Root Length Growth of Eight Crop Species in Haplustoll Soils

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ABSTRACT

Quantifying the dynamics of root growth is necessary for knowledge about development of rhizoplane and rhizosphere structure, and will indicate potentials for soil C sequestration and for water and nutrient usage. Root growth was measured during 3 yr in spring wheat (*Triticum aestivum* L.) on fallow and in seven crops in spring wheat–winter wheat–alternative crop rotation under minimum tillage on Wilton silt loam (fine silty, mixed, superactive, frigid Pachic Haplustolls). Two types of minirhizotrons (standard [Stand MR] and pressurized-wall [P-wall MR]) were read with a microvideo camera. Average maximum rooting depths fell into agronomic groups: oilseeds safflower (*Carthamus tinctoris* L.), 1.64 m, and sunflower (*Helianthus annuus* L.), 1.45 m; spring wheat, 1.31 m; mustard family crops crambe (*Crambe abysinnica* Hochst. ex R. E. Fr.), 1.17 m, and canola (*Brassica rapa*), 1.13 m; and legumes dry bean (*Phaseolus vulgaris* L.), 1.00 m, soybean [*Glycine max* (L.) Merr.], 0.99 m, and dry pea (*Pisum sativum* L.), 0.99 m. Median depths of root length growth ranged from 0.92 m for safflower to 0.46 m for dry bean, and ratios of median to maximum depths averaged 0.51. Six out of eight crops showed greatest rooting depths in relatively wet 1995, likely because of wetter subsoil. Greatest total root length in safflower, crambe, canola, soybean and dry bean occurred in drier-than-average 1997, which is interpreted as a response to soil water deficit. Results indicate that diverse crop rotations have the potential to utilize water and nutrients and input C over different soil profile positions than spring wheat-based monocropping.

Crops alternative to wheat in dryland agriculture have potential to utilize water and nutrients and input C over different soil-profile positions than wheat-based monocropping. Research focused on root growth dynamics is necessary to quantify such potential and to reach better understanding of soil ecology and health. Models of soil–plant interaction for management guidance and prediction of nutrient use, such as the Root Zone Water Quality Model (RZWQM; Ahuja et al., 1999), require information about roots, including the depth of root growth (Hanson et al., 1999).

In dryland agriculture, the replacement of wheat-fallow dominated rotations with more complex crop rotations having a diversity of crops is essential for improving soil health and decreasing the depredations of disease, weeds, and insects. Furthermore, cultivation of crops alternative to wheat appears to improve economic survival of farm operators beset by input costs and market dynamics over which they have no control in the current political-economic system. Comparative root growth information will help guide design and implementation of new diverse cropping systems.

Root growth of a plant species has a potential pattern set by genetics, but there is a variable plastic component of root growth that responds to conditions of the soil environment and climatic demands placed on the whole plant (Zobel, 1992). Brouwer and deWit (1969) emphasize the dynamic balance between root and aboveground growth for plant growth modeling: deficiencies in water and nutrient supply can result in greater belowground allocation of physiological resources and increased root growth. Different patterns of root growth responses to water regimes in semiarid zones are reported in the literature. In one pattern, more frequent irrigation or rainfall results in more shallow depths of root growth (Hoogenboom et al., 1987, with soybean; Merrill and Rawlins, 1979, with sorghum [*Sorghum bicolor* (L.) Moench]). Another response is the tendency for root growth to penetrate less deeply in the profile as drought lowers the water content of subsoil (Merrill et al., 1996, with spring wheat).

Root growth systems are hierarchical, and each lower-ordered class of root members has lower diameter, less mass per length unit, shorter length, and less life span than higher-ordered roots. Thus, much of a plant's root length is found in the finer and smaller members of root systems. For example, Fiscus (1981) reported that two-thirds of the total area of *Phaseolus vulgaris* L. roots had an average diameter of 0.2 mm while about one-fifth of total area was on roots averaging 0.5-mm diameter. Zobel (1992) summarizes two studies on corn (*Zea mays* L.) and one on barley (*Hordeum vulgare* L.) as showing that the smallest class of roots have an active growing period of ~2 d with a lifetime of ~2 wk.

With the exception of very careful and time-consuming floatation-pail techniques, the majority of root recovery methods do not assure the conservation of the finer more active and more fragile part of root systems. The use of clear plastic tubes, known as minirhizotrons, installed in the field (Taylor, 1987) has made effective nondestructive measurements of fine root growth possible. One of the most functional versions of this methodology makes use of a miniaturized video camera (microvideo system) that allows both viewing and recording of root growth observations (Upchurch and Ritchie, 1984). The magnification provided by the minirhizotron-microvideo system allows the fine-root fraction to be imaged and measured.

The objective of research presented here was to determine root-length growth of eight crop species (safflower,

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Abbreviations: ANOVA, analysis of variance; CV, coefficient of variation; GRLD, greatest root length density, defined as the average RLD value in an 0.3-m depth segment with the greatest values in the uppermost 1.2-m of the soil profile; LTA, long-term average (precipitation); P-wall MR, pressurized-wall minirhizotron; RDI, Rooting Depth Index; RLD, root length density; Stand MR, standard minirhizotron; TRL, total root length.

sunflower, spring wheat, crambe, canola, soybean, dry pea, and dry bean) grown in dryland cropping systems in the Northern Great Plains. The measurements were repeated over a 3-yr period to enable the effect of variant climate on root growth to be assessed.

MATERIALS AND METHODS

Crops that are potential alternatives to small grains in dryland rotations were grown at the Area IV SCD-ARS Cooperative Research Farm located in Morton County, ND (Tanaka et al., 1998). The predominant soil type was Wilton silt loam. Surface soils to ~0.6-m depth consist of aeolian-derived material. A transition zone, typically 0.2 m or more thick, and consisting of variably coarser-textured material with lime inclusions, underlies this. The glacial-till subsoil is root penetrable and of finer-textured material.

The experiment was conducted over a 3-yr period, from 1995 to 1997, and was moved to a new site each year. Alternate crops were in a 3-yr rotation consisting of spring wheat– winter wheat-alternative crop. In 1995, crop plots were split into no-till and minimum-till zones. The 1995 root growth observations were conducted under minimal-till management, which consisted of two passes of an undercutter with 0.81-m sweeps and with application of Sonalan (ethyltrifluralin, $C_{13}H_{14}F_3N_3O_4$) herbicide at 1.1 kg ha^{-1} a.i. In 1996 and 1997, a single tillage treatment was applied consisting of a single undercutter pass with Sonalan application. Nitrogen (67.3 kg ha^{-1}) and P (11.2 kg ha^{-1}) fertilizers were applied at time of seeding. Seven crops were seeded in randomized order within three replications using a no-till drill: dry bean, soybean, dry pea, crambe, canola, sunflower, and safflower. Individual plots were 9-m wide by 46-m long. In addition to the seven alternative crops, the root growth of spring wheat growing on land fallowed the previous season was observed for comparison. Because of the previous year of fallowing, the spring wheat crop would usually have greater soil water availability than the alternative crops.

