Vegetable Seedling Root Systems: Morphology, Development, and Importance

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Seedling root systems have important physical and physiological roles from the onset of seed germination (radicle protrusion) and emergence through subsequent seedling growth and development. Important root functions include shoot anchorage, water uptake, nutrient uptake, and hormone production. The size, morphology, or architecture of a root system may control the relative size and growth rate of the shoot. Optimum root systems throughout the plant life cycle can ensure optimum shoot growth, shoot development, and subsequent yields. However, abiotic stresses originating in the root zone can be expressed in the shoots, thereby affecting the dry-matter partitioning and, ultimately, the productivity of the plant. Understanding the relationships of root and shoot components to stand establishment, particularly as influenced by abiotic stresses, is essential for developing optimum cultural and management techniques for field planting systems.

Selection of root study methods is critical in evaluating associations or relationships among root and shoot components. Root study methods have been developed for destructive and nondestructive sampling. Selection of methodology depends on the crop(s) to be studied, purpose of the investigation, root variables to be measured, time constraints, and costs. Root study methods have been reviewed by Böhm (1979), Schuurman and Goedewaagen (1971), and Taylor (1986). Quantification of roots from image analysis using a minirhizotron has been reviewed by Smucker et al. (1987). Techniques for measuring root geometry using image analysis and resin-impregnated blocks were reported by Commins et al. (1991).

SEEDLING ROOT MORPHOLOGY

To establish seedling root system relationships with shoot growth or development, a clear understanding of root morphology is required. Klepper and Rickman (1991) described root systems in terms of axes and their branches: 1) vertical or main axes (or taproots), 2) horizontal or vertical axes (first-order laterals), and 3) second- or higher-order laterals. Generally, seedling root morphology differs between monocotyledonous and dicotyledonous species. For example, the seedling root systems of mungbean (*Vigna radiata* L.), corn (*Zea mays* L.), and onion (*Allium cepa* L.) are distinctly different (Fig. 1). Mungbean, a dicotyledonous species, has a defined taproot (originating from the radicle), lateral roots (initiating from the taproot, or pericycle cells), basal roots (originating from the basal part of the hypocotyl or shoot-root transition zone when pericycle cells do not originate in this area), and adventitious roots (originating from the hypocotyl). This root-origin classification was first described by Zobel (1975) for tomato (*Lycopersicon esculentum* Mill.) and by Stoffella et al. (1979b) for beans (*Phaseolus vulgaris* L.). Onion, a monocot, has no defined taproot, but only an accumulation of adventitious roots and lateral roots (which originate from the preexisting adventitious roots). However, distinctive root morphological differences occur within monocots (Fig. 1) and dicots. Root systems have been illustrated for field-grown vegetable (Weaver and Bruner, 1927) and agronomic crops (Weaver, 1926).

Root dry-weight accumulation, number, diameter, length, surface area, and distribution in a soil profile can differ within crop species. Seedling taproot, basal root, and adventitious root variables differ between genotypes of beans (Kahn et al., 1985; Lynch and van Beem, 1993), peppers (*Capsicum annuum* L.) (Leskovar et al., 1989; Stoffella et al., 1988a), and mature tomatoes (Stoffella, 1983). In cowpea [*Vigna unguiculata* (L.) Walp.], 'California Blackeye #5' seedlings had longer taproots, more lateral roots, taller shoots, and heavier roots and shoots than 'Knuckle Purple Hull' or 'Texas Cream 40' seedlings when measured 11 days after radicle protrusion (Table 1). Mean taproot growth rate (length) and lateral root production from 3 to 11 days after radicle protrusion also differed among these three cowpea cultivars (Table 2).

