

# Organic fertilization leads to increased peach root production and lifespan

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**Summary** We evaluated the effects of mineral and organic fertilizers on peach root dynamics in the growing season from 2003 to 2006 in a nectarine (*Prunus persica* L.) orchard, planted in 2001 and located in the Po valley, north-eastern Italy. Very few studies have conducted long-term investigations of root dynamics of fruit crops. Our main objective was to determine whether organic fertilizers affect root dynamics differently than mineral fertilizers. The experiment was a completely randomized block design with four replicates of three treatments: unfertilized, mineral fertilized and composted with municipal waste. Mineral fertilizers included P (100 kg ha<sup>-1</sup> year<sup>-1</sup>) and K (200 kg ha<sup>-1</sup> year<sup>-1</sup>) applied only at planting and N (70–130 kg ha<sup>-1</sup> year<sup>-1</sup>) split into two applications, one at 40 days after full bloom (60%) and the other in September (40%) each year. The compost fertilization represented a yearly rate of 10 metric tons (t) dry weight ha<sup>-1</sup>, which approximates (in kg ha<sup>-1</sup> year<sup>-1</sup>) 240 N, 100 P and 200 K, split similarly to that described for the mineral fertilization of N. Both root growth and survival were evaluated at 20-day intervals during the growing season by the minirhizotron technique. Compost increased the production of new roots compared with the other treatments ( $P < 0.01$ ). Roots were mainly produced at a depth of 41–80 cm and from March to May and in late summer. An analysis of covariance indicated no significant effect of soil nitrate on root production ( $P = 0.47$ ). The root lifespan was longer in compost-treated trees than in mineral-fertilized or unfertilized trees ( $P < 0.01$ ) and it was strongly affected by time of birth; roots born later in the summer lived longer than those born in the spring. Across years and treatments, the average root lifespan was positively correlated with soil nitrate ( $r = 0.60$ ;  $P < 0.001$ ). Variation in root lifespan with method of fertilization could be accounted for by variation in soil nitrate concentration as indicated by no effect of fertilizer treatment on root lifespan when soil nitrate was included as a covariate. These results reveal how shifting from mineral to organic fertilizers may shift both soil properties and nutrient availability, leading to changes in both root production and lifespan.

**Keywords:** compost, minirhizotron, *Prunus persica*, root lifespan, root suberization.

## Introduction

Although many studies have contrasted in detailing the effects of organic fertilizers when compared with mineral fertilizers on aboveground traits of fruit trees (Gallardo-Lara and Nogales 1987), there is very little understanding of how these treatments differentially influence root production and root lifespan in belowground traits. Moreover, studies examining the effects of nitrogen (N) fertilizers on root dynamics in fruit trees and nut crops are quite limited, in contrast to the numerous studies in forest trees.

In most agricultural regions, soil organic matter (SOM) has diminished (Burke et al. 1989, Paul et al. 1996); e.g., in Eastern Po Valley, Italy, the SOM was estimated to be ~2.8% in 1935 (Tabaglio et al. 2004) and is <1.5% now (Ungaro et al. 2005). The recycling of composted organic materials from agri-food industry and from municipal solid waste represents a sustainable source of organic matter (OM) that is now used broadly to both rebuild the SOM pools and replace chemical fertilizers in low-impact agricultural systems. However, the effects of this shift to organic materials on soil fertility and root dynamics are poorly understood.

The study of root dynamics needs to account for the heterogeneity of the root system. The root system has diverse functions, including nutrient and water absorption, anchorage and storage. Fine lateral roots associated with the absorptive portion of the root system may be replaced once or several times per year. Typically, only the finest two orders of roots have an important role in nutrient absorption and represent the most dynamic portion of the root system (Pregitzer et al. 1997, Wells and Eissenstat 2001, Comas et al. 2002). In most woody species, these roots seldom undergo secondary development of the vascular tissue or of the periderm, contributing to their ephemeral nature (Brundrett and Kendrick 1988,

Eissenstat and Achor 1999). However, first- and second-order roots (using a stream-based ordering nomenclature, Pregitzer et al. 2002) may undergo significant developmental changes, including mycorrhizal colonization and accumulation of condensed tannins reflected in root pigmentation, without undergoing radial growth (Eissenstat and Volder 2005). Pigmented roots often exhibit considerably lower respiratory and nutrient-absorptive capacities than white roots (Comas et al. 2000, Volder et al. 2005, 2009, Baldi et al. 2010). Among temperate fruit crops, root production has strong seasonal patterns (Eissenstat et al. 2005) and the median root lifespan typically ranges from 30 to 100 days (grape: 90 Anderson et al. 2003; apple: 90 Wells and Eissenstat 2001; peach: 100 Wells et al. 2002).

Although there are limited investigation on the effects of compost and mulching on root dynamics, the effects of N addition has been relatively well studied. Root standing crop or root density can be affected by the N supply, but the direction of the effect is inconsistent. Some studies in temperate forests indicate a negative relation between soil fertility or the N supply and fine root biomass (Aber et al. 1985, Vogt et al. 1987, Nadelhoffer 2000, Bakker et al., 2009), while other experiments demonstrate that N fertilizers can stimulate fine root biomass (Finn 1995, Rasse 2002). These contradictory results represent the complex interplay between factors affecting root production, including positive effects of N addition on whole plant photosynthesis but reductions in carbohydrate allocation to the root system (Ingestad and Agren 1991), and factors affecting lifespan, which has been shown to be both positively (Burton et al. 2000) and negatively (Pregitzer et al. 1995, Tingey et al. 2000, Rasse 2002) affected by N addition.

Nitrogen availability to the root system strongly affects the growth rate and proliferation of roots. Increases in both ammonium ( $\text{NH}_4^+$ ) and nitrate ( $\text{NO}_3^-$ ) ions can enhance branching of axial roots and the elongation of lateral roots, although long-term supplies of these forms of N may enhance the root growth to different extents (Boukcim et al. 2006). Moreover, mineral fertilizers