Root Growth Measurements

Two types of minirhizotrons were used: a standard type with rigid walls and a pressurized-wall type. The pressurized-wall minirhizotrons (P-wall MRs) (Merrill, 1992) have a working diam. of 9.6 cm and consist of a rigid inner plastic tube of 7.6 cm-diam. and an outer, flexible, tubular wall of 0.5-mm thick polyvinyl sheeting sealed to the inner tube at either end. After placement in access holes, P-wall MRs were inflated and kept under a constant pressure of ~20 kPa using solar panel-powered air pumps. The standard minirhizotrons (stand MRs) were made of Lexan plastic, 5.6-cm outside diam., and 5.0-cm i.d. The P-wall MRs were either 2- or 3-m long, while the standard type were 2-m long. In 1995 and 1996, four minirhizotrons were installed in each of two replications of each crop. In 1997, six minirhizotrons were installed in each of two replications. The mix of minirhizotron types was as follows: In 1995, each crop treatment received six P-wall MRs and two stand MRs. In 1996, six pressurized-wall and two standard types 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 of the pressurized-wall and eight of the standard type. All P-wall MRs in safflower and sunflower crops were 3-m long, while all minirhizotrons of both types in other crops were 2-m long.

Two different types of minirhizotrons were used because they have apparently complementary working qualities. Standard minirhizotrons have superior viewing quality and P-wall MRs are designed to give physical control of the soil-wall interface.

Access holes for minirhizotrons were drilled by rotary auger using a special tractor-mounted hydraulic soil-sampling probe that could be positioned accurately in the *x*-*y* plane and set to an angle. Holes were drilled at an angle of 30° with respect to the vertical. Holes for stand MRs were ~5-cm diam., and these tubes were forced into the soil with an hydraulic probe, establishing tight soil-wall interfaces. Holes for P-walls MRs were ~10-cm diam., allowing for relatively easy insertion of the tubes into access holes, but contact with the soil was firm when the minirhizotrons were pressurized. Minirhizotrons could not be removed from the soil while under pressurization. Installation of minirhizotrons in a crop occurred within 2 wk or less time after seeding.

Minirhizotrons were viewed with a microvideo camera (Bartz Technology Corp.[1], Santa Barbara, CA) at weekly or biweekly intervals. Equipment was mounted on a hand-push field cart, and included a video monitor, higher quality video recorder, and electric generator. Video images were recorded with audio annotation. Minirhizotrons were viewed at two nearly side-by-side places on the upward side at marks placed every 5 cm along the tubes (4.3-cm intervals of depth). The equipment gave 16-fold magnification with 12 by 17 mm viewing areas in stand MRs and 11-fold magnification with 18 by 25 mm viewing areas in P-wall MRs.

When installed in access holes at an angle of 30°, the 2-m minirhizotrons allowed observations to a depth of 1.4 m, and the 3-m minirhizotrons allowed observations to 1.8 m depth. Before the harvesting of crops with machinery, minirhizotrons were extracted from access holes for reuse in subsequent years.

To assure that root growth observations were not confounded by appearance of roots from weed species, areas around and particularly above minirhizotrons were kept weed-free by pulling them out by hand.

Conversion of Minirhizotron Data to Root-Length Density

Minirhizotron images were displayed on a video monitor of ~500 cm^2 area with three horizontal and three vertical lines superimposed on the screen. Intersections of root images with the monitor lines were enumerated. Only those roots of white or lighter color were counted; dark, brown-colored roots, often partially or fully shrunken, were assumed dead or decayed, and were not counted. Theories for converting minirhizotron observations to equivalent root-length density (RLD) values require root numbers per unit of wall area data (Upchurch, 1987). Root number data consists of a counting of each root member, with a branch being counted as a separate member. Root intersection values were converted to root number data by factors determined through field-made calibrations of intersections vs. numbers using zero-intercept linear regressions.

Root length density (in km m^{-3}) is the most useful measure of root length growth for application to environmental soil science. Minirhizotron root numbers per area data were converted to equivalent RLD values by application of a specific conversion model (Merrill and Upchurch, 1994; Upchurch, 1985). The model is based on an analytical geometric construction that considers root length growth that would occur inside the volume occupied by a minirhizotron if the device were not present in the soil. All possible root growth directions are considered equiprobable, and the model calculates the mean

[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.

theoretical nonbranched length of root that would grow from a root impinging on the minirhizotron wall. Merrill et al. (1994b) present experimental evidence for the existence of a wide range in the directions of fine-root growth, including directions more upward than horizontal.

The conversion model has been validated by application of studies in which both minirhizotron root number data were taken and direct measurements of RLD were made on root material recovered from soil (Merrill and Upchurch, 1994). To make these comparisons, minirhizotron RLD values were calculated by application of the conversion model. In studies by Meyer and Barrs (1985) in wheat using minirhizotrons of two sizes, regression values linking soil sample-derived RLD to minirhizotron RLD were within 10% of the model-predicted conversion factor. For a study of cotton (*Gossypium hirsutum* L.; Upchurch, 1985), the regression value between soil sample RLD and minirhizotron RLD was within 7% of the model conversion factor. The regression between RLD from an apparently efficient horizontal minirhizotron installation and soil sample RLD for cotton (Bland and Dugas, 1988) had ~50% less value than the model conversion factor. In contrast, regression between RLD of an inefficient mirror-telescope and minirhizotron system and well-recovered soil RLD (Merrill et al., 1987) was three times greater than the model conversion factor.

The actual form of the model conversion equation (Merrill and Upchurch, 1994) is:

$$N_r \times C_f \times 10 = \text{RLD} \qquad [1]$$

where N_r is minirhizotron root number per square centimeter area, C_f is the dimensionless conversion factor, and RLD is in units of kilometer per cubic meter. The conversion factor, C_f, depends on minirhizotron diameter, and $C_f = 3.0$ for P-wall MRs (diam. = 9.6 cm) and $C_f = 3.4$ for stand MRs (diam. = 5.6 cm). Many prior root growth studies have reported RLD in units of centimeter per cubic centimeter, which are converted to SI units of kilometer per cubic meter by multiplication by 10.

