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Response of 'Honeycrisp®' Apple Trees to Combinations of Pre-plant Fumigation, Deep Ripping, and Hog Manure Compost Incorporation in a Soil with Replant Disease

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Abstract*. This study evaluated the effects of pre-plant treatments: deep ripping (DR), fumigation (F), deep ripping plus fumigation (DRF), deep ripping plus hog manure compost (DRC), and deep ripping plus fumigation plus hog manure compost (DRFC) in comparison with a non-treated control (NTC) on shoot and root performance of 'Honeycrisp' apple trees on M.4 rootstocks in an old orchard site with apple replant disease (ARD). *Cylindrocarpon* spp., *Pythium* spp., and *Pratylenchus penetrans* Cobb, all potential agents of ARD, were present in the orchard soil. Fine-root numbers (1 to 2.9 mm diameter) were significantly greater in the DRC and DRFC treatments than the DR treatment. After 6 years, trunk cross-sectional area (TCSA) and yield were largest for the DRFC treatment followed closely by F. The DR treatment had no effect on TCSA, yield, or yield efficiency when applied alone compared with the NTC. Contrast analysis demonstrated that F was significantly better than non-F for yield in all years and TCSA and yield efficiency in 2007. Also, there was a significant interaction between DR and F treatment in 2005 that significantly reduced yield in the DRF treatment. Contrast analysis showed that compost had a significant positive effect on yield in all three production years and TCSA and yield efficiency in 2007. Yield efficiency in the third production year was largest for F, DRC, and the DRFC treatments. Nutrient analysis revealed that soil phosphorus concentrations in compost-treated plots were double those in other treatments. High phosphorus content of compost may have contributed to the amelioration of ARD symptoms. This study found that in 2007, soil fumigation alone, as conventionally used for ARD control, and composted hog manure were equally effective in increasing yield and yield efficiency of apple trees planted in an ARD soil. The DRFC treatment was the overall best treatment in all years.

Compost applications alone or in combination with cultural practices or chemicals have the potential to contribute to the control of root pathogens (Mazzola et al., 2006; Peryea and Covey, 1989; van Bruggen, 1995; Zinati, 2005). ARD is a condition in which the replacement of old orchards with newly planted trees results in the failure of the new orchard to thrive (Hoestra, 1968). This phenomenon has been documented in apple-growing regions around the world (Mai and Abawi, 1981; Traquair, 1984). Numerous research papers have concluded that the primary cause of ARD is biotic (Covey et al., 1979; Savory, 1966). Broad-spectrum soil fumigants such as chloropicrin, methylbromide, and a combination of 1,3 dichloropropene, 1,2 dichloropropane, and methyl isothiocyanate were shown effective in managing this disease (Covey et al., 1979; Ross et al., 1983). A few micro-organisms and a nematode have been repeatedly identified as probable causal agents: *Cylindrocarpon* spp., *Pythium* spp., *Rhizoctonia solani* Kühn, and *Pratylenchus penetrans* Cobb (Braun, 1991; Jaffee et al., 1982a, 1982b; Manici et al., 2003; Mazzola, 1998; Merwin and Stiles, 1989). Long-term cultivation of a perennial crop, like apple [*Malus ×sylvestris* (L.) Mill. var. *domestica* (Borkh.) Mansf.], would result in an accumulation of root pathogens in the rhizosphere soil of these plants (van Bruggen, 1995; van Bruggen et al., 2006). Therefore, planting a bare-rooted nursery tree in the root zone of an old apple tree would present significant challenges for the new tree to establish roots without being rapidly attacked by root pathogens. This scenario fits well with the concept that some plant diseases are caused by an imbalance of micro-organism populations that favor pathogens and should be readily amendable to correction by biological control (van Bruggen et al., 2006). However, van Schoor et al. (2008) and Wilson et al. (2004) were unsuccessful in managing ARD with applications of composted cow or horse manure mixed with green waste or pine bark, respectively, at ≈2 $kg\cdot m^{-2}$, whereas Gur et al. (1998) significantly improved tree growth with 1 kg of "farmyard waste" compost per 40 L of soil. The response of apple trees in replanted orchards to compost in the studies by Leinfelder and Merwin (2006) and Yao et al. (2006a, 2006b) were inconclusive. Noble and Coventry (2005) concluded that, in general, compost rates of at least 20% (v/v) were required for consistent disease suppression. The aim of this study was to compare the effects of 1) incorporation of large volumes of hog manure compost; and 2) deep soil loosening with fumigation, the current standard control measure, on root development, tree growth, and yield in a commercial apple orchard with ARD.