Root architectural traits, such as secondary and tertiary root branching, angles, and radii, also should be considered in evaluating seedling root systems. Fitter (1987, 1991) reported an architectural approach to studying plant root systems and suggested that topological models and architectural root system components, such as link lengths, branching angles, and diameters, should be used for comparative ecological studies of plant root systems. Detecting differences in root growth patterns and architecture between genotypes may offer unique genetic selection criteria for tolerance to root diseases and pests, lodging, drought, flooding, stressful root-zone temperatures, or edaphic adaptations. Reviews of genotypic variation in root morphological characteristics and variation in root system phenotypes have been reported by O'Toole and Bland (1987), and of rhizogenetic variation in vegetable crops by Zobel (1975, 1986). Root morphological traits can be directly related to plant lodging (Ennos, 1990; Kahn, 1985; Stoffella and Kahn, 1986; Stoffella et al., 1979a), flooding tolerance (Kahn et al., 1985), and nodule formation (Kahn and Stoffella, 1991). Zobel (1989) has reviewed studies on the effects of edaphic and environmental factors, such as moisture, temperature, mineral concentration, and gaseous atmosphere, on root morphology. O'Toole and Bland (1987) also emphasized the importance of specific root morphological traits and their importance in improving or overcoming physiological stresses.

SEEDLING ROOT DEVELOPMENT

Minimal research has focused on the development of seedling root systems and implications for optimum stand establishment and subsequent seedling shoot growth and development. Previous investigations have addressed improvement in percent or rate of seed germination and seedling emergence via seed enhancement treatments, research that has been extensively reviewed by Bradford (1986), Khan (1992), and Heydecker and Coolbear (1977).

Initiation, organization, and emergence of lateral roots are complex processes involving growth regulators and specific gene expression (Keller and Lamb, 1989; Wightman et al., 1981). Auxin transported from the cotyledons has a controlling role in the position, spacing, and development of lateral root primordia in peas (*Pisum sativum* L.) (Hinchee and Rost, 1992). In peas, the first lateral roots are initiated in the radicle before germination (Rost and Toriyama, 1991). After seeding, initiation of root primordia on the primary root and hypocotyl of tomato seedlings varied between genotypes and the number of primordia on the primary root and hypocotyl was increased either by Hoagland's solution or by presoaking seeds with abscisic acid (ABA) or 6-benzylamino purine (BA) (Aung, 1982). Treatments with 3-indolylacetic acid (IAA) or other auxins promoted the initiation of the

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Fig. 1. Root morphological components of mungbean, corn, and onion seedlings depicting adventitious (adv), basal, lateral, and taproots (tap).

Table 1. Cowpea taproot length, lateral root number, fresh root weight, fresh shoot weight, and shoot : root ratio 11 days after radicle protrusion (data on a per plant basis).

Cultivar	Taproot length (cm)	cv ^z	Lateral root (no.)	cv	Root wt (mg)	cv	Shoot wt (mg)	cv	Shoot : root (ratio)	cv	Shoot ht (cm)	cv
California Blackeye #5	27.7 a ^y	18	126 a	27	0.57 a	41	1.42 a	26	2.94	48	16.5 a	33
Knuckle Purple Hull	12.6 c	47	51 c	49	0.41 b	36	1.14 b	17	3.05	35	13.5 b	19
Texas Cream 40	19.2 b	36	70 b	36	0.24 c	46	0.71 c	27	3.32	34	11.5 c	19

^zCoefficient of variation (%).

^yMean separation within columns by Duncan's multiple range test, $P \leq 0.05$.

Table 2. Linear regression equations of mean taproot length or total number of lateral roots on days after radicle protrusion (3–11 days) of three cowpea cultivars.

Cultivar	Regression equation ^z	R ²	CV ^y
<i>Taproot length</i>			
California Blackeye #5	$-6.9 + 3.4D^x$	0.86	21
Knuckle Purple Hull	$-2.1 + 1.4D$	0.46	51
Texas Cream 40	$-5.5 + 2.3D$	0.72	35
<i>No. lateral roots</i>			
California Blackeye #5	$-64.1 + 17.9D^x$	0.80	38
Knuckle Purple Hull	$-22.8 + 6.8D$	0.63	54
Texas Cream 40	$-33.4 + 9.0D$	0.71	51

^zD = days after radicle protrusion.

^yCoefficient of variation (%).