It should be noted that the Merrill and Upchurch (1994) theory for converting minirhizotron root numbers to RLD is somewhat related to the Lang and Melhuish (1970) theory for converting core-break root counts per area to RLD. The Lang and Melhuish theory relates roots intersecting an unit of area to the associated length of roots in a contingent cube of unit volume, and has a conversion factor value of 2.0.

Data Analysis and Display

Because the spring wheat measurements were made on crops growing on fallowed land and all other crops were part of continuously cropped rotations, minirhizotrons in this crop were read on fewer dates and spring wheat data is included only in summary tabularizations of rooting depth measures and greatest RLD (GRLD) and in only one of the figures.

1. Median values of RLD were determined for 0.087-m depth increments for each crop, date, and minirhizotron type group. Medians for the two minirhizotron types were logarithmically averaged, and depth profiles of RLD have been displayed.
2. To compare the largest RLD values observed in this study with RLD values found in the literature, we define a GRLD value as the average RLD in an 0.3-m segment with the greatest values which is located within the uppermost 1.2 m of the soil profile. The 0.3-m zone does not need to be continuous, and the GRLD value is calculated for a given experimental treatment at that observation date for which the greatest TRL is found. Comparable GRLD values were derived from RLD profiles reported in the literature.
3. The maximum depth of root growth for a given crop on a given day or two-day reading period was taken as the average of the greatest rooting depths observed in the two minirhizotrons of those installed which showed the deepest root penetration.
4. The median value of root length growth (depth above which one half of the TRL was measured) was determined for each date and crop.
5. Total root length cumulated over soil depth was averaged separately for the two minirhizotron types for each date and crop. Means of TRL measurements on three dates with highest values for a given crop and year were tabulated.

RESULTS AND DISCUSSION

Weather and Aboveground Growth

Total precipitation in 1995 was 47% greater than the long-term average (LTA, 1961–1990), and the four months of May through August received 79% more precipitation than the LTA (Table 1). In 1996, precipitation was near average, with precipitation during the four months of May through August being ~10% above the LTA. Precipitation during the four months in 1997 was 75% of the LTA, with the two month period of May and June being significantly drier than average, only 45% of the LTA.

Aboveground dry matter yields for the three legume pulse crops, dry pea, dry bean, and soybean, and the two mustard family crops, crambe and canola, were all lower in 1996 and 1997 than in 1995 (Table 2). For the dry-adapted safflower crop, dry matter yields were highest in drier 1997 and lowest in 1996. Yields for the longer-season sunflower crop were relatively even for the 3 yr. Dry matter yields of mustard family crops, crambe and canola, were low in 1996, with the principal cause apparently being proliferation of wild mustard weed [*Brassica kaber* (D.C.) Wheeler].

Development and Intensity of Root Growth

Figure 1 shows the development of the root systems with time. Root growth in 1995 was somewhat deeper than during the other years. Both sunflower and safflower in 1995 reached the bottoms of the longer minirhizotrons used to observe them (1.8-m depth). Thus, maximum root growth depths for these crops were probably >1.8 m in 1995. None of the other six crops (spring wheat not shown) appeared to have reached the bottoms of the shorter minirhizotrons used for their observation (1.4-m depth). Several crops show lesser depth of root-

Table 1. Precipitation recorded at USDI-NOAA meteorological site located ~10 km from the experimental site.

	1995	1996	1997	Average 1961–1990
	mm			
May	**173**	**61**	**16**	**57**
June	**66**	**60**	**44**	**75**
July	**152**	**102**	**95**	**60**
August	**43**	**45**	**27**	**49**
4 Months	**434**	**267**	**181**	**242**
Annual	**587**	**493**	**360**	**400**

Table 2. Agronomic information and aboveground dry matter yield for alternative crops.

Crop	Variety	Year	Aboveground dry matter	Seeding date	Harvest date	Plant population
			Mg ha^{-1}			1000 plants ha^{-1}
Safflower	Montola 2000	1995	5.02	30 May	20 Sep.	568
	Montola 2000	1996	3.02	29 Apr.	10 Sep.	454
	Montola 2000	1997	7.00	12 May	18 Sep.	277
Sunflower	Pioneer 6339	1995	6.53	6 June	16 Oct.	58
	Cenex 803	1996	6.56	23 May	17 Sep.	71
	Cenex 803	1997	6.95	12 May	18 Sep.	64
Spring Wheat	Pioneer 2375	1995		18 May	16 Aug.	
	Kulm	1996		29 Apr.	02 Aug.	
	Butte 86	1997		30 May	01 Aug.	
Crambe	Meyer	1995	6.44	30 May	21 Aug.	745
	Meyer	1996	2.60	29 Apr.	6 Aug.	440
	Meyer	1997	4.91	12 May	9 Sep.	239
Canola†	Reward	1995	6.28	30 May	15 Aug.	613
	Reward	1996	0.82	29 Apr.	25 July	737
	Reward	1997	4.10	12 May	14 Aug.	383
Soybean	Interstate‡	1995	6.78	12 June	16 Oct.	425
	Interstate	1996	3.96	23 May	16 Oct.	301
	Interstate	1997	3.67	28 May	18 Sep.	282
Dry Pea	Profi	1995	9.41	30 May	23 Aug.	659
	Profi	1996	4.87	29 Apr.	30 July	655
	Profi	1997	5.24	9 May	28 July	474
Dry Bean	Black Turtle	1995	5.84	12 June	12 Sep.	259
	Black Turtle	1996	4.74	23 May	4 Sep.	230
	Black Turtle	1997	3.02	28 May	9 Sep.	273

† Polish type canola.
‡ Interstate Payco 9206.

ing in 1996 compared with 1995, including sunflower, soybean, and dry bean. The greater depths of root penetration observed in 1995 are believed to be because of occurrence of wetter subsoil caused by greater precipitation that year.

The typical pattern seen in the regular RLD profiles (Fig. 1) is an increase in the depth of rooting followed by a period of net root decay usually beginning somewhere in the middle of the time series. The most notable net decays of root length growth appear relatively later in the growing season. The clearer examples include 1996 and 1997 safflower, 1996 sunflower, 1997 canola, 1996 and 1997 soybean, and dry pea and dry bean in 1996.

Many examples of minirhizotron-observed RLD profiles in the literature, and indeed, in the present study, exhibit relatively lower values near the soil surface. This has been attributed to such artifacts of the system as poor soil-wall contact at the shallowest depths nearest the soil surface and an inhibition of root growth caused by incomplete shielding from sunlight near the surface (Levan et al., 1987). However, in our study, the earliest RLD profiles for canola and for the three legume crops in 1997 show no lesser values at the shallowest soil depth, 0.04 m, than at immediately greater depths.

