of fixed-wall (F-wall) MRs, 5.6 cm in diam., and pressurized-wall (P-wall) MRs, 9.6 cm in diam., with an inner cylinder and an outer wall of plastic sheeting kept under constant air pressure. Root growth was measured with a micro-video camera for 3 yr in eight crop species growing on Pachic Haplustoll soil: canola, *Brassica rapa* L.; crambe, *Crambe abysinnica* Hochst. ex R.E. Fries; dry bean, *Phaseolus vulgaris* L.; dry pea, *Pisum sativum* L.; safflower, *Carthamus tinctoris* L.; spring wheat, *Triticum aestivum* L.; soybean, *Glycine max* (L.) Merr.; and sunflower, *Helianthus anuus* L. Midpoint depths of root length density profiles measured with P-wall MRs were on average 20% greater than those from F-wall MRs, and maximum rooting depths observed were 15% greater with P-wall than with F-wall MRs. Fixed-wall MRs were forced into tight access holes to establish soil contact while the expectedly more uniform interfaces of P-wall MRs apparently allowed more root penetration. Averages of total root lengths (TRL) over rootzones and of root length per MR area (for upper halves of rootzones) measured by F-wall MRs were 47 and 32% greater, respectively, than those measured by P-wall MRs. This is attributed to greater clarity and visibility in F-wall MRs compared with P-wall MRs. Significantly more effort is required to build and maintain P-wall MRs compared with F-wall MRs, but P-wall MRs could be considered for use in problem soils with swelling clay content, stoniness, or gravel. In soils with fine-textured, difficult subsoils, use of P-wall MRs to supplement F-wall MRs could increase the accuracy of root growth depth measures.

Movement of C through the terrestrial environment is probably the most important part of the global biogeochemical system (Schlesinger, 1997), and the root systems of land plants provide structures by which movement of C from air to soil predominantly occurs. Currently, studies of C movement through the plant–soil system, such as those using ^{13}C methodology with corn (Allmaras et al., 2004; Wilts et al., 2004) and wheat (Palta and Gregory, 1997), depend on root recovery and root biomass methodologies for working interpretation of the plant–soil interface. Interpretation of information from plant–soil C flow studies, such as the relationships of fine root turnover and "rhizodeposition" (Allmaras et al., 2004) to "net primary production" (Schlessinger, 1997, Chap. 5) and "total source C" (Allmaras et al., 2004), will be greatly enhanced by effective information about the dynamics of fine root growth and dependent rhizosphere biology. Another area of application for fine root growth information is in soil and crop management. For example, Merrill et al. (1996) have linked the effects of conservation tillage management on wheat growth through MR measurement of fine root growth. A general model of plant–soil interactions for understanding the effects of crop–soil management on the environment, the Root Zone Water Quality Model (RZWQM; Hanson et al., 1999), critically depends on information about the soil profile distribution and depth of effective (meaning fine) root growth.

The needs for nondestructive imaging and measurement of active, fine root growth, which have been outlined here, are being met with the MR system. The development and use of MRs have been reviewed by Taylor (1987) and Johnson et al. (2001) among others. A current MR system typically consists of clear, plastic tubes installed in field or greenhouse soil, a color micro-video camera, a video tape recorder with a microphone for audio annotation, and a video monitor (Johnson et al., 2001).

Root systems are hierarchical structures, and a large fraction of the length of a plant's root system is comprised of higher-order root branches with diameters that are a fraction of a millimeter (Fiscus, 1981; Zobel, 1992). One of the key elements of the MR system is the ability to effectively magnify images at the soil–wall interface, which has been provided by various devices used in MRs, such as boroscopes, endoscopes, fiber optics (Johnson et al., 2001), and more typically, by micro-video cameras (Upchurch and Ritchie, 1983, 1984).

Minirhizotrons are typically forced into the soil using access holes that are sized to give as much soil–wall contact as possible. Use of MRs in soils with high clay content or that are stony or gravelly is problematic. Difficulties with use of MRs include soil smearing, separation of soil from the MR wall and the viewing difficulty this causes, and concern about high soil strength next to the MR wall. Upchurch and Ritchie (1983) have documented difficulties with contact between soil and walls of MRs. To overcome problems with soil interfaces, Merrill (1992) and Merrill et al. (1987) described a pressured-wall MR (P-wall MR) that featured a flexible, outer wall that was kept in contact with soil with constant air pressure. The concept of the P-wall MR was experimentally demonstrated by Merrill and Rawlins (1979). Kosola (1999) has described an expandable-wall MR that uses mechanical force to establish wall contact.