^xRegression coefficients (slopes) are significantly different from each other by *t* tests, $P \leq 0.05$.

lateral root primordia in peas (Wightman et al., 1981) and increased the number of primordia formed along the primary axis in peas (Zeadan and MacLeod, 1984) and corn (Hurren et al., 1988). MacIsaac et al. (1989) reported that 2-naphthaleneacetic acid (NAA) increased the number of lateral root primordia, but kinetin prevented their spontaneous formation and inhibited the NAA-enhanced lateral root primordia of lettuce (*Lactuca sativa* L.). In corn, most primordia from the primary root completed their development and emerged as laterals within a fixed period, irrespective of their origin along the main axis (MacLeod, 1990). Cytokinins, particularly zeatin, inhibited the initiation and formation of lateral roots on decapitated primary roots of pea seedlings (Wightman et al., 1981). Removal of adventitious root tips promoted the formation of primordia along most of the remaining axis in onion seedlings (Abadia-Fenoll et al., 1986); however, normal onion roots appeared to be unbranched (Fig. 1) over distances of up to 400 mm from the apex (Melchior and Steudle, 1993).

Root developmental sequence in bell pepper has been reported as

radicle protrusion from the seed, rapid taproot elongation until cotyledon development, and production of basal and lateral roots subsequent to cotyledon expansion (Stoffella et al., 1988a). Medium pH (Stoffella et al., 1991), seed enhancement treatments (Stoffella et al., 1988b, 1992), and temperature (Stoffella et al., 1988b) influenced pepper seedling root system development. Portas and Dordio (1980) have reviewed investigations on root length, width, depth, and density of tomatoes. Tanaka (1964) classified root development of legume crops into alfalfa (*Medicago sativa* L.), vetch (*Vicia* spp.), and intermediate [soybean, *Glycine max* (L.) Marr.] types. Tanaka (1977) also reported that root elongation, branching, and thickening ability differed among 26 legume crops. Models developed from derived equations of root (length) density in relation to shoot weight for several vegetable crops were described by Greenwood et al. (1982).

STRESS EFFECTS ON SEEDLING GROWTH

The abiotic root-soil environment is seldom optimum for continuous growth and can have a profound influence on root anatomical characteristics, root developmental patterns, and the seedling physiology of roots. Root systems in relation to stress tolerance have been reviewed by Miller (1986), who discussed the effects of water, O₂, mechanical impedance, and temperature stress on mature plants. Latimer (1991) reviewed vegetable seedling growth responses to mechanical stress. Adverse environments that include the interaction of factors such as nonoptimum temperature, deficiency or imbalance of nutrients, drought, and waterlogging have received less attention in seedlings.

Temperature

Early root elongation, branching, and function are highly temperature-dependent mechanisms (Russell, 1977). Results from root studies conducted at constant temperatures are difficult to extrapolate to estimates of root responses in the field due to fluctuating air and soil-depth temperatures. No lateral roots developed for 12 legumes exposed to constant 10 or 30C, and lateral and taproot elongation were highly variable between 15 and 25C (Brar et al., 1990). Taproot elongation rate was slower for pregerminated than for raw or primed pepper seeds incubated at 15C, but similar at 25 or 35C (Stoffella et al., 1988b).

Root systems of tropical or subtropical origin species are sensitive to chilling temperatures. For example, root growth decreased when squash (*Cucurbita pepo* L. var. *melo*pepo) and cucumber (*Cucumis sativus* L.) seedlings were exposed to 2 and 6C for 48 h, and when seedlings were returned to 26C, irreversible damage (inability to resume growth) occurred after 96 h (Reyes and Jennings, 1994). Short-term cyclic cold stresses (2C) before transplanting generally stimulated seedling height, leaf area, and shoot and root growth, but decreased chlorophyll content in tomato seedlings (Dufault and Melton, 1990). Temperatures between 10 to 13C suppressed tomato root growth (Hardenburg et al., 1986). However, Leskovar and Cantliffe (1991) reported that stem length, and root fresh and dry weights were not suppressed when containerized tomato transplants were stored at 5C for 8 days. When containerized tomato seedlings were transplanted and mulched in beds with clear polyethylene, seedling root extension rates between 1 to 2 weeks after transplanting were significantly correlated with soil temperature during the first week (Wien et al., 1993).