The largest RLD values for various crops and years (Fig. 1) show a considerable range of variation, from about 10 km m^{-3} to somewhat over 60 km m^{-3}. The overall accuracy of RLD values depends on the quality of minirhizotron functioning, including root growth in the wall-soil interface zone and observational efficiency. Accuracy also depends on the quantitative validity of the conversion of minirhizotron root counts to equivalent RLD. To compare our RLD measurements with those found in the literature, we have defined a GRLD value (see Materials and Methods).

For sunflower, our GRLD values (Table 3) range from 6.0 km m^{-3} for P-wall MRs in 1997 to 26.3 km m^{-3} for Stand MRs in 1997. Maertens and Bosc (1981) measured RLD from soil cores in field-grown sunflower, yielding a GRLD value of 21.8 km m^{-3}. Jaafar et al. (1993) observed sunflower root growth in the field with the core-break technique, and their root counts may be converted to RLD by the theory of Lang and Melhuish (1970). From their data for two different years, the GRLD values extracted were 3.7 and 7.9 km m^{-3}.

For spring wheat, our GRLD values (Table 3) ranged from 11.0 km m^{-3} for P-wall MRs in 1995 to 36.1 km m^{-3} for P-wall MRs in 1996. Meyer and Barrs (1985) report soil-core RLD for spring wheat growing in undisturbed and repacked large soil cylinders. Their largest GRLD values for two treatments were 72.7 and 75.3 km m^{-3}. Merrill et al. (1996) report minirhizotron RLD values for spring wheat under drought (using the Merrill and Upchurch [1994] conversion), yielding 38 and 53 km m^{-3} for the top two treatment-year combinations.

For soybean, our GRLD values (Table 3) ranged from 8.6 km m^{-3} for P-wall MRs in 1995 to 29.8 km m^{-3} for Stand MR in 1997. Mason et al. (1982) measured RLD on material recovered from soil blocks taken from supplementally irrigated soybeans, giving largest two GRLD values of 4.2 and 4.6 km m^{-3}. Nickel et al. (1995) reported soil-core RLD from a field experiment in Minnesota, giving largest two GRLD values of 17 and 25 km m^{-3}.

Fine-root growth tends to be clumped, and minirhizotron root count data often contain many zeroes, tend to be nonnormally distributed, and typically display relatively high coefficient of variation (CV) values. Average annual CV values by minirhizotron type for data used to calculate GRLD values (Table 3) ranged from 50 to

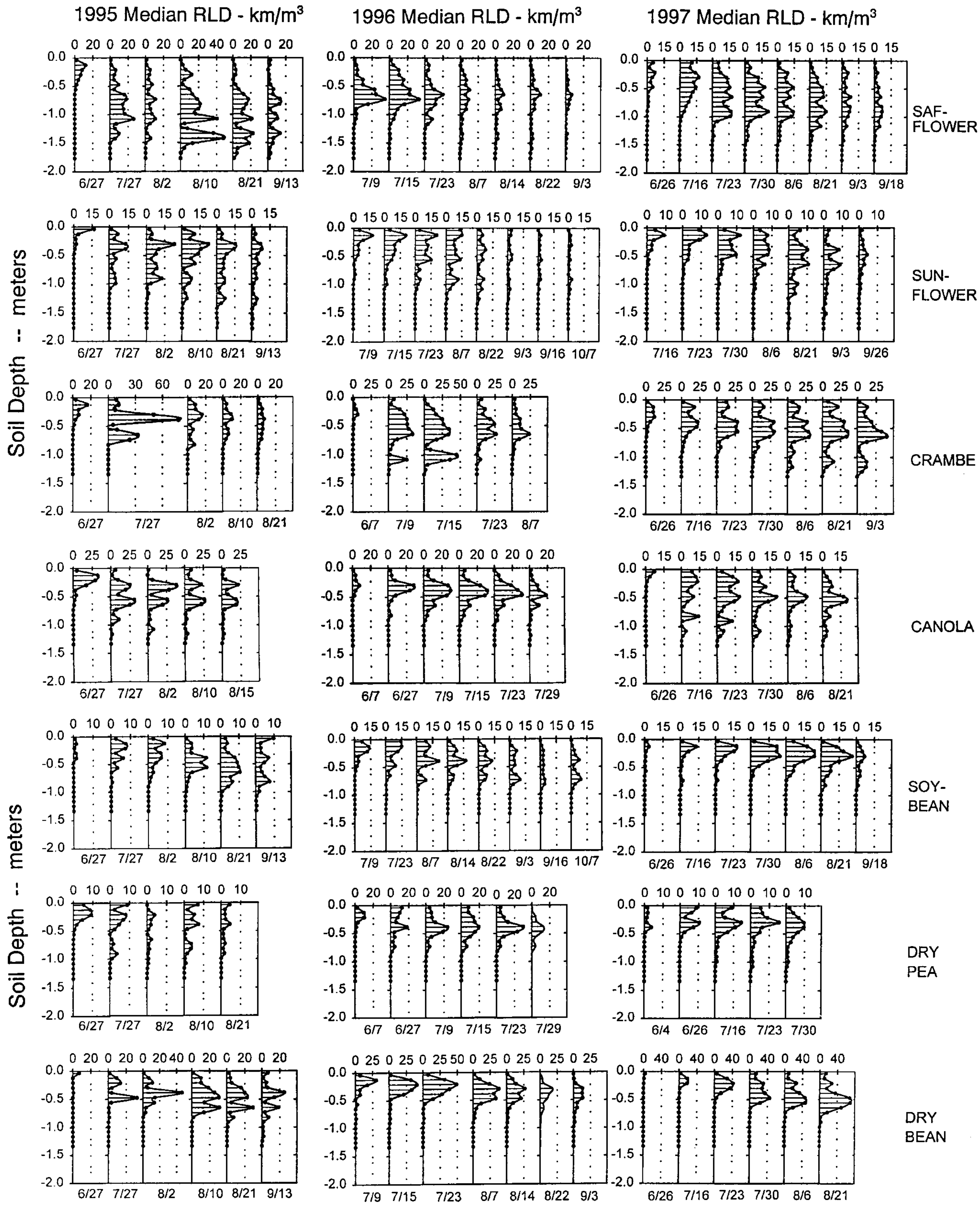

Fig. 1. Profiles of root length density (RLD) for crops grown in 1995, 1996, and 1997.