Materials and Methods

Site selection and preparation. An orchard block in nearly continuous apple production since 1942 near Berwick, Nova Scotia, was selected for the experiment. In 1942, the orchard was planted with trees at a 12 m × 12-m spacing that was replaced in 1970 by trees at a 5.5 m × 7.3-m spacing. These trees were removed from the orchard in the summer of 2001. The land was ploughed and old roots removed using a tractor-drawn root rake. Soil investigation at the site revealed the presence of a well-drained, coarse-textured Orthic Humo-Ferric Podzol on a 3% to 5% slope (Agriculture Canada Expert Committee on Soil Survey, 1987) also referred to in the U.S. Soil Taxonomy as a Haplorthod. A soil analysis indicated a pH of 6.1 with sufficient levels of phosphorus, potassium, and magnesium for apple production (Atlantic Committee on Fruit Crops, 1998). Twenty soil samples to a depth of 30 cm and ≈1 L in volume were taken randomly along a "W-shaped" sampling path over the orchard site. The soil was mixed, sieved, and roots and stones removed before half of the soil was steam-pasteurized. The pasteurized and non-pasteurized soils were then used in a greenhouse ARD bioassay to determine the severity of ARD in a representative soil sample using the method of Nolte and Heyns (1990).

Application of soil treatments. A randomized complete block design with four replications of six treatments and nine trees per plot with four buffer trees between each plot and without buffer rows was laid out over the orchard site with blocks assigned to account for the slope of the land. The six treatments, 1) NTC; 2) F [Telone C17® at 280 $L\cdot ha^{-1}$ (Dow AgroSciences LLC., Indianapolis, IN)]; 3) DR;

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4) DRF; 5) DRC; and 6) DRFC, were randomly assigned to plots. Treatments began and ended within the buffer trees at the beginning and end of each plot. All soil treatments were applied in Sept. and early Oct. 2001. Treatments were applied in the following order: deep ripping, compost incorporation, and fumigation. Physical loosening of the soil and preparation of deep-ripped plots and compost incorporation was accomplished using a combination of ripper shanks and a large mouldboard plough drawn by a D6 Caterpillar® (Caterpillar Inc., West Peoria, IL). A 2-m-wide band of soil centered on the tree row was ripped at 45-cm intervals to a depth of 80 cm to break up a cemented subsoil to improve rooting depth, soil drainage, and aeration. Application of fumigant with a six-tooth injector was in a 2-m band at a depth of 30 to 40 cm centered on the planting row. The soil temperature at fumigation was ≈12 °C and the soil moisture was sufficient to meet the requirements for effective fumigation. Hog manure compost was chosen as the organic amendment treatment because it best alleviated ARD symptoms in a greenhouse study in which chicken, horse, mink, and hog manure composts were compared (data not shown). In the summer of 2001, hog manure was composted over a 6-week period in windrows on a concrete pad and turned three times when the internal temperature of the pile exceeded 60 °C and water was added as needed. The compost nutrient composition was 2.7% nitrogen, 1.2% phosphorus, and 1.1% potassium with a C:N ratio of 14.2. It was applied to plots by opening a trench 40 cm deep and 50 cm wide with a mouldboard plough centered on the planting row and filling it with compost at 0.17 $m^3 \cdot m^{-1}$ of trench. After all the treatments were applied, the entire site was harrowed at 90° to the rows to cover the compost-filled trenches and to loosen the soil in all the plots and then again along the rows to level the soil.

Planting and orchard management practices. At the end of May 2002, healthy and uniform 2-year-old 'Honeycrisp®' trees on M.4 rootstock with a 2-cm trunk diameter were planted with a tree planter. Trees were planted 1.8 m apart within rows and 4.2 m between rows. No attempt was made to plant trees directly into the rows of the previous orchards. However, the different spacing of the previous orchards and large tree sizes increased the likelihood that all trees would fall within the root zones of previous orchard trees. The orchard was planted to a fescue sward except for a 2-m-wide herbicide strip beneath the trees that was maintained as a standard orchard practice. All trees received a post-plant application of 28 g of 17N–17P–17K fertilizer in a circle ≈0.75 m from the trunk in the first week of June. In the first year of the 6-year experiment, non-compost-treated trees received a second fertilizer application of 50 g ammonium nitrate per tree in a circle ≈0.75 m from the trunk on 27 July to eliminate the possibility of limited nitrogen availability in non-compost-treated plots contributing to growth differences (Webster, 1993). During subsequent growing seasons, all orchard management practices, including weed, disease, insect, and fertility management, were applied uniformly across the entire orchard block following the standard practices for commercial apple production.