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Abbreviations: F-wall MR, fixed-wall minirhizotron; MR, minirhizotron; P-wall MR, pressurized-wall minirhizotron; RLD, root length density; TRL, total root length.

Another design alternative to rigid-wall MRs has been the inflatable MRs described by Gijsman et al. (1991) and Lopez et al. (1996).

This report grew out of a study of alternative crops in central North Dakota. The agronomic and soil management characteristics of seven crop species were studied under conservation tillage (Anderson et al., 2003). One of the goals of the project was to determine how root growth of the seven species along with that of regionally dominant spring wheat was linked to agronomic and soil management characteristics of the crops. The Haploustoll soil involved in the work had an aeolian-derived upper soil zone overlying a heavier-textured glacial till zone. Both P-wall MRs and more standard F-wall MRs were used for the study (Merrill et al., 2002) to overcome problems with potentially adverse soil conditions, particular in the subsoil zone. The objective of the research reported here was to compare the performance of F-wall MRs with P-wall MRs as applied to root growth measurements on eight crop species under the conditions of a semiarid, dryland cropping system.

MATERIALS AND METHODS

Details of the agronomic study in which root measurements were made have been given in Anderson et al. (2003) and Merrill et al. (2002). Seven alternate crops were grown in a 3-yr rotation consisting of spring wheat–winter wheat–alternative crop at the Area IV SCDs-ARS Cooperative Research Farm located in Morton County in south-central North Dakota. Crops were grown under minimal-tillage management using a no-till drill for seeding. Field plots were 9 m wide by 46 m long and were replicated three times. The seven crops were safflower, sunflower, crambe, canola, dry bean, soybean, and dry pea. Root measurements were also conducted on spring wheat grown in a biennial wheat–summerfallow rotation under the same general type of management as the other crops. The 3-yr rotation was begun at a different location each year, and root measurements were conducted on the alternative crop phase of the rotation during 1995, 1996, and 1997. The predominant soil type was Wilton silt loam (fine-silty, mixed, superactive, frigid Pachic Haplustolls). Soil consists of a silt loam 0.6-m-thick aeolian-derived surface zone and glacial till subsoil with finer-textured material.

Construction, Installation, and Use of Minirhizotrons

Root growth observations were made using MRs of two types: a standard type with rigid, fixed walls (F-wall MR) and a pressurized-wall type (P-wall MR; Merrill, 1992). The F-wall MRs were 1.9 m long and made of Lexan[1] plastic, with 5.6-cm outside diameter and 5.0-cm inside diameter. This type of plastic has superior hardness. The P-wall MRs (Merrill, 1992) were either 1.9 or 2.7 m long and had a working diameter of 9.6 cm and consisted of an inner plastic tube of 7.6-cm diam. and an outer, flexible, tubular wall of 0.5-mm-thick polyvinyl sheeting. The polyvinyl was sealed along a longitudinal seam with vinyl cement to form a cylinder and was clamped to the plastic cylinder at either end with steel banding over rubber strips and then sealed with silicone cement. Walls of the inner cylinders of P-wall MRs and the F-wall MRs were scribed every 5 cm with circular grooves and also with several longitudinal positioning grooves and were marked with position numbers.

Minirhizotrons were installed in the spring soon after the seeding of each crop. Access holes were drilled with rotary augurs at an angle of 30° with respect to the vertical using a special tractor-mounted hydraulic probing system. Holes for F-wall MRs were made slightly lesser in diameter than the MRs, which were forced into the soil under hydraulic pressure, establishing initially tight soil–wall interfaces. Pressurized-wall MRs were easily inserted into access holes in a deflated state. Minirhizotrons were removed from the field at the end of each crop's growing season before machine harvest and were reused in subsequent years.