71% for nonzero data and from 87 to 117% for data with zeroes included. Vos and Groenwold (1987) studied minirhizotrons in soil containers and published data showing that CV values of ~100% at an RLD of 10 km m^{-3} declined to ~50% as RLD increased to 35 km m^{-3}. Meyer and Barrs (1985) measured root counts at intervals along horizontal minirhizotrons and showed lesser to similar variability for undisturbed large soil cores and

Table 3. Average greatest root length density (GRLD)† values, which are defined here as the greatest quarter of values from root length density (RLD) profiles measured at the date of greatest total root length (TRL); average soil depth of GRLD values; and day of year (DOY) for greatest TRL. Values are tabulated separately for pressurized-wall and standard minirhizotrons.

	1995					1996					1997				
	Press-wall		Standard			Press-wall		Standard			Press-wall		Standard		
CROP parameter	GRLD	Depth	GRLD	Depth	DOY	GRLD	Depth	GRLD	Depth	DOY	GRLD	Depth	GRLD	Depth	DOY
	km m^{-3}	m	km m^{-3}	m		km m^{-3}	m	km m^{-3}	m		km m^{-3}	m	km m^{-3}	m	
Safflower	37.2	1.25	19.9	0.62	222	16.2	0.60	36.9	0.58	197	18.2	0.78	22.3	0.56	211
Sunflower	11.3	0.32	23.5	0.45	222	7.0	0.47	26.3	0.58	220	6.2	0.73	20.8	0.47	233
Spring Wheat	11.0	0.58	25.0	0.56	219	36.1	0.71	43.3	0.56	197	16.4	0.78	26.1	0.69	204
Crambe	5.5	0.34	46.0	0.52	222	34.5	0.76	33.6	0.47	197	31.3	0.73	37.6	0.52	233
Canola	18.6	0.45	36.7	0.47	208	28.1	0.43	21.2	0.45	191	22.6	0.62	17.2	0.36	204
Soybean	8.6	0.60	10.8	0.52	233	12.1	0.23	21.9	0.17	220	11.3	0.32	29.8	0.26	233
Dry Pea	3.4	0.56	10.2	0.19	222	12.6	0.41	28.1	0.34	197	16.1	0.43	8.7	0.26	197
Dry Bean	48.5	0.52	14.8	0.26	222	40.5	0.43	27.4	0.34	220	29.4	0.52	67.0	0.34	218
Avg. no. miniR.‡ sunfl. & saffl.	4.5		2			6		2			6		6		
Avg. no. miniR. 6 other crops	4.5		2			3.8		4			4		7.3		
Avg. CV§, CV range for non-zero data	68, 55–82		50, 20–84			61, 37–68		71, 53–97			69, 42–96		63, 54–72		
Avg. CV, CV range for all data	117, 62–173		87, 60–108			89, 66–122		90, 71–107			99, 68–121		90, 62–109		

† Defined as the average RLD value in an 0.3-m depth interval with the greatest values, from the upper 1.2-m of the soil profile.
‡ MiniR. = minirhizotron; sunfl. = sunflower; saffl. = safflower.
§ Coefficient of variation values are based on root numbers observed in a 4.33-cm depth increment, calculated over the set of minirhizotrons of one type, and averaged over data that was included in the GRLD value.

disturbed soil: CV values ranging from 33 to 58% at an RLD level of ~15 km m^{-3}.

Soil Depths of Root Growth

The time courses of maximum observed root depths and of median depths of root length are shown in Fig. 2. The time courses of maximum growth depths were not generally as stable as those for median values. Depths of medians were approximately one-half of the maximum depths. The ratios of median to maximum depths (Table 4) ranged from 0.47 for dry bean to 0.57 for spring wheat, and the average ratio value was 0.51.

Our results showing that median soil depths of root length growth are approximately one-half of the maximum depths are not in accord with general results of studies using soil core and related techniques. Typical soil core RLD profiles show median depths that are less than one-half of maximum depths, provided that the depth of study covers most of the rootzone. Publications that have minirhizotron and soil-core RLD profiles graphed together, illustrating this difference include Meyer and Barrs (Fig. 1, 1985) and Vos and Groenwold (Fig. 4 and 3, 1987).

As a means of summarizing the rooting depth results, we have constructed a rooting depth index (RDI) that gives approximately equal weight to both the maximum and the median depths.

Because the average median value is roughly one-half of the maximum, multiplying the median by two achieves this:

$$RDI = (2 \times \text{median} + \text{maximum})/2. \quad [2]$$

Thus, RDI = 2 for a plant with a maximum rooting depth of 2 units and a median depth of 1 unit. By this index, the crops fall into agronomic and botanical family groups (Table 4). Foremost, at RDI = 1.73 is the deeply rooted, dry-loving safflower crop, which is a member of the Compositae family, followed by another oilseed crop, sunflower (RDI = 1.45), also a member of the Compositae family. Spring wheat (RDI = 1.31) is sandwiched between the more deeply rooted oilseeds and the mustard family crops, crambe and canola, with RDI values of 1.17 and 1.13, respectively. The three legume pulse crops, soybean, dry pea, and dry bean are the shallowest rooted, with RDI values of 1.03, 0.97, and 0.96, respectively.

Summarization of root growth data by parameterization and summary equations is important for application of the data to models. Borg and Grimes (1986) fitted time courses of maximum rooting depth of 48 crop species to a common parameterization by normalization of the data to relative time on a scale of days to attain maximum depth after seeding (DTM), and relative depth on a scale of the maximum root depth, RD_m, where RD is relative depth and DAP is days after planting:

$$RD = RD_m \{0.5 + 0.5 \sin [3.03 (DAP/DTM) - 1.47]\} \quad [3]$$

This gives a sigmoidal curve with an intermediate section that appears quasi-linear, a form that both our maximum and median curves appear to generally follow. The Borg and Grimes (1986) data set was taken from literature before any substantial use of minirhizotrons or higher quality, soil-recovered RLD was published, and much of it comes from trench-profile work. Modern minirhizotron data, with their more reliable representation of fine-root growth, provide more accurate median depth values than trench profile or root recovery techniques. Thus, it makes more sense to base parameteriza-