Nutrient and mineral analysis. In Aug. 2005, composite soil and leaf samples were collected for mineral and nutrient analysis from all replicate plots of each treatment. Four soil cores to a depth of 15 cm were taken from within the canopy dripline of nine trees in each replicate plot. Samples from all replicate blocks of a treatment were bulked together and thoroughly mixed to form a composite sample. A subsample of ≈500 cm^3 was sent for mineral analysis. Leaves for mineral and nutrient analysis were collected randomly from the middle of the current year's terminal shoot growth. Leaves were collected from all nine trees in each treatment plot and subsamples were combined, mixed, and a representative composite subsample for each treatment was submitted for analysis. Samples for nutrient and mineral analysis were submitted to the Nova Scotia Department of Agriculture laboratory services for analysis (Truro, Nova Scotia) using standard methods (Douglas et al., 1992).

Nematode counts. Representative soils collected for nutrient analysis in 2005 were also used to assess root-lesion nematode densities by the Baermann funnel technique (Hooper, 1986). A total of 100 cm^3 of soil was placed onto a Kimwipe® paper tissue (Kimberly-Clark Inc., Mississauga, Ontario, Canada) supported in a sieve. The sieve was placed in a funnel with a short length of rubber tubing and a clamp on the spout of the funnel to hold water in the apparatus. Water was added to the funnel until the soil was suspended at the water surface keeping the soil saturated. The samples were left in this condition for 48 h and then the water and nematodes were drawn off the bottom of the funnel into a centrifuge tube. The water containing nematodes was centrifuged to concentrate the nematodes and all but 1 to 2 mL of water was removed. The remaining water and nematodes were dropped onto microscope slides and the number of *P. penetrans* counted and recorded.

Tree measurements. Trunk diameters were measured 5 cm above the graft union at the end of each growing season (2002 to 2007) and TCSAs calculated for the nine trees in the center of each plot. Fruit yields for each treatment (2005 to 2007) were estimated by randomly selecting two trees in each plot for fruit counts. Only the total number of fruit per tree was recorded in 2005. In 2006 and 2007, tree yield and average fruit size were estimated by measuring the weight of a subsample of 10 apples collected from each of the two trees per plot. This subsample represented ≈25% and 10% of the apples per tree in 2006 and 2007, respectively. The average apple weight was multiplied by the average number of apples per tree to give an estimated yield. In 2007, the yield efficiency was calculated by dividing the average yield per tree by the average TCSA for that year.

Rooting depth and distribution. In July 2005, during the fourth growing season, the depth and distribution of roots in the DR, DRC, and DRFC treatments were recorded by digging, perpendicular to the tree row, a 2-m-long and 1-m-deep trench centered on the row and equidistantly between two trees in each plot. Exposed roots on the soil trench faces ≈60 cm from the tree trunks were classified into four diameter categories, 1 to 2.9 mm, 3 to 4.9 mm, 5 to 9.9 mm, and 10 mm or larger. The location of each root was recorded in two dimensions, down from the soil surface and either to the left or right of the tree row center line (east, west quadrants) on both opposing walls of the trench (north, south planes), thus giving two samples for each treatment replicate.

Statistical procedures. The Genstat Release 12.1 (VSN International Ltd., Hemel Hempstead, U.K.) statistical program was used for the analysis of variance (ANOVA) on square root transformed and non-transformed data as indicated in figures or the table to evaluate the effects of the treatments. Orthogonal contrasts were used to compare effects of the factorial combination of the presence or absence of fumigant to three levels of deep ripping (no-DR, DR, DRC) (Table 1). TCSA was recorded from the same nine trees in the center of each treatment plot from 2002 to 2007. Treatment means across years were analyzed for differences in line means and slopes (Fig. 1). Root measurements were collected from treatments DR, DRC, and DRF. Each root profile was split into two depths (20 cm or less, greater than 20 cm) for each of four root sizes (1 to 2.9 mm, 3 to 4.9 mm, 5 to 9.9 mm, 10 to 20 mm). The root measurements were analyzed in a split-split plot model for the factorial combination of treatments by depths by root size in an ANOVA. Orthogonal contrasts were used to evaluate different levels of treatments and polynomial contrast for the change across depths.

