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Phenotypic Correlations between Root and Shoot Traits of Strawberry in Fumigated and Nonfumigated Soils

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Abstract. **Strawberry seedlings (*Fragaria ×ananassa* Duch.) from the Univ. of California strawberry improvement program were assigned randomly to soils prepared either with or without preplant fumigation with a mixture of 2 methyl bromide : 1 chloropicrin (by mass; 392 kg·ha^{-1}) in order to evaluate sampling methods for root characters. After 5 months in annual hill culture, individual plant root systems were sampled with a single 1.9-cm-diameter × 24-cm-long soil core probe to determine root mass (RM), secondary rootlet mass (SRM), and a subjective root appearance score (RAS) based on root color and morphology. Whole plants were subsequently extracted and used to measure these root characters and total above-ground (shoot) mass. Soil core samples captured <1% of total RM on average but explained 45% to 74% of the variability for whole-plant RM and SRM in both soil environments. Plants grown in fumigated soils had greater shoot mass, plant diameter, RM, SRM, and RAS than those grown in nonfumigated soils, regardless of sampling method. Phenotypic correlations between traits were fairly consistent across fumigation treatments, differing by more than ±0.20 only for associations involving RAS as a variable. Highly significant ($P < 0.01$) phenotypic correlations were detected among shoot mass, plant size, and root core and whole-plant RM and SRM in both fumigation environments; correlations between whole-plant RM and shoot mass were $r = 0.84$ and 0.96 in fumigated and nonfumigated soils, respectively. Conversely, nearly all correlations between pairs of traits involving either soil core or whole-plant RAS were nonsignificant. Together, these results indicate that a strong correspondence exists between above- and below-ground vegetative growth and that most correlations between traits are consistent across fumigation treatments. Further, the strong relationship between soil core RM and whole-plant RM indicates that soil cores provide an accurate description of root growth relationships at the whole-plant level and can be substituted effectively for whole-plant (destructive) samples. Chemical name used: trichloronitromethane (chloropicrin).**

Preplant soil fumigation with methyl bromide and chloropicrin mixtures has enhanced plant vigor and fruit yield of strawberry in numerous studies (Fort et al., 1996; Himelrick and Dozier, 1991; Larson and Shaw, 1995). This response has been attributed to elimination of soilborne pathogens, such as weeds, fungi, and nematodes, that attack the root system or compete with it for nutrients (Wilhelm and Paulus, 1980). Roots therefore play a critical role in the response to soil fumigation and are potentially involved in plant adaptation to different rhizosphere environments. The first detailed analyses of root growth responses of strawberry to fumigation treatments have been published only recently. Using root samples obtained with soil cores, Yuen et al. (1991) found that plants grown in fumigated soils had higher root length densities and fewer diseased rootlets than plants in nonfumigated soils at most test locations. In another study, Larson and Shaw (1996) utilized destructive sampling methods to determine that root mass and shoot : root mass ratios were greater for plants grown in fumigated soils than in nonfumigated soils during most of the initial growth and fruit production period.

Other important questions regarding strawberry root performance, such as the relationship between root characters and productivity or their relevance to evaluation of soil treatment alternatives, have not been addressed experimentally. Successful investigation of these questions will depend greatly on the efficiency of the root sampling methods employed. Options for measuring associations between root traits and other season-specific traits using standard whole-plant (destructive) sampling methods are limited. For example, the use of individual plants for joint measurement of early-season root attributes and seasonal yield is not possible with destructive sampling. Association of seasonal characters on different plants of the same genotype is possible in strawberry through replicated clonal plantings, but the resources required to conduct such experiments increase dramatically. Also, unaccountable error variance is increased by the fact that plants sampled for yield and root traits do not share field microenvironments. Fractional root sampling methods, if informative, would permit multiple root samples to be collected on individual plants without sacrificing data on subsequent plant growth and yield. Further, fractional root samples collected using soil cores require less collection and processing effort per plant than whole-plant samples and may be especially efficient for genetic studies in which large numbers of genotypes are evaluated.

The present study was conducted to examine the relationship between root mass and appearance measures obtained from individual plants using soil core and whole-plant sampling methods; fractional root measures and whole-plant samples have never been assessed for their correspondence or relative information content. To further evaluate the potential usefulness of soil core observations, strawberry plants were examined for correlations between root traits and above-ground vegetative growth traits and for the consistency of these correlations across fumigated and nonfumigated soil environments.