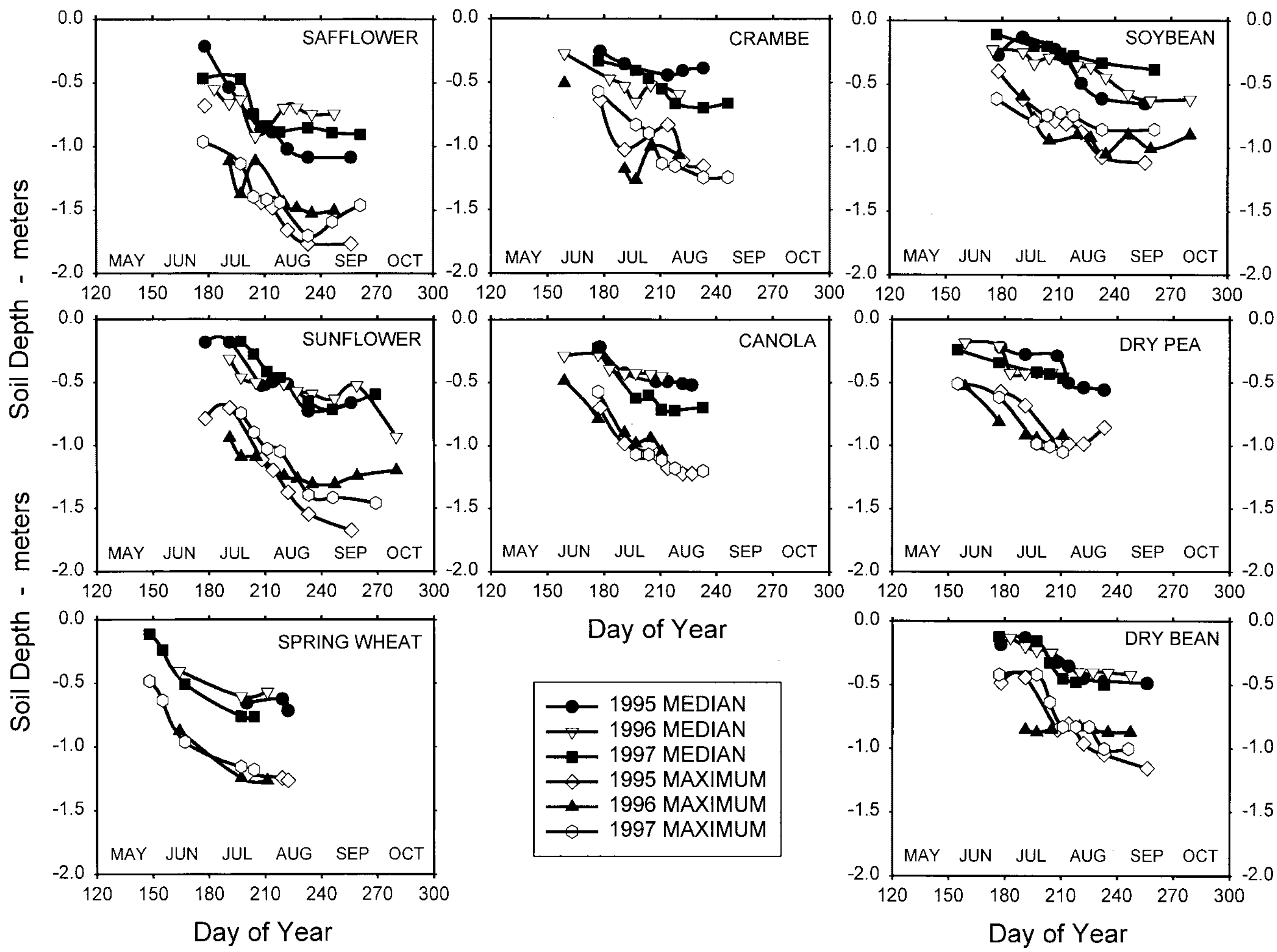

Fig. 2. Time courses of median and maximum depths of root length growth.

tion of minirhizotron data primarily on more useful and indicative median depths, with maximum depth used as either a secondary parameter or a coparameter.

The sigmoidal type of parameterization such as that used by Borg and Grimes (1986) appears useful for time courses of both maximum and median rooting depths. Our data in Fig. 2 generally appears to fit sigmoidal parameterization. Except for dry pea data, the parts of the curves with steepest slopes project towards the *x*-axis to dates in May or June, dates near or clearly after seeding.

How do our results compare with those of others? The most available datum is maximum observed rooting depth. Merrill et al. (1994a) report a trench profile observation of safflower rooting to 1.9 m at the same general site as that used for the present study, which compares with the 1.8-m maximum depth observed in safflower in 1995 (the greatest depth that was possible to observe with our minirhizotrons). Our 1.4- to 1.6-m range of maximum sunflower depths compares favorably with a number of sunflower results in the literature. Jaafar et al. (1993) found a 2.2-m sunflower maximum

Table 4. Maximum and greatest median depths (meters) of root length growth summarized.

	Median depth†				Maximum depth					
CROP	1995	1996	1997	Avg.	1995	1996	1997	Avg.	Ratio of median to maximum‡	Rooting depth index§
Safflower	1.09	0.75	0.90	0.92	1.77	1.52	1.65	1.64	0.551	1.731
Sunflower	0.70	0.78	0.68	0.72	1.61	1.31	1.44	1.45	0.501	1.447
Spring Wheat	0.72	0.61	0.76	0.70	1.26	1.25	1.17	1.23	0.570	1.306
Crambe	0.43	0.62	0.68	0.58	1.14	1.17	1.25	1.18	0.485	1.169
Canola	0.51	0.44	0.72	0.56	1.22	1.02	1.19	1.14	0.485	1.129
Soybean	0.63	0.62	0.36	0.56	1.09	1.03	0.86	0.99	0.535	1.034
Dry Pea	0.55	0.44	0.45	0.48	0.99	0.97	1.03	0.99	0.482	0.974
Dry Bean	0.48	0.41	0.49	0.46	1.10	0.88	1.01	1.00	0.466	0.960

† Average of median root length growth depths on two dates at which values were greatest.
‡ Calculated annually then averaged.
§ RDI = (Median * 2 + Maximum)/2. Calculated annually then averaged.

with core-break technique in Kansas. Merrill et al. (1994a) reported a trench profile-observed maximum depth of 1.7 m on the same general site as the present study. Borg and Grimes (1986) quoted the classical trench profile observations of J.E. Weaver, who observed that sunflower rooted to depths of 1.5 to 3.0 m.

Our soybean maximum depths of 0.86 to 1.09 m compared with maximum depths of 1.15 to 1.45 m observed in three cultivars through use of recovered monoliths in southwestern Minnesota (Allmaras et al., 1975), 1.0 m observed with minirhizotrons, also in southwestern Minnesota (Nickel et al., 1995), and a 1.3-m maximum observed with minirhizotrons in Kansas (Grecu et al., 1988). Our dry pea maximum depths of 0.96 to 1.03 m compare with 0.8 to 1.0 m measured on green pea cultivars in Denmark with minirhizotrons by Thorup-Kristensen (1998).

There was a generally consistent pattern of maximum depth results, with six out of eight crops exhibiting their deepest maximum depths in the relatively wet year, 1995 (Table 4). Only crambe and dry pea had greatest maximum depths in relatively dry 1997. Results for greatest median depths (Table 4) showed no consistent pattern with years. Three crops had deepest medians in 1995, one in 1996, and four in 1997.