Before installation, P-wall MRs were leak-tested by immersion in an animal watering tank. After placement in access holes, P-wall MRs were inflated and kept under a constant pressure of approximately 10 to 20 kPa using solar panel powered air pumps, which were of the type used for aeration of aquariums or live fishing bait (Merrill, 1992). Solar panels and air pumps were connected to deep cycle storage batteries to provide continuation of power during evenings and cloudy days. A pressure gauge was installed on the air lines to each pair of P-wall MRs, and individual MRs were periodically checked for air leakage.

Minirhizotrons were installed in plots of two replications of each crop species treatment. All crops except sunflower were seeded in narrow rows about 0.2 m wide, and MRs, which were as wide as a considerable part of the row width, were placed without regard to row position. Sunflower was seeded in 0.8-m-wide rows, and MRs were installed 0.15 m away from the crop row. In each replicate plot, four to six MRs were installed in a row spread over a distance of about 20 m in 1995 and 1996 and about 30 m in 1997, with groups of two or three MRs of each type being placed consecutively within the row of MRs. In 1995, each crop treatment received six P-wall and two F-wall MRs (four MRs in each of two replications). In 1996, six P-wall and two F-wall MRs were installed in safflower and sunflower crops, and four of each type were installed in the six other crops. In 1997, safflower and sunflower crops received six of each type, and the other crops received four P-wall and eight F-wall MRs (six MRs in each replication). Because of greater depth of root growth in safflower and sunflower, P-wall MRs installed in these crops were 2.7 m long while all MRs of both types in the other crops were 1.9 m long.

Minirhizotrons were viewed with a micro-video camera (Bartz Technology Co., Santa Barbara, CA)[1] at weekly or biweekly intervals. Equipment, including video monitor, higher quality video recorder, and electric generator, was mounted on a field cart. Minirhizotrons were viewed every 5 cm (4.3-cm depth intervals) on the upward side of the tube at two places on either side of a longitudinal positioning mark. Because of differences in the diameters of the two types of MRs, the micro-video camera objective is farther from the wall of P-wall MRs than of F-wall MRs. The equipment gave 11-fold magnification with 18- by 25-mm viewing areas in P-wall MRs and 16-fold magnification with 12- by 17-mm viewing areas in F-wall MRs. Video images were displayed on a video monitor of 560-cm^2 area, and intersections of root images with lines (three horizontal and three vertical) superimposed on the monitor face were recorded.

Minirhizotron Data Analysis

For purposes of analysis and interpretation, raw MR data (line intersections from MR images) were converted to equiva-

[1] Mention of trade names or products is for the convenience of the reader and does not indicate endorsement nor preferential treatment by the USDA-ARS.

lent bulk soil *root length density* (RLD, or here, RLD_{cm}) values through application of a specific MR conversion model (Merrill and Upchurch, 1994). Data on root length per MR viewing window area (L_R/A_W), which has been termed *root intensity* in the literature, were also generated from raw MR data for use in this study. The maximum observed depth of root growth for each MR type, crop, and date combination was noted.

The MR conversion model used here (Merrill and Upchurch, 1994) requires root number per area data. Intersections with lines data were converted to root number data by calibrations of root intersections vs. numbers using zero-intercept linear regressions. The calibration coefficients, $C_{i/n}$, were equal to 0.6235 and 0.4244 for P-wall and F-wall MRs, respectively.

The conversion model (Merrill and Upchurch, 1994) was based on a mathematical reformulation of an earlier version due to Upchurch (1985). The model is based on an analytical-geometric construction that considers theoretical root length growth that would occur inside the volume occupied by a MR if it were not present in the soil. It has been validated by application of four different studies in which MR root number data were compared with direct measurements of RLD using root material recovered from soil. Application of the model is simple, involving use of the equation:

$$(N_R/A_W) \times C_f \times 10 = RLD_{cm}$$

where (N_R/A_W) is root number per square centimeter gotten from MR images, C_f is the dimensionless conversion factor from the model, and RLD_{cm} is in units of km m^{-3}. The factor C_f equals 3.0 and 3.4 for P-wall and F-wall MRs, respectively.

Median RLD values were determined by MR type for each 0.04330-m depth increment. For the many depth increment, crop, and date combinations for which there were few roots and a majority of zero data values, averages were used instead of medians. Soil depth profiles of RLD_{cm} values were tabulated from these calculations. The midpoint depths of RLD_{cm} profile areas (D_m) were determined (i.e., depth above which one-half of the TRL was measured) for each date and crop. Total root length (TRL; units of km m^{-2}) over the root zone was determined by summation of MR data, conversion to RLD_{cm} units, and multiplication by depth increments.