Temperature directly influences the nutrient status of seedlings by affecting nutrient absorption and transport from the roots to the shoots. Seedling root elongation of beans, cucumber, eggplant (*Solanum melongena* L.), pea, pepper, radish (*Raphanus sativus* L.), and spinach (*Spinacia oleracea* L.) was optimum when constant in the 16.7 to 21.1C range, and a synergistic effect with P nutrition occurred on beans, cucumber, eggplant, and pepper, but not on radish, spinach, and pea (Wilcox and Pfeiffer, 1990). Enhanced early root growth and nutrition uptake, particularly P, characterized tomato transplants grown with clear polyethylene mulch where soil temperatures were 5 to 7C higher than soil not mulched (Wien et al., 1993). Papadopoulos and Tiessen (1987) reported that leaf tissue accumulation of nutrients at

high root temperatures (27 vs. 21C) was greater for P than for N, with minimum or no effect on the accumulation of K, Ca, and Mg.

Nutrition, salinity, and pH

Seedlings have a high demand for mineral nutrients, which, in part, is thought to be a result of their fast growth rates relative to mature plants (Widders and Lorenz, 1982). A strategy used to facilitate root growth, minimize transplant shock, and increase seedling survival is to enhance the seedling nutrient content before transplanting (Dufault, 1986). This technique, known as pretransplant nutritional conditioning (PNC), recently has been reviewed by Dufault (1994). While pretransplant treatment with P did not enhance shoot growth of tomato seedlings, root initiation and growth were stimulated by N and P pretransplant treatments (Garton and Widders, 1990; Widders, 1989). In five bell pepper genotypes, total and basal root length increased linearly with increasing N rates from 56 to 112 mg-liter⁻¹ when measured 40 days after seeding (Leskovar et al., 1989). Localized feeding of NO₃ stimulated lateral root initiation in corn (Granato and Raper, 1989). Shoot : root ratio in tomato seedlings was reduced from 4.0 to 2.3 when N rate was decreased from 400 to 100 mg-liter⁻¹ regardless of P rate (15 to 60 mg-liter⁻¹) (Weston and Zandstra, 1989). Small shoot : root ratio differences occurred on cauliflower (*Brassica oleracea* L. Botrytis Group) seedlings exposed to N rates between 0 and 155 mg-liter⁻¹ (Booij, 1992). Increasing N rates between 150 to 350 mg-liter⁻¹ increased shoot dry weight and shoot : root ratio, but decreased root dry weight in celery (*Apium graveolens* L.) seedlings (Tremblay and Gosselin, 1989). Barker (1989) has cited several investigations in which root morphology was found to be associated with root affinity for NO₃ or NH₄, root ability to discriminate between NO₃ or NH₄, and root detoxification of NH₄.

Root growth is generally less sensitive to salinity than shoot growth (Lauchli and Epstein, 1990), as reflected by lower shoot : root ratios when salinity is increased. However, salinity effects on root systems can be significant. For example, Snapp and Shennan (1992) reported that root-length density of two tomato cultivars (CX8303, root-rot tolerant to *Phytophthora parasitica* Dast., and UC82B, sensitive to root rot) was reduced between 21% and 39% at a moderate salinity level of 75 mM NaCl plus CaCl₂ (4 Na : 1 Ca molar ratio) as compared to 3 mM. Calcium plays an important role in adapting seedling plant tissue to saline conditions (Kent and Lauchli, 1985). Calcium also has a role in the root cap in regulating root growth and is translocated to the shoots mainly from young roots (Russell, 1977). Harrison-Murray and Clarkson (1973) indicated that absorption and translocation were greater within 3 cm of the root apex in taproots of marrow (*Cucurbita pepo* L.) than in more distal positions. Takahashi et al. (1992) reported that exogenous Ca²⁺ applied at 10 or 20 mM directly to the root cap stimulated root elongation in pea and corn seedlings. They suggested that differences in responsiveness of roots to Ca²⁺ may result from water conditions at the root tip that differ from those along the older portions. Inhibitory effects of 100 mM NaCl on maize root elongation were partially reversed by Ca²⁺ levels at 10 mM in the root medium, as evidenced by increasing root diameter and root hydraulic conductivity in the apical 4 cm of the primary roots (Azaizah et al., 1992; Evlagon et al., 1992).