As reviewed by Zobel (1992), root depth and distribution are generally under the influence of many edaphic factors, but three in particular are influenced by management: nutrients, temperature, and water. Generally adequate nutrition may be assumed in a fertilized field experiment. Temperature influences root distributions in northern dryland crops, as soils heat up more slowly in the spring in wetter years, or in situations where management results in higher soil water content. In our study, the maximum root depths developed in late spring or summer, later than springtime warmup of soil. Thus, our observations of generally greatest maximum rooting depths occurring in 1995 are probably best explained as root growth responses to differences in soil water content that were created by the precipitation differences among the years of the study.

Two types of relationships between soil-water regime and root growth results are reported in the literature. In the first kind, comparing moderately watered situations with irrigated ones, or different degrees or patterns of irrigation, reports typically indicate that more shallow average rooting depth occurs under greater or more frequent irrigation regimes. Examples are Hoogenboom et al. (1987) comparing irrigated and nonirrigated soybean, and Merrill and Rawlins (1979) comparing different irrigation frequencies applied to sorghum [*Sorghum bicolor* (L.) Moench]. However, another type of water-regime relationship appears responsible for the general pattern of results reported here: typically in dryland situations, inadequate precipitation can limit rooting depth. Progressively greater subsoil drying during a 3-yr drought cycle caused the maximum rooting depths of spring wheat in a continuous crop rotation to decline from 1.10 to 0.75 m (Merrill et al., 1996). Our alternate crops were in continuous crop rotation, and our results showing lesser maximum root growth depths in six out of eight crops under average to below-average precipitation are most credibly explained as a response to lowered subsoil moisture.

Total Root Length Growth

Time courses of TRL are shown in Fig. 3, with P-wall MR and Stand MR results distinguished. The time courses of many of crops reveal consistent patterns of root decay after midseason buildup of TRL. Cases where the data patterns measured with both types of minirhizotron consistently indicated that root decays had occurred, were all 3 yr for both safflower and sunflower, 1995 and 1996 crambe, and 1997 soybean. Another interesting result is the relatively higher peak TRL values measured in low-precipitation 1997 compared with 1995 and 1996 for the crops crambe, soybean, and dry bean.

The root literature contains a number of general references to increases of root growth in response to relative lack of nutrients or water in the rootzone. This concept of dynamic balance between root and aboveground growth is discussed by Brouwer and DeWitt (1969). An example of this type of root growth response to water would be Hoogenboom et al. (1987), who observed significantly greater TRL growth of nonirrigated soybean compared with the irrigated crop.

The pattern of our TRL results indicates a general fine-root growth response to lowered soil water availability. The TRL values averaged over minirhizotron type (Table 5) indicate a general increase in growth in drier 1997 compared with much wetter 1995. Five out of eight crops showed greatest TRL growth in 1997 (safflower, crambe, canola, soybean, and dry bean). Two crops had highest average TRL in 1996 (spring wheat and pea). A number of the crops showed considerable increases of average TRL in dry 1997 compared with wet 1995: 3.3 times higher for crambe, 2.5 times for dry bean, and 1.8 times for soybean. Only sunflower had highest average TRL growth in wet 1995. This is probably related to the fact that sunflower aboveground biomass yield (Table 2) was relatively even over the 3 yr, being highest in dry 1997.

Pressurized-Wall vs. Standard Minirhizotrons

Standard minirhizotrons were inserted into access holes sized slightly smaller than the tube diameter with considerable force to insure good soil contact, and there is concern that root growth at the wall-soil interface may be hindered. Pressurized-wall minirhizotrons (Merrill, 1992) were designed to overcome such operational concerns. While results obtained with Stand MRs and P-wall MRs in this study were generally similar, several of the data compilations and displays given here show Stand MR and P-wall MR data separately so that differential responses may be analyzed.

The average soil depths of the largest RLD profile values (GRLD, Table 3) were generally greater for P-wall MRs than for Stand MRs. In 1995, average depths where GRLD values were observed for P-wall MRs were greater than GRLD depths for Stand MRs in five out of eight crops; P-wall MR depths were greater than