Average values of root length per MR viewing window area (L_R/A_W) for the upper half of rootzones (defined by midpoint depths of RLD profile areas, D_m) were recovered from TRL and midpoint depth values by (i) calculation of average RLD as converted from MR data, RLD_{cm} = (TRL)/D_m; (ii) reconversion of RLD_{cm} to root number per area (N_R/A_W) data using the above-discussed conversion model; and (iii) calculation of MR line intersections data by division of N_R/A_W values by intersections-to-numbers calibration coefficients, $C_{i/n}$, and then conversion of MR line intersections to root length per area (L_R/A_W) data by application of Newman's (1966) formula.

RESULTS AND DISCUSSION

Minirhizotron Performance Results

The time courses of maximum root growth depths and midpoint depths of RLD profile areas are shown for F-wall and P-wall MRs in Fig. 1. Data are shown for those years and crops for which there was an approximate balance between numbers of the two types of MRs: the years 1996 and 1997 for five of the crops and just 1997 in the cases of safflower and sunflower. In general, maximum and midpoint depths observed with P-wall MRs were greater than those observed with F-wall MRs for the majority of crops and years (Fig. 1). The greatest differences between the two MR types were generally found in the two deeply rooted oilseed crops, sunflower and safflower. The 1997 canola crop also showed considerable root growth depth differences between the MR types, but these differences were not apparent in the 1996 canola crop (Fig. 1). The relatively more shallow rooted pulse crops, especially soybean and dry bean, exhibited the least differences between P-wall MRs and F-wall MRs.

Table 1 displays maximum root growth depths and midpoint depths of RLD profile areas observed with the two MR types averaged over the two dates when the greatest midpoint depths occurred for each crop. Attainment of deepest midpoint depths roughly coincides with maximum development of the rooting system of each crop, which is typically at flowering or early reproductive stages (Merrill et al., 2002). Average midpoint depths observed with P-wall MRs were greater then midpoint depths observed with F-wall MRs for all crops except for canola and soybean, for which the ratios of P-wall to F-wall MR midpoint depths were slightly less than 1.0 (Table 1). The average ratio of P-wall to F-wall MR midpoint depths for 1996–1997 was 1.20.

As was the case with midpoint depths, maximum root growth depths (Table 1) were also greater for P-wall MRs than for F-wall MRs. The exception to this was dry pea, for which the ratio of average maximum depth of P-wall MRs to that of F-wall MRs was 0.96. The P-wall to F-wall ratio of eight-crop, 2-yr average maximum depths was 1.15.

Maximum root growth depths reported here (Table 1) may be compared to those given in a summary report of trench profile technique observations in sunflower and safflower made in 1993 at the same research facility location (Merrill et al., 1994). The maximum sunflower depths observed with P-wall MRs in this study ranged from 1.3 to 1.5 m (Table 1). This compares to a trench profile-observed maximum depth of 1.7 m. For safflower, maximum depths ranged from 1.5 to 1.6 m in this study compared with a greatest safflower rooting depth of 1.9 m using the trench profile method. It should be noted that 1.85 m was the greatest depth at which it was possible to observe roots with 2.7-m-long P-wall MRs installed at a 30° angle with respect to the vertical.

Data for root length per MR viewing area, with dimensional units of (length) (length)$^{-2}$ (with the area idiosyncratically referring to MR wall), are not immediately suitable for quantitative ecological or agronomic applications, unlike RLD and TRL data, which are dimensioned to apply to soil volume and land area. However, root length data do have the advantage that, for the purposes of this study, they represent direct MR measurements that are free of MR data conversion model or MR intersections-to-numbers calibration that could change differences observable between the MR types. Annual average root length per MR area (L_R/A_W) values for the upper halves of crop rootzones (defined by D_m) were greater for F-wall MRs compared with P-wall MRs by 59, 16, and 78% in years 1995, 1996, and 1997, respectively (Table 2). The 3-yr average L_R/A_W value for P-wall MRs was 47% greater than that for