Root and shoot weights were higher and taproot growth rate was faster for bell pepper seedlings grown at pH 5.9 as compared with pH 4.0 or 7.3 (Stoffella et al., 1991). Plant roots increased (Liu, 1980; Marschner et al., 1986) or decreased rhizosphere pH (Grünsted et al., 1982; Schaller, 1987). Rhizosphere pH changes are influenced by soil buffering capacity (Schaller, 1987), mineral absorption capacity, absorption efficiency of the plant species (Marschner and Romheld, 1983), and initial soil pH (Youssef and Chino, 1989).

Water

Effect on root growth. Root activity throughout the soil profile has been investigated for water uptake (Klepper, 1990). Water potential of the root medium influences root growth and the water potential gradient between the medium and root. Significant root elongation restrictions occur when soil water potential is below -0.8 MPa (Klepper,

Table 3. Root and shoot characteristics of 'Texas Grano 1015Y' onion transplants in response to cell volume of transplant flat and transplant age, Uvalde, Texas.

Cell size (cm ³)	Age (weeks)	Root		Bulb diam (mm)	Shoot		Shoot : root ratio
		No.	Dry wt (mg)		Leaf (no.)	Dry wt (mg)	
7.1 ²	6	19.6	5.5	3.7	3.9	23.0	4.2
	8	25.0	9.3	4.1	4.3	33.9	3.7
	10	32.0	11.6	4.3	4.8	40.5	3.5
	12	36.6	21.1	5.7	5.9	73.6	3.5
Significance		L**	Q**	Q*	L**	Q*	NS
	6	18.3	5.0	3.2	3.6	22.1	4.5
	8	28.2	8.2	4.2	4.4	29.0	3.6
	10	30.8	9.1	3.8	4.4	30.5	3.4
4.0 ²	12	41.9	15.6	4.7	5.5	50.4	3.3
		L*	Q*	L**	NS	NS	NS
	6	18.3	5.0	3.2	3.6	22.1	4.5
	8	28.2	8.2	4.2	4.4	29.0	3.6
	10	30.8	9.1	3.8	4.4	30.5	3.4
	12	41.9	15.6	4.7	5.5	50.4	3.3
		L*	Q*	L**	NS	NS	NS

²Transplant flats O80A and 595M contained 338 and 595 cells, respectively. Samples were taken at time of transplanting, 8 Dec. 1993.

NS, *, ** Nonsignificant or significant F test at $P \leq 0.05$ or 0.01 , respectively. Significant age effects were linear (L) or quadratic (Q).

1991). Although taproots have the capacity to explore deep layers of the soil profile, under drought conditions, monocot and dicot seedlings may also highly depend for survival and subsequent growth on crown (or nodal), adventitious, basal, or lateral roots. In maize, the water potential at which growth stopped was -0.5 , -1.0 , and -1.4 MPa for stems, leaves, and nodal roots, respectively (Westgate and Boyer, 1985).

Water flux is a function of water potential differences and hydraulic conductances (Melchior and Steudle, 1993). In dry surface soils, roots may develop strong axial and radial resistance to the pathway of water flow from root to shoot tissues (Cornish et al., 1984; Steudle et al., 1987). The main resistance to water flux lies in the radial pathway (from the soil solution to the tracheary elements) and not in the axial path (within the tracheary elements) (Frensch and Steudle, 1989).

McCully and Canny (1988) reported that the diameters of the largest nonoccluded tracheary element(s) are the most important characteristic influencing hydraulic conductivity. The number of first-order branch roots and the diameter of their largest tracheary element differed at nodes along the root axes of corn (Varney et al., 1991).