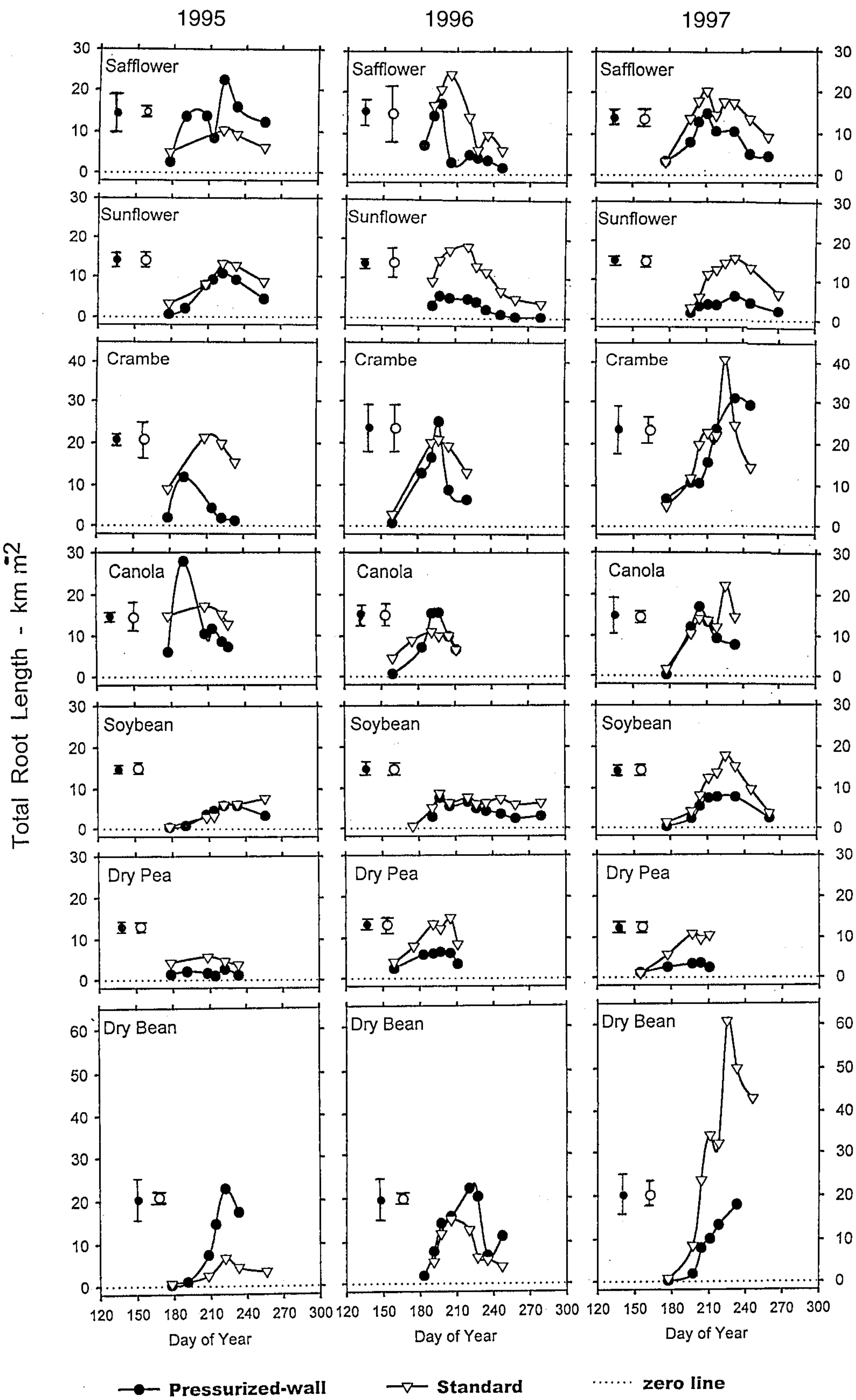

Fig. 3. Total root length (TRL) of crops measured with pressurized-wall and standard minirhizotrons. Error bars indicate standard error of the means for averages of three dates on which highest TRL values occurred.

Table 5. Median values of total root length (TRL) from pressurized-wall (P-wall) and standard (Stand) type minirhizotrons as averages of measurements on three dates with highest values for a given crop and year. Standard errors of mean are in parentheses. Also, geometric averages (Gavg) of P-wall and Stand measurements. All values have units of km m^{-2}.

	1995			1996			1997		
Crop	P-wall	Stand	GAvg	P-wall	Stand	GAvg	P-wall	Stand	GAvg
Safflower	17.3 (5.1)	9.8 (0.9)	13.0	11.5 (3.4)	20.6 (7.2)	15.4	12.9 (1.6)	18.7 (2.4)	15.5
Sunflower	9.7 (1.7)	12.3 (1.9)	10.9	5.1 (1.3)	16.7 (3.8)	9.3	4.6 (0.7)	13.7 (1.6)	7.9
Sp. Wheat†	5.6 (5.1)	10.0 (1.9)	7.5	26.9 (8.4)	25.3 (4.4)	26.1	9.8 (1.1)	16.6 (1.7)	12.8
Crambe	2.4 (1.4)	20.9 (4.3)	7.1	16.9 (5.8)	20.2 (5.8)	18.5	27.7 (6.0)	20.1 (3.1)	23.6
Canola	8.4 (1.5)	15.9 (3.8)	11.5	13.8 (2.6)	10.4 (3.0)	12.0	14.2 (4.4)	12.8 (1.5)	13.5
Soybean	5.0 (0.7)	6.7 (1.4)	5.8	6.5 (1.6)	7.6 (1.1)	7.1	7.7 (1.1)	13.9 (1.3)	10.3
Dry Pea	1.8 (0.8)	4.8 (1.3)	3.0	6.3 (0.7)	13.6 (2.2)	9.3	3.1 (1.4)	10.3 (1.2)	5.7
Dry Bean	18.1 (5.1)	4.9 (0.8)	9.4	19.5 (5.3)	11.5 (1.2)	15.0	13.8 (5.1)	38.7 (3.5)	23.1

† Medians from top two dates averaged for spring wheat values.

Stand MR depths in six out of eight crops in 1996; and P-wall MR depths were greater for all eight crops in 1997. The two greatest depths of rooting that occurred on each date for a given crop, and which were averaged to determine maximum rooting depth (Fig. 3), were observed in P-wall MRs more often than would be expected from the relative numbers of P-wall MRs vs. Stand MR's installed in each crop each year. These observed differences between the minirhizotron types are consistent with the interpretation that there were elevated soil strengths at wall-soil interfaces of Stand MRs, particularly deeper in the soil, and that this was a hinderance to root growth.

The amounts of TRL growth observed with the two minirhizotron types differed somewhat (Table 5). In 1995, the TRL for Stand MRs was greater than that for P-wall MRs for six out of eight crops, TRL for Stand MRs was greater than P-wall MRs for five out of eight crops in 1996, and Stand MR TRL was greater in six out of eight crops in 1997. This is consistent with the observation that Stand MRs were more optically efficient than P-wall MRs. Viewing is through two separate layers of material in P-wall MR's, as compared with only one layer in Stand MRs, and water condensation between inner and outer walls was a problem at lower depths for some P-wall MRs.

CONCLUSIONS

Four out of eight plant species studied exhibited a consistent pattern of having a greater TRL in dry 1997, intermediate values of TRL in average precipitation 1996, and lower TRL in wetter 1995. Based on RDI values (Table 4), these four species ranked from eighth and last (dry bean) to fourth (crambe), with only dry pea (seventh) not showing the same pattern of TRL response. This pattern of results appears to indicate a general principle of soil-plant ecology: that relatively more shallow-rooted plants can exhibit an increase in fine-root growth as an adaptive response to relative drought, while more deeply rooted plants growing on nonrestrictive soil profiles do not exhibit this root growth response.

For six out of the eight species, maximum depths of root growth were greater in relatively wet 1995. For a given species, differences in maximum rooting depth varied between years by about 0.1 to 0.3 m. However, with few and minor exceptions, the relative rankings of the crops for measures of rooting depth were the same over the 3 yr. These results increase confidence in the use of comparative-species root growth data and information collected in a given year for use in agro-ecological management.

The rooting depth results indicate considerable difference among the crops in potential for using water and nutrients at deeper positions in the soil profile. Average rooting depth values for first-ranked safflower (Table 4, maximum = 1.64 m, median = 0.92 m) were from 60 to 100% greater than those of last-ranked dry bean (maximum = 1.00 m, median = 0.46m). These rooting depth differences among the eight crops positively correlate with soil water extraction during the 1999 and 2000 growing seasons (May to October). Measurements on the same general site as the present study idicated that sunflowere and safflower had net depletions of soil water that were 20% to over 100% greater than those of the other six crop species (Merill et al., 2001a,b). These results show that inclusion of deeply rooted oilseed crops in dryland rotations can result in water and N use in subsoil positions, positively benefiting water quality in soil, land, and climate situations of excess precipitation or overland flow and unused, mobile fertilizer N.

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