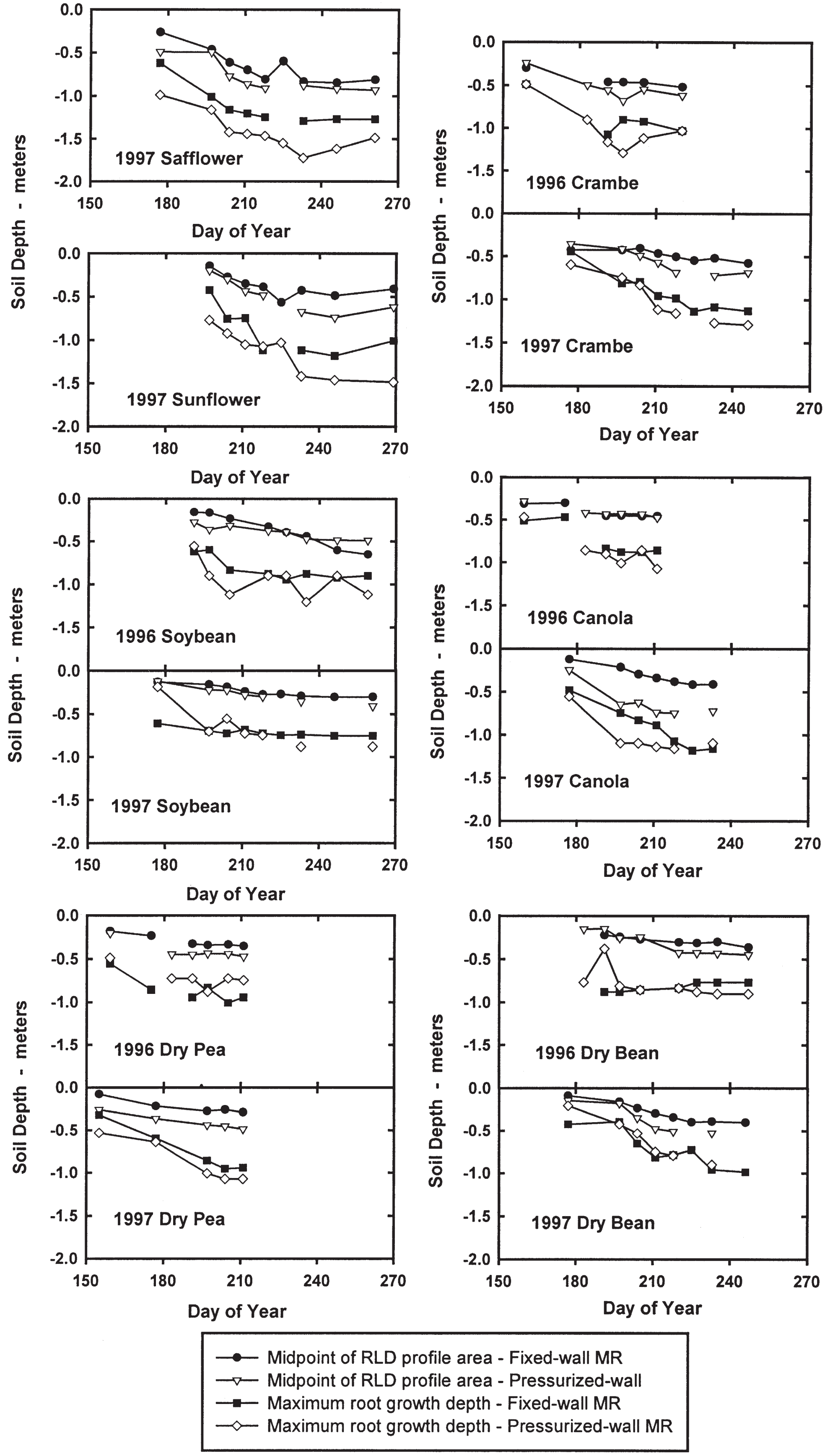

Fig. 1. Time courses of midpoint depths of root length density (RLD) profile areas and maximum root growth depths measured with fixed-wall minirhizotrons (F-wall MRs) and pressurized-wall minirhizotrons (P-wall MRs) in various crops species.