Materials and Methods

A total of 60 strawberry seedlings were chosen at random for testing and analysis from 10 crosses (four to 10 seedlings per cross) among cultivars and advanced selections within the Univ. of California (UC) breeding program. These seedlings were planted on 27 Sept. 1994 at the UC Watsonville Strawberry Research Facility in offset two-row beds (60 cm between plants along rows and 30 cm between rows) and managed according to guidelines established for experimental seedling trials (Shaw et al., 1989). An equal number of seedlings from each cross were assigned to fumigation treatments consisting of either 1) standard preplant soil fumigation with 2 methyl bromide : 1 chloropicrin (by mass; 392 kg·ha^{-1}) or 2) no fumigation. Fumigation treatments were applied to adjacent plots of sandy loam soil in which strawberry had been grown in alternate years for several production cycles; these soils were free of any identifiable lethal pathogen problem (Larson and Shaw, 1995). Six plants were excluded from analysis due to inadequate growth related to initial plant quality; the final number of seedlings evaluated is listed in Table 1.

Cross-sectional plant diameters (Shaw, 1993) were obtained on 23 Dec. 1994 as a measure of early-season above-ground vegetative growth. Root systems of individual plants were sampled on 17 Feb. 1995 by inserting a 1.9-cm-diameter × 24-cm-long metal probe (soil corer) into the soil 10 cm from the center of each plant, at a 60° angle aimed underneath the plant, and parallel to drip lines along the center length of each bed. Subsequently, entire plants were removed from beds (to a depth of 45 cm) and washed free of soil; minor overlaps of adjacent root systems impeded complete recovery of roots in some cases, but this was rare. After washing, whole plants were processed further by separating

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Table 1. Effects of preplant soil fumigation on means and standard deviations (in parentheses) for two above-ground and six below-ground vegetative growth traits of strawberry seedlings at Watsonville, Calif.

Fumigation treatment[z]	Plant diameter (cm)	Mass (g/plant)					Root appearance score (RAS)	
			Root (RM)		Secondary rootlet (SRM)			
		Shoot	Whole plant	Soil core	Whole plant	Soil core	Whole plant	Soil core
Nonfumigated	13.1	3.12	1.11	0.0103	0.88	0.0074	2.8	3.0
	(3.8)	(2.30)	(0.80)	(0.0090)	(0.59)	(0.0048)	(0.7)	(0.7)
Fumigated	15.4	5.95	1.78	0.0175	1.52	0.0111	3.5	4.2
	(3.8)	(3.42)	(1.01)	(0.0111)	(0.90)	(0.0067)	(0.7)	(0.8)

[z]Nonfumigated and fumigated indicate no soil fumigation vs. preplant soil fumigation with 392 kg·ha^{-1} of 2 methyl bromide : 1 chloropicrin (trichloronitromethane) (by mass), respectively; N = 29 for fumigated treatment means, and N = 25 for nonfumigated treatment means.

the roots from the shoot, which included all crowns, leaves, runners, and inflorescences, and placing them in separate bags. Both soil core and whole-plant samples were then refrigerated no longer than 10 d prior to further processing.

Soil core samples were washed to free the roots of soil and assigned a subjective root appearance score (RAS) on a scale of 1–5 (5 = best) based primarily on their degree of blackening/necrosis (light-beige = higher score; dark-brown = lower score) and, secondarily, on their extent of branching structure (higher score for more fine rootlets). RAS was intended as an indicator of root health; root blackening and feeder rootlet mortality are symptomatic of the black root rot disease complex occurring in nonfumigated soils throughout California (Wilhelm, 1961), and both characters have been cited as general indicators of strawberry root quality (Yuen et al., 1991). The relative contributions of biotic and abiotic factors to RAS were not assessed, but roots also darken due to natural aging processes (Wilhelm, 1961). After scoring, roots were dried for at least 3 d at 60° C and their total root mass (RM) and secondary rootlet mass (SRM) were measured at room temperature. SRM is a subset of RM obtained by removing root pieces >0.5 mm in diameter from the dried root sample and weighing the remaining fraction. Whole-plant root and shoot portions were analyzed separately. The shoot was measured solely for its dry mass, while the whole-plant root sample was assigned a RAS and measured for RM and SRM similarly to the soil core samples described above.

In order to assess how phenotypic relationships among above- and below-ground traits differed across fumigation treatments, phenotypic (product-moment) correlations between pairs of traits were calculated for fumigated and nonfumigated soils independently. Analogous correlations based on individual-plant data combined across treatments were not performed.

Results and Discussion

Plants grown in fumigated soils had greater means for all eight of the traits measured in this study (Table 1). SRM as a percentage of RM was slightly greater for plants grown in fumigated soils (85%) than for plants in nonfumigated soils (79%), and shoot : root mass ratios were slightly greater for plants in fumigated soils (3.34) than in nonfumigated soils (2.81). Soil core RM was 0.98% and 0.93% of whole-plant RM for plants in the fumigated and nonfumigated treatments, respectively. As fumigation treatments were not replicated, statistical methods of means separation, such as Student's *t*, were not performed on treatment means.