Results

Tree growth and yield. The initial greenhouse ARD test conducted in 2001 on soil from the Berwick orchard site resulted in a 150% increase in seedling height over an 8-week period in response to pasteurization of the soil. When annual TCSA values from the orchard trial were compared over the period from 2002 through 2007, the DRFC and F treatments were superior to all other treatments for the rate of TCSA increase and means over the 6 years of the study (Fig. 1). Also, the data show that with the addition of F to the DR treatments, there was a quadratic rate of change in the TCSA across the 6 years of the study ($P = 0.021$). The mean TCSA had a significantly different response for DR compared with DRC across the presence or absence of F ($P = 0.019$). There was a quadratic response across years for F, DRF, and DRFC compared with NTC, DR, and DRC. The presence of fumigant in the treatment increased TCSA overall but DR with compost

Table 1. Means table and results of an analysis of variance and contrast analysis on yield, trunk cross-sectional area (TCSA), and yield efficiency for apple trees in apple replant disease infested soil.[z]

Treatments[y]	Yield (apples/tree) 2005	Yield (kg/tree)[x] 2006	Yield (kg/tree)[x] 2007	TCSA (cm^2) 2007	Yield efficiency (kg/cm^2 TCSA) 2007
NTC	36	6.4	17.2	21.6	0.76
F	104	8.9	28.0	30.4	0.98
DR	35	6.8	15.7	23.1	0.74
DRF	57	6.4	21.6	25.0	0.88
DRC	73	10.7	30.0	24.5	1.24
DRFC	114	14.2	37.4	33.4	1.19
df	15	39	38	203	38
SE	8.24	1.82	2.91	0.685	0.111
F probability					
No F versus F	<0.001	0.006	0.002	<0.001	<0.001
F × (no DR versus DR)	0.023	NS	NS	NS	NS
F × (DR versus DRC)	NS	NS	NS	0.040	NS
Deep ripping means					
No DR	70.1	7.6	22.6	25.9	0.869
DR	46.2	6.6	18.7	24.0	0.811
DRC	93.5	12.5	33.3	28.9	1.202
F probability					
No DR versus DR	NS	NS	NS	NS	NS
DR versus DRC	<0.001	0.003	<0.001	0.007	<0.001

[z] Treatments were a non-treated control (NTC), fumigation with Telone C-17 (F), deep ripping (DR), deep ripping plus fumigation (DRF), deep ripping plus compost (DRC), and deep ripping plus fumigation plus compost (DRFC).

[y] F = fumigation with Telone C-17 at 280 L·ha^{-1}; DR = soil deep ripping to a depth of 80 cm along the tree row, compost in the DRC and DRFC treatments was applied to a 40 cm × 50 cm trench at the rate of 0.17 m^3·m^{-1} of row and covered with soil. Treatments were applied in the September and October of 2001 in the following order: deep ripping, compost incorporation, and then fumigation.

[x] Yields were estimates based on the average weights of subsamples collected from two randomly selected trees from the nine trees in each plot.

NS = non-significant.

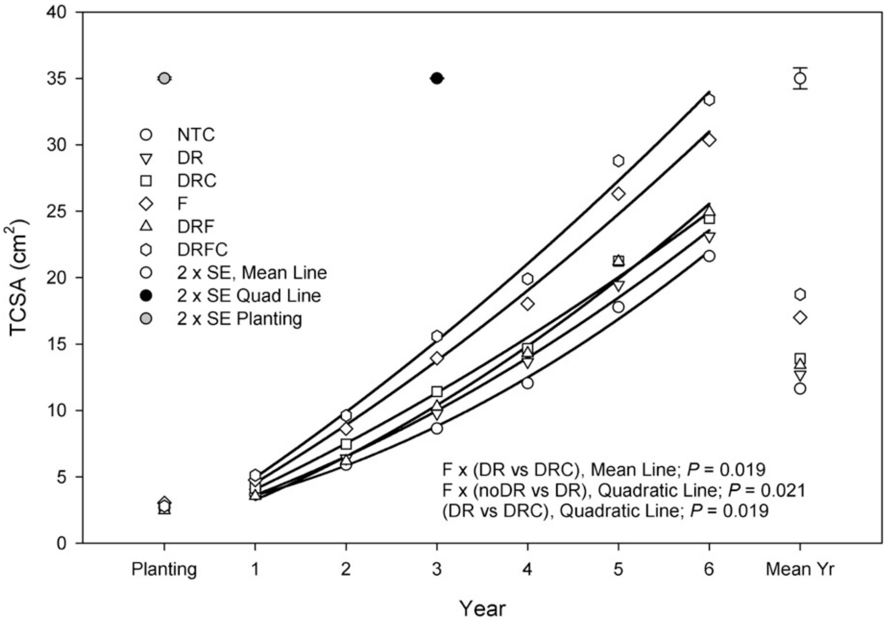

Fig. 1. Yearly means (2002 to 2007) and regression analysis of the trunk cross-sectional area of 'Honeycrisp' apple trees on M.4 rootstock planted into apple replant disease infested soil with various pre-plant soil treatments. Treatments were a non-treated control (NTC), fumigation with Telone C-17 (F), deep ripping (DR), deep ripping plus fumigation (DRF), deep ripping plus compost (DRC), and deep ripping plus fumigation plus compost (DRFC).

improved TCSA equivalent to DRF. Trees in the F, DRFC, DRF, and DRC-treated soils had TCSAs that were significantly greater than the NTC 6 years after treatment application. In addition, TCSA increases in the DRC treatment were significantly greater than DR alone ($P = 0.037$).