Table 1. Midpoint depths of root length density (RLD) profile areas and maximum root length growth depths for pressurized-wall (P-wall) and fixed-wall (F-wall) minirhizotrons, and ratio of P-wall to F-wall values (*P/F* ratio). Values for a given crop in a given year are averages of measurements taken on two dates at which midpoint depth values were greatest for the crop and year indicated.

		Midpoint depths				Maximum depths			
Crop	Minirhizotron type	1996	1997	Avg.	*P/F* ratio	1996	1997	Avg.	*P/F* ratio
		m				m			
Safflower	P-wall	0.77	0.92	0.85	1.13	1.54	1.55	1.55	1.40
	F-wall	0.67	0.82	0.75		0.94	1.27	1.11	
Sunflower	P-wall	0.64	0.71	0.68	1.55	1.28	1.44	1.36	1.13
	F-wall	0.42	0.46	0.44		1.25	1.15	1.20	
Spring wheat	P-wall	0.53	0.79	0.66	1.14	1.25	1.19	1.22	1.11
	F-wall	0.61	0.55	0.58		1.14	1.05	1.10	
Crambe	P-wall	0.65	0.71	0.68	1.36	1.16	1.21	1.19	1.18
	F-wall	0.49	0.51	0.50		0.97	1.04	1.01	
Canola	P-wall	0.45	0.45	0.45	0.98	0.99	1.15	1.07	1.19
	F-wall	0.46	0.46	0.46		0.85	0.98	0.90	
Soybean	P-wall	0.54	0.38	0.46	0.96	1.03	0.88	0.96	1.16
	F-wall	0.65	0.30	0.46		0.90	0.75	0.83	
Dry pea	P-wall	0.46	0.47	0.47	1.57	0.74	1.07	0.91	0.96
	F-wall	0.34	0.26	0.30		0.94	0.95	0.95	
Dry bean	P-wall	0.44	0.52	0.48	1.33	0.90	0.85	0.88	1.07
	F-wall	0.33	0.38	0.36		0.77	0.87	0.82	
Averages	P-wall	0.56	0.62	0.59	1.20	1.11	1.17	1.14	1.15
	F-wall	0.50	0.47	0.49		0.97	1.01	0.99	

F-wall MRs. This result compares with the 3-yr TRL average for P-wall MRs being 32% greater than that for F-wall MRs (Table 3).

Converting direct MR data forms (root intersections, numbers) to RLD_{cm}, and TRL data derived from RLD_{cm}, affects P-wall vs. F-wall MR differences. This is shown by multiplying the ratio of P-wall to F-wall MR average L_R/A_W values—1.473—by the ratio of P-wall to F-wall MR values of the conversion model (Merrill and Upchurch, 1994) factors, C_f—3.0/3.4. The result—1.300—is close to the P-wall to F-wall ratio of average TRL values (Table 3), 1.321.

Fixed-wall MRs were inserted into the soil with considerable mechanical force to establish initial soil-to-MR wall contact. After pressurization, soil-to-wall contact in P-wall MRs appeared to be generally consistent, but the level of applied air pressure (about 10 to 20 kPa) should not have been a significant hindrance to root penetration between wall and soil. Thus, one probable cause of the greater maximum depths observed for P-wall MR compared with F-wall MR would be greater ease of root penetration at the soil–MR interface for the former MR type. This apparent greater ease of root penetration at the interface of P-wall MRs is probably the most important reason for the greater midpoint and maximum depth values compared with F-wall MRs, but it is believed that other issues are involved in this difference. Total root length (Table 3) observed with F-wall MRs was significantly greater (at the $P < 0.1$ level) than P-wall MR-observed TRL for four out of eight crops in 1995, for two out of eight crops in 1996, and for six out eight crops in 1997. Overall, TRL values measured by F-wall MRs were greater than those measured by P-wall MRs in over 70% of the 24 cases tabulated, and the 3-yr average TRL value was 32% greater for F-wall MRs than that for P-wall MRs.

Total root length measured in 1995 with both MR types was lower than TRL measured in 1996 and 1997 (Table 3). This result has been linked to significantly higher-than-average growing season precipitation in 1995 compared with near-average precipitation in 1996 and below-average precipitation in 1997. Literature is reviewed in Merrill et al. (2002) linking this pattern of results to the concept that relative crop water stress can enhance fine root growth.