Highly significant ($P < 0.01$) and positive phenotypic correlations were detected among plant diameter, shoot mass, and root mass traits in both fumigation environments (Table 2). Whole-plant RM was strongly correlated with plant size and shoot mass in fumigated (r = 0.82, 0.84, respectively) and nonfumigated soils (r = 0.89, 0.96), indicating that a balance between above- and below-ground vegetative growth is strictly maintained in each soil environment. Correlations between whole-plant RAS or soil core RAS and the other six characters were nonsignificant, with the exception of whole-plant RAS with plant size (r = 0.47, $P < 0.05$) in nonfumigated soils. In general, relationships between pairs of traits were similar across fumigation treatments. Of the six correlations between trait pairs that differed by an absolute value of 0.20 or more across fumigation treatments, all had either whole-plant RAS or soil core RAS as a common variable and all were nonsignificant in both soil environments.

Highly significant and near-perfect correlations (r = 0.99) were detected between whole-plant RM and SRM in both soil fumigation environments (Table 2); SRM is a subset of RM that constitutes 79% to 85% of its mass (Table 1), so these characters were expected to have an inherently strong relationship. Conversely, primary root mass, the root fraction removed from RM to obtain SRM, showed a much weaker correlation with SRM in fumigated soils (r = 0.55, $P < 0.01$) than in nonfumigated soils (r = 0.92, $P < 0.01$) for whole-plant samples (data not presented). The 95% confidence intervals for ρ at r = 0.55 and r = 0.92 do not overlap for the sample sizes used in this study, so it appears that plants in fumigated and nonfumigated soils may differ in the extent to which primary and secondary root masses are associated.

Highly significant correlations were detected between soil core RM and whole-plant RM in both fumigated soils (r = 0.76) and nonfumigated soils (r = 0.68) (Table 2). The proportion of variance for whole-plant RM explained by variance for soil core RM (r^2) was therefore 46% to 58%, and analogous values for SRM were 45% to 74%. This extent of correspondence is very high considering that the average soil core sample captured <1% of total root mass on a per-plant basis within either fumigation environment (Table 1). Sampling multiple soil cores for individual plants would further improve the percentage of variation explained. With multiple cores, the proportion of variance explained is predicted as $\sigma^2_E/(\sigma^2_E + \sigma^2_U/n)$, where σ^2_E and σ^2_U are the percentages of variance explained and unexplained by individual soil cores, respectively, and n is the number of core samples per plant (Steel and Torrie, 1960). Thus, for RM, two soil cores would improve the range of variance explained among whole-root samples from 46% to 58% to 63% to 73% and three cores would improve the range to 72% to 81%. Alternatively, the correlation of soil core RAS with whole-plant RAS was nonsignificant for both the fumigated (r = 0.37) and nonfumigated (r = 0.28) treatments (Table 2). Visual inspection of whole root systems indicated that root appearance varied greatly among different branchlets. Together, these observations suggest that variation for RAS may be predominantly environmental rather than genetic in origin, and that as many as seven to 12 soil cores may be required to explain 50% of the variation for whole-plant RAS.

Overall, these results provide initial evidence of a strong relationship between root

Table 2. Phenotypic correlation coefficients (r) for two above-ground and six below-ground vegetative growth traits of strawberry seedlings in soils with (above the diagonal) and without (below the diagonal) preplant fumigation at Watsonville, Calif.

		Plant size	Shoot mass	RM[z] Whole plant	RM[z] Soil core	SRM Whole plant	SRM Soil core	RAS Whole plant	RAS Soil core
Plant size			0.87**	0.82**	0.54**	0.79**	0.57**	0.31	0.10
Shoot mass		0.87**		0.84**	0.66**	0.81**	0.73**	0.30	0.11
RM	Whole plant	0.89**	0.96**		0.76**	0.99**	0.82**	0.25	–0.20
	Soil core	0.64**	0.72**	0.68**		0.79**	0.92**	0.08	–0.17
SRM	Whole plant	0.90**	0.94**	0.99**	0.66**		0.86**	0.27	–0.23
	Soil core	0.61**	0.70**	0.68**	0.93**	0.67**		–0.01	–0.30
RAS	Whole plant	0.47*	0.36	0.34	0.39	0.37	0.39		0.37
	Soil core	0.01	0.13	0.06	0.23	0.05	0.17	0.28	

[z]RM = root mass; SRM = secondary rootlet mass; RAS = root appearance score.
*, **Significant at $P < 0.05$ and 0.01, respectively.

growth and above-ground vegetative growth in each of two different soil fumigation environments, at least at this point in the season. Whether these relationships undergo seasonal changes, as has been observed for root : shoot mass ratios, is not yet known (Larson and Shaw, 1996). Moreover, these results demonstrate substantial correspondence between variability for soil core and whole-plant root mass samples, indicating that changes in root system growth can be effectively measured using soil cores. Soil core samples required no more than 10% of the time to collect and process as did whole-root samples, and they appear to be a preferable alternative in many instances to destructive and time-consuming whole-plant samples.

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