In 2005, the number of apples per tree was significantly greater in the F and DRFC treatments ($P < 0.001$) (Table 1). Also, the DRF and DRC treatments were statistically the same and the DRC treatment was better than the NTC and DR treatments. In 2006, the yield of the trees in DRFC and DRC soil was significantly greater than all other treatments. In 2007, tree yields in F, DRC, and DRFC-treated soils were significantly greater than NTC trees. The TCSA in 2007 was 33.3% larger in the DRFC treatment than the NTC (Table 1). The TCSA of trees in the F treatment was next in size to the DRFC treatment. The TCSAs of trees in DRC-treated plots were statistically equivalent to trees in DRF and DR-treated plots but exceeded the TCSA of NTC trees. Trees in the DRC plots had the highest yield efficiency in 2007, although not statistically significantly different from DRFC or F treatments. Contrast analysis revealed that fumigation had a significant positive effect on yield in all 3 years and TCSA and yield efficiency in 2007. In addition, the interaction of F with DR resulted in a significant negative effect on yield in 2005 when compared with fumigation alone in the contrast analysis ($P = 0.023$). The interaction of F on DRC significantly increased the TCSA in 2007 compared with the interaction of F on DR. Also, contrast analysis revealed that DR alone did not significantly increase yield in any year, TCSA in 2007, or yield efficiency in 2007. However, DRC-treated plots were significantly larger than DR-treated plots for yield in all years, TCSA in 2007, and yield efficiency in 2007 (Table 1).

Nutrient and mineral content. In 2005, soil and leaf nutrient and mineral analysis was conducted to determine the effects of compost application on nutrient levels. The compost-treated soils were higher in pH, organic matter, and phosphorus (P) content compared with the rest of the treatments. The pH for DRC and DRFC-treated soils was 5.6 and the pH for the NTC, F, DR, and DRF soil treatments ranged from 5.2 to 5.3. The percent organic matter was 4.2 for the DRC and DRFC-treated soils and ranged from 3.4 to 3.5 for the non-compost-treated soils. The P content (as P_2O_5) of the two treatments containing hog compost (DRC, DRFC) ranged from 3363 kg·ha^{-1} to 3426 kg·ha^{-1}, whereas the NTC, F, DR, and DRF-treated soils ranged from 1029 kg·ha^{-1} to 1772 kg·ha^{-1}. Leaf tissue analysis revealed that the plant nutrient and mineral levels, including P, were similar for all treatments. Phosphorus in leaves for all six treatments ranged from 0.16% to 0.18% and in compost-treated trees ranged from 0.17% to 0.18%. The nitrogen in leaves from compost-treated plots ranged from 2.7% to 3.0%, whereas the leaves from non-compost-treated soils ranged from 2.2% to 2.7%.

Nematode counts. P. penetrans concentrations in 2005 were significantly larger in the NTC (186 per 100 cm^3 soil) compared with the treatments, DR, F, DRF, DRC, and DRFC (55, 23, 46, 75, 0 per 100 cm^3 soil, respectively) that were not significantly different from each other ($P = 0.034$).

Root numbers and distribution. There was a significant quadratic decrease in root number with increasing root diameter at the 0-cm to 20-cm soil depth (Fig. 2). There were significantly more roots in the 1.0- to 9.9-mm diameter range in the 0- to 20-cm soil depth than in depths greater than 20 cm. At depths greater than 20 cm, there was a large drop in root numbers between the 1.0- to 2.9-mm root size category and the 3.0- to 4.9-mm category after which there was little change in root numbers. Analysis of variance of treatment effects on root numbers was significant ($P = 0.05$) as was the interaction of treatment on root diameter ($P = 0.001$) (Fig. 3). However, the effect on root numbers of the interaction of treatment on root depth and treatment by root depth by root diameter was not significant ($P > 0.05$). The interaction between treatment and root diameter demonstrated that the linear decrease in root number with increasing root size for the DR treatment was significantly different from the DRFC and DRC treatments that were more similar to each other (Fig. 3). There were significantly greater numbers of fine roots (1.0 to 2.9 mm) in the DRC and the DRFC-treated soils. Although the roots in all three of these treatments had a linear decline in numbers with increasing diameter, the root numbers in DRC and to a lesser extent the DRFC-treated soils in the middle range of root diameters (3.0 to 4.9 mm and 5.0 to 9.9 mm) did not decline as rapidly or showed no significant change. At root diameters equal to or greater than 10 mm, there was no difference between soil treatments.