Differences between Minirhizotron Types

Data showing greater TRL and root length per MR area measured by F-wall compared with P-wall MRs indicated apparently higher efficiency of F-wall MRs, and this is believed to have been predominantly a matter of relatively greater visual efficiency of the fixed-wall type.

Reasons for greater apparent root visibility in F-wall MRs compared with P-wall MRs are listed here in decreasing order of their importance or validity, in our opinion:

1. Observation in P-wall MRs was hindered by condensation forming on the inside of the outer walls at lower soil depths during cooler, wetter weather. This occurred only in some minority of the P-wall MRs.
2. The surface of the polyvinyl sheeting of P-wall

Table 2. Calculations by minirhizotron (MR) type of eight-crop annual average root numbers per MR viewing area (N_R/A_W) and average root lengths per MR viewing area (L_R/A_W) for upper half of rootzones [as defined by midpoint depths of root length density (RLD_{cm}) profile areas, D_m]. Total root length (TRL) and D_m values were input data for calculations. MR type: P, P-wall MR; F, F-wall MR.

Year	MR type	TRL	D_m	RLD_{cm}	N_R/A_W	L_R/A_W
		cm cm^{-2}	cm	cm cm^{-3}	cm^{-2}	cm cm^{-2}
1995	P	85	62	0.685	0.228	0.201
1995	F	107	43	1.244	0.366	0.319
1996	P	133	56	1.188	0.396	0.348
1996	F	157	50	1.570	0.462	0.403
1997	P	117	62	0.944	0.315	0.277
1997	F	181	47	1.926	0.566	0.494
3-year avg.	P	112	60	0.939	0.313	0.275
3-year avg.	F	148	47	1.580	0.465	0.405

Table 3. Median values of total root length (TRL) from pressurized-wall (P-wall) and fixed-wall (F-wall) minirhizotrons (MR) and ratios of P-wall to F-wall average values. Averages of measurements on three dates with highest TRL values for a given crop and year are shown.

	1995			1996			1997			Averages		
Crop	P-wall	F-wall	Prob. gr. t†	P-wall	F-wall	Prob. gr. t	P-wall	F-wall	Prob. gr. t	P-wall	F-wall	P/F ratio
	—— km/m^2 ——			—— km/m^2 ——			—— km/m^2 ——					
Safflower	17.3	9.8	ns	11.5	20.6	ns	12.9	18.7	<0.1	13.9	16.4	0.85
Sunflower	9.7	12.3	ns	5.1	16.7	<0.025	4.6	13.7	<0.001	6.5	14.2	0.46
Spring wheat‡	5.6	10.0	ns	26.9	25.3	ns	9.8	16.6	<0.005	14.1	17.3	0.82
Crambe	2.4	20.9	<0.005	16.9	20.2	ns	27.7	20.1	ns	15.7	20.4	0.77
Canola	8.4	15.9	<0.1	13.8	10.4	ns	14.2	12.8	ns	12.1	13.0	0.93
Soybean	5.0	6.7	<0.1	6.5	7.6.4	ns	7.7	13.9	<0.005	6.4	9.4	0.68
Dry pea	1.8	4.8	<0.1	6.3	13.6	<0.01	3.1	10.3	<0.005	3.7	9.6	0.39
Dry bean	18.1	4.9	<0.05	19.5	11.5	ns	13.8	38.7	<0.001	17.1	18.4	0.92
Averages	8.5	10.7		13.3	15.7		11.7	18,.1		11.2	14.8	0.76
Median SEM§	1.6	1.7		3.0	3.4		1.5	1.7				
Avg. no. MR in sunf. and safl.¶	4.5	2		6	2		6	6				
Avg. no. MR in other crops	4.5	2		3.8	4		4	7.3				

† Probability of a greater value of t for the difference.
‡ The top two dates were averaged for spring wheat values.
§ Standard error of mean.
¶ sunfl. = sunflower; saffl. = safflower.