Drought stress and abscisic acid (ABA). Pepper seedlings exposed to mild drought conditions had lower root dry weight, basal root number and diameter, and shoot growth as compared with well-watered seedlings (Leskovar and Cantliffe, 1992; Watts et al., 1981). The influence of drought stress on root and shoot growth is mediated by endogenous changes in ABA concentration acting as a signal for control of growth processes (Davis et al., 1986). ABA synthesis induced by water stress has been correlated with a reduction of shoot : root ratio either by shoot growth reduction (Creelman et al.,

Fig. 2. (A) Field survival of onion transplants grown in O80A and 595M (7.1- and 4.0-cm³ cells, respectively) transplant flats in response to transplant age. Transplants were set in the field on 8 Dec. 1993. Error bars represent a mean $\pm$ SE. (B) Field survival of onion transplants grown in 595M transplant flats as influenced by cultivar. Transplants were set in the field on 20 Dec. 1993 and were exposed to freezing temperatures (-3 to -5°C) 1 week after transplanting.

Fig. 3. (A) Seedling root number and (B) seedling root weight of onion cultivars. Seedlings were seeded in 595M transplant flats (4.0-cm³ cells) on 19 Oct. 1993. Sampling times 1, 2, and 3 correspond to 11 and 29 Nov. and 16 Dec. 1993.

1990) or by more root growth relative to shoot growth (Karmoker and Van Steveninck, 1979). ABA was studied as a substitute for drought stress to control seedling growth and improve transplant field establishment in pepper and eggplant seedlings. When ABA was applied at 10^{-4} M to pepper seedlings 3 weeks after seeding, there was a transient inhibition of leaf weight increase, but root growth was unaffected (Leskovar and Cantliffe, 1992). ABA at 10^{-3} M reduced relative growth rates of eggplant seedlings (Latimer and Mitchell, 1988). Increased seedling survival due to exogenous application of ABA was related to increased leaf resistance and leaf water potential in pepper seedlings (Berkowitz and Rabin, 1988).

Flooding. Soil flooding limits the diffusion of O_2 to the root zone (Bradford and Yang, 1981; Drew, 1992), affecting young plants with a high percentage of primary roots as compared to more mature roots in older plants (Letey et al., 1962). Adventitious roots play a major role in the survival of many mesophytes by partially replacing the functions of the original roots (Jackson and Drew, 1984). Aloni and Rosenshtein (1982), Jackson (1955) (1979), and Kramer (1951) reported that flooding-induced root injury is limited if adventitious roots develop, indicating that these roots are important for recovery of shoot growth following flooding. Kahn et al. (1985) reported that adventitious roots became the predominant root component (highest weight as compared to taproot or basal roots) after bean seedlings were exposed to 7 days of flooding, followed by 7 days of recovery. Similarly, in continuously flooded tomato cultivars, adventitious roots accounted for more than 50% of the total root mass (Poysa et al., 1987). However, adventitious root development did not overcome flooding injury of sunflower (*Helianthus annuum* L.) (Wample and Reid, 1978).

ESTABLISHMENT METHODS: EFFECT ON ROOT DEVELOPMENT

Seedling establishment in any field environment depends on the adequate development of a taproot, associated laterals, and basal roots for dicot species, or adventitious roots and associated lateral roots for most monocot species. Root growth patterns of plants established by direct seeding differ from those of plants established by transplanting. Direct-seeded plants develop a strong taproot (Weaver and Bruner, 1927), while transplants develop a distinctive root system caused by modification of the taproot (McKee, 1981) and subsequent development of lateral and basal roots (Leskovar et al., 1989; Stoffella et al., 1988a). Direct-seeded pepper plants, established with primed or raw seeds, had variable root growth over time as compared with a constant rate of root growth from transplants (Leskovar et al., 1990). Early root development was unaffected by seed priming in pepper (Stoffella et al., 1992), and total root growth (dry-weight basis) was similar for primed or untreated pepper plants when measured at maturity (Leskovar et al., 1990). Basal, lateral, and taproot dry weights accounted for 81%, 15%, and 4%, respectively, of the total root dry weights for containerized transplants and 25%, 57%, and 18%, respectively, of the total root dry weights for direct-seeded bell pepper plants (Leskovar and Cantliffe, 1993). The latter also exhibited greater root relative growth rates and total root growth than transplants. As a consequence, transplanted pepper plants may be more prone to lodging than direct-seeded plants. Cooksey et al. (1994) reported that the force to uproot pepper plants established by transplanting was 15% lower than for plants established by direct seeding.