Discussion

The significantly greater height of apple seedlings grown in pasteurized orchard soil compared with natural orchard soil in the greenhouse experiment indicated that the Berwick orchard soil had a significant ARD problem. In the United States (Jaffee et al., 1982a) and Europe (Jackson, 1979), significant increases in apple tree growth in response to soil fumigation has been accepted as evidence of ARD. In addition, we isolated *Cylindrocarpon* and *Pythium* species, causal agents of ARD in Nova Scotia from the roots of trees in this orchard and from apple seedlings grown in soil from this orchard (data not shown) (Braun, 1991). In addition, root lesion nematodes also implicated as causal agents of ARD (Jaffee et al., 1982a) were present in the soil.

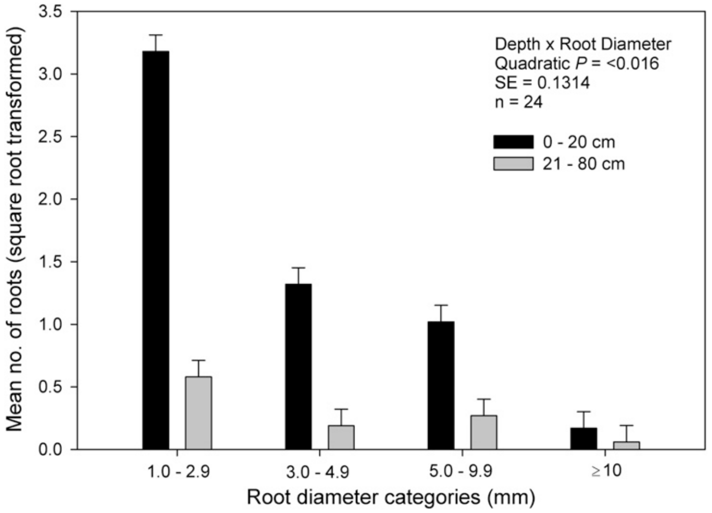

Fig. 2. Results of an analysis of variance on root numbers and the interaction between root depth and root diameter in the soil deep ripping treatments, including deep ripping plus compost and deep ripping plus compost plus fumigation.

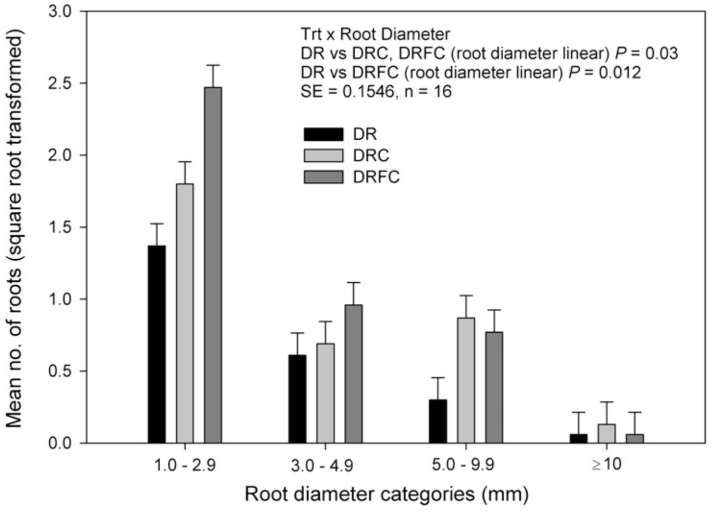

Fig. 3. Results of an analysis of variance and orthogonal contrasts of root numbers in the top 80 cm of soil for the significant treatment by root diameter interaction of the deep ripping (DR), deep ripping plus compost (DRC), and deep ripping plus compost plus fumigation (DRCF) treatments.