MRs appeared to have very small-scale imperfections, which was in contrast to the hard, polished surfaces of the Lexan plastic used for F-wall MRs.
3. Viewing in P-wall MRs was through two separate layers of material compared with only one layer in the case of F-wall MRs.
4. Because F-wall MRs were forced into soil and reused in subsequent seasons, they eventually became scratched and marked up more than P-wall MRs, which were inserted and extracted from access holes in a deflated state. This apparent degradation of visibility in F-wall MRs with seasonal withdrawals and reinstallations constitutes a counter reason here.
5. Because of its larger diameter, magnification by micro-video camera was less for P-wall MRs than for F-wall MRs, 11 vs. 16 diameters, respectively. Thus, for example, a fine branch root of 0.2-mm diameter would appear on a video monitor as being 2.2 mm wide in a P-wall MR image vs. 3.2 mm wide in a F-wall MR image. This does not appear to be a particularly important difference, given that root hairs of considerably lesser diameter than fine branch roots were visible.
6. Possibly, the polyvinyl in P-wall MRs, which exudes a chemical odor when fresh but is relatively odorless when aged, had some negative effect compared with relatively odorless Lexan plastic in F-wall MRs. Withington et al. (2003) compared the effects of several different chemical types of MR plastic on MR performance, reporting that butyrate in MRs decreased root survivorship compared with acrylic plastic but not root number.

Differences between the MR types that possibly caused the soil depths of root length growth (maximum and midpoint depths) to appear deeper in the soil profile when viewed with P-wall MRs rather than with F-wall MRs generally involve issues other than those of relative root visibility:

1. The idea that there would be a relatively greater degree of soil compaction at the wall of F-wall MRs, causing greater resistance to root growth compared with P-wall MRs, has already been discussed.
2. The portion of MRs protruding above the soil surface must be shielded from sunlight as it is widely believed that light is deleterious to root growth, and some evidence of this view has been presented (Levan et al., 1987). Because of greater size and relative lack of rigidity due to the flexible outer wall, it was more difficult to provide reliable light shielding to P-wall MRs compared with the smaller-diameter, more rigid F-wall MRs.
3. There could be possible air leakage problems with P-wall MRs or other factors (lack of power, lack of sunlight to energize solar panels) that might result in loss of firm contact with the soil. Air pressure was monitored, and several P-wall MRs were removed from service, and this was one of the reasons for smaller average numbers of MRs being listed in Table 3 compared with numbers initially planned to be installed, as given in the Methods section. In case of low air pressure, there could be a possibility of larger roots running along the axis of P-wall MRs, but obvious instances of this did not appear to any noticeable extent. Installation of MRs at an angle with respect to the vertical is believed to attenuate this potential problem.
4. It is conceivable that air leakage in a subsoil zone might provide additional oxygen to roots and result in additional growth at depth with P-wall MRs. This factor is difficult to assess but would appear to be less of a concern in the case of this study as our soils were typically well below field capacity water content levels much of the time.

CONCLUSIONS

1. The current design of the P-wall MR gives inferior working visibility compared with more standard

F-wall MRs. This study was conducted with use of the technique of counting line intersections of root images to quantify root length. For use with image analysis technologies, which may very well require relatively higher image quality, the inferior visibility of P-wall MRs may become a greater problem.

2. Pressurized-wall MRs require a significantly greater investment of labor for preparation, operation, and maintenance. However, they are generally easier to install in the soil than F-wall MRs.
3. It is generally recommended that F-wall MR installations be allowed to age over a considerable part of the year or longer (Johnson et al., 2001). This may be difficult to do with P-wall MRs, especially in northern climatic and annual crop contexts.
4. The current P-wall MR design can only be definitely recommended for use in cases where significant difficulties may be encountered in use of more standard, F-wall MRs, such as high shrink–swell clay soils or soils with stoniness or gravel problems.
5. There are cases involving heavier-textured high-clay subsoils, and where there is a research premium on relative accuracy of root profile and root depth information, in which use of P-wall MRs can usefully supplement and enhance installation of standard F-wall MRs.
6. The current design of the P-wall MR (Merrill, 1992) as used in this study could be improved (i) by using a flexible wall material that has higher optical quality than standard polyvinyl sheeting and that possibly has superior chemical nonreactivity, (ii) by use of a regulated air supply, (iii) by use of a desiccant in the air supply, (iv) through improvement of light shielding in the upper part of the MR, and (v) by placement of semicircular spacers between the inner plastic tube and the flexible outer MR wall that would be positioned on the downside of the MR when installed.

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