Transplant production systems, including flotation and overhead irrigation, also influenced root and shoot growth characteristics in bell pepper and tomato seedlings in the greenhouse (Leskovar and Cantliffe, 1993; Leskovar et al., 1994). In jalapeño peppers, overhead irrigation enhanced basal root elongation and root weight as compared with seedlings grown with flotation irrigation; however, the flotation irrigation system improved water-use efficiency, reduced shoot : root ratio, and promoted seedling hardiness (Leskovar and Heineman, 1994). Providing uniform moisture levels around the hypocotyl during the last 2 weeks before field establishment is also thought to enhance basal root primordia development in transplants. The importance of basal root development in the field has been emphasized in peppers (Leskovar and Cantliffe, 1993), black beans (Stoffella et al., 1979a), and tomatoes (Zobel, 1975).

The ability of a transplant (bareroot or containerized) to overcome transplant shock and become established in a field environment following transplanting depends on how seedlings withstand root disturbance (McKee, 1981), and how water and nutrient uptake capacity of the roots and the capacity of the preexisting roots to rapidly regenerate new lateral, basal, or adventitious roots are affected. Root pruning before transplanting tomatoes delayed reestablishment (McKee, 1981), and the net rate of root and shoot biomass increase was limited (Leskovar et al., 1994). Enhanced early tomato root growth and nutrient uptake are key factors in increasing shoot growth (Wien et al., 1993).

Early root and shoot seedling response to various cultural systems and environments also depends on the physiological state of the seedlings. Under favorable field conditions, young tomato transplants had a higher relative root growth rate and greater capacity to resume shoot growth than older transplants (Leskovar and Cantliffe, 1991; Weston and Zandstra, 1989). Under windy or sandblasting conditions, older tomato seedlings survived better than young seedlings (Liptay, 1987). Older onion transplants, with more root and shoot growth (Table 3), had higher survival rates compared to younger seedlings when exposed to low winter temperatures after transplanting (Fig. 2A). Survival can also depend on the cultivar (Fig. 2B) and differences in root characteristics between cultivars. For example, root counts were higher, but dry weights lower, for onion cultivars Texas 1015 and Early White Supreme than for cultivars Henry Special and Red Granex (Fig. 3 A and B).

Information on the effects of establishment methods (direct-seeding or transplanting) or seed enhancement treatments of vegetable crops on subsequent seedling root growth, development, or architecture is limited. The influence of cultural practices on mature root systems has been reported for various vegetables; e.g., plant population density on root morphological characteristics in beans and peppers (Kahn et al., 1981; Stoffella et al., 1981; Stoffella and Bryan, 1988); establishment methods on tomato and pepper root growth (Leskovar and Cantliffe, 1993; Leskovar et al., 1994); irrigation on lettuce root elongation, weight, and diameter (Rowse, 1974); irrigation on root length and density in tomato (Sanders et al., 1989); and irrigation on root distribution of sweet corn (Phene et al., 1991).

CONCLUSIONS

Investigations are needed on seed enhancement treatments and environmental influences after radicle protrusion to understand implications to further root system development and, ultimately, stand establishment and seedling growth. Few investigations have focused on variability of growth and development of root systems or root components. Genetic or environmental influences on root variability need further exploration. Root study methods and statistical procedures need to be improved or developed to further understand seedling root morphology, architecture, and development. Rhizogenetics, plant root physiological roles and functions, and root architecture investigations can clearly assist in defining the importance of seedling root system components to stand establishment and subsequent development of the shoot system.

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