The TCSA growth response of trees in fumigated soil in the orchard study confirmed the presence of an ARD problem and supports previous findings that ARD is primarily a biotic disease that can be effectively managed with a broad-spectrum chemical fumigant (Fig. 1) (Braun, 1991; Covey et al., 1979; Mai and Abawi, 1981; Mazzola, 1998; Ross et al., 1983). In this study, composted hog manure also increased TCSA growth compared with the NTC but not to the same extent as fumigation. The consistently higher TCSA of the F, DRF, DRC, and DRFC treatments compared with the NTC over the first 6 years of growth demonstrated the long-term growth improvement of apple trees in the fumigated and compost-treated ARD soil. Likewise, the increased yield of apples in 2005 and 2007 in response to the F, DRC, and DRFC treatments also demonstrated the effectiveness of fumigation and compost applications to manage ARD. The lack of yield differences in most treatments in 2006 may be the result of a biennial bearing phenomenon in ‘Honeycrisp’ apple trees (Embree et al., 2007). Surprisingly, the DR treatment was ineffective in improving growth or yield. In this experiment, deep ripping was used to break up a variably cemented subsoil, encourage deeper rooting, and provide trees with greater resistance to moisture stress during periods of drought, which are experienced every few years in the Annapolis Valley. The lack of response to deep ripping can be attributed to the absence of significant drought stress during the study. A lack of severity in subsoil restrictions (cementation) to root penetration in some areas at the site may also have been a contributing factor. The negative impact of deep ripping on the effect of fumigation in increasing yield in 2005 may have been the result of excessive aeration of this coarse-textured soil, allowing the fumigant to dissipate more rapidly than desired for effective control of ARD. However, fumigation applied to DRC-treated plots had larger TCSAs when compared with the DRF or DRC treatments, suggesting that compost reduced the negative effect of DR on fumigation. We speculate that the addition and incorporation of compost may have led to enhanced retention of the fumigant.

The TCSA of a given rootstock–scion combination is widely considered a reliable index of tree growth (canopy size) and also yield potential (Robinson and Lakso, 1991; Strong and Azarenko, 2000; Wright et al., 2006). The DRFC and F treatments had the largest TCSAs and thus predictably the highest yields. However, it is worth noting that in 2007, the DRC-treated plot yield and yield efficiency were equal to the F-treated plots despite DRC-treated trees having smaller TCSAs. This may indicate an unidentified effect of hog compost on the trees that resulted in a higher than expected yield efficiency. This study confirms the observations of Peryea and Covey (1989) and van Schoor et al. (2009) that growth of apple trees planted in ARD soil increased in response to organic matter addition to orchard soil. Treatments resulting in larger TCSAs and yields in the early-bearing years are a benefit to the grower because these differences can never be recovered over the life of the orchard.

Soil nutrient analyses before the onset of the trial revealed that soil P content in all plots was in excess of 1000 kg P_20_5/ha (Mehlich III extractable), which is considered high for apple production in Atlantic Canada (Atlantic Committee on Fruit Crops, 1998). A soil pH of between 5.2 and 5.6 should have made a sufficient amount of this residual P available to the tree roots. Soil analysis after implementation of treatments revealed that soil P content of compost-treated plots (DRC, DRFC), which had significantly greater TCSAs, yields, and yield efficiencies in 2007, were nearly double those of other treatments. In addition, leaf P levels were similar for all treatments in 2005 and did not reflect the higher levels of soil P in the DRC and DRFC treatments or a P deficiency in plots not receiving compost. Therefore, P deficiency does not appear to be a reasonable cause of reduced tree growth in ARD soil. However, Slykhuis and Li (1985) advocated the use of monoammonium phosphate (MAP) to alleviate the symptoms of ARD. Wojcik and Klamkowski (2005) also noted the beneficial effects of MAP on apple tree growth and yield. Braun (1991) observed that apple seedlings with replant disease symptoms had significantly fewer fine roots. The reduction of fine roots would reduce the capacity to absorb nutrients and in particular P that has relatively low soil mobility. Slykhuis and Li (1985) contend that seedlings responded to the P in MAP independent of soil P levels but with little explanation of the mode of action. Therefore, although additional P from hog manure compost does not appear to be a logical reason for the improved tree growth in ARD soil in this study, it cannot be definitively ruled out.

Pratylenchus penetrans numbers ranged from 0 to 75 per 100 cm^3 of soil in the treated plots and 186 per 100 cm^3 in the NTC. Although these nematode counts were made 4 years after the treatments were applied, *P. penetrans* in the treated plots were still significantly lower than the NTC. Hoestra and Oostenbrink (1962) reported that 35 *P. penetrans* per 100 cm^3 of soil was the minimum damaging level for apple trees in The Netherlands and Jaffee et al. (1982a) reported that more than 140 *P. penetrans* per 100 cm^3 of soil caused significant stunting and root necrosis. All the treatments in this experiment except the NTC were below the Jaffee et al. (1982a) threshold in the fourth year after treatment. Mai et al. (1970) speculated that nematode numbers remain low for only 1 or 2 years in response to a treatment. They further suggested that the critical period to protect apple roots from damage was in the year of establishment. It is likely that the nematode numbers in the treated plots in the first year of this experiment were lower than in the fourth year and probably below the damage threshold. The number of *P. penetrans* in the NTC exceeded the number Jaffee et al. (1982a) reported causing considerable root damage and may have contributed to the ARD symptoms observed in the NTC.

Our observation that the largest numbers of fine roots were in the top 20 cm of soil might have been anticipated based on the work of Atkinson (1977) and Haynes (1981) who showed that herbicide strips encourage tree fruit root growth near the soil surface. Yao et al. (2006a) also used herbicides strips and found that the depth of fine roots for M.9 rootstock was in the upper 25 cm of soil, whereas other rootstocks had typically deeper roots. All treatments in this study had a 2-m-wide herbicide strip under the trees, but the DR treatment had fewer fine roots in the upper 20 cm compared with the DRC and DRFC-treated plots. The compost application in this study was made to the top 40 cm of soil and the concentration of fine roots in the top 20 cm in compost-treated plots must be in response to the compost rather than the deep ripping or just a root zone without weed or grass competition. Also, there were a greater number of the roots in the middle two diameter categories in the treatments that received compost. Tree roots growing in the DRC and DRFC treatment zones would have encountered a layer of organic matter rich in minerals and nutrients with a higher water retention capacity and low bulk density allowing easy root penetration. In addition, the compost layer initially would contain a reduced number of pathogens as a result of fumigation and/or by dilution or isolation because of the large volume of incorporated compost. Yao et al. (2006a) concluded that ‘‘a robust rootstock that supports rapid tree establishment’’ would be better able to resist or tolerate ARD without the need for fumigation. Establishing a good network of roots in the compost layer in the early years of growth would have resulted in healthier and more vigorous trees better able to establish the supportive framework roots for future years. These framework roots would provide for more extensive branching of finer roots to better exploit the available soil volume for water, nutrients, minerals, and anchorage. All these factors would logically lead to healthier trees with larger TCSAs, yields, and yield efficiencies and an enhanced tolerance of ARD.

In this study, incorporation of hog manure compost significantly reduced the effects of ARD and may provide an alternative to soil fumigation for the management of ARD. This may be of use to organic apple producers or in situations where fumigant use is restricted or not desirable. Combinations of fumigation and compost with and without deep ripping further improved growth and yield that may be of interest to all apple producers. Although the response to compost was not equal in all respects to fumigation, it was significantly better than the NTC and yield efficiency in 2007 was equal to the standard practice of fumigation for ARD control. A review of compost suppression of soilborne diseases by Noble and Coventry (2005) listed the following possible modes of action: production of antibiotics or fungitoxins by microbial populations in compost, destruction or absorption of phytotoxins by compost or the organisms it supports, improved plant nutrition and vigor, induced systemic resistance by microbes in compost, successful competition for nutrients by compost supported micro-organisms, parasitism of pathogens by compost-supported microbes, beneficial changes to the physical characteristics of the soil, or in soil pH or salt concentration by compost. No one particular mode of alleviating ARD could be identified in this study, yet the increased fine root growth in response to the hog manure compost and fumigation was certainly an important factor. Darby et al. (2006) demonstrated that the primary effect of compost or soil fumigation was greatest in the year of application. In this study, treatment effects were evident 6 years later in TCSA, yield, and yield efficiency compared with the NTC. An explanation of the success of this compost trial to control ARD compared with other published studies (Neilsen et al., 2004; van Schoor et al., 2008; Wilson et al., 2004) may be the source of compost (hog manure) with a high P content but more likely the substantially larger amount of compost applied in this study and the unique placement of the compost. Noble and Coventry (2005) were also convinced that disease suppression increased with increasing rates of compost application. In addition, the larger volume of compost applied in a trench in this study may be much like growing plants in bags or tubes of soilless media (Millner, 2006). This potentially isolated the developing tree roots from fungal root pathogens and parasitic nematodes, reduced soil bulk density, and slowly released nutrients and water resulting in a hospitable rooting environment in the critical establishment year. The apparent preferential growth of roots in the compost-treated plots and in the top 20 cm where the compost was placed support such a hypothesis. The establishment of a healthy root network in the early years may have given the trees in compost-treated soils a growth advantage similar to fumigation that helped them outperform the other treatments in subsequent years. Studies on the effects of soil deep ripping, fumigation, and compost on soil microbial populations and specific organisms within these populations are currently being conducted to determine if microbial population shifts or individual micro-organisms were responsible for the treatment effects observed in this study and will be presented in a future article. More research is required to understand how composts alleviate ARD symptoms and to improve the efficacy of compost equivalent to fumigation. It is also necessary to determine if compost composition is critical for ARD control and whether hog manure compost would be equally as effective in different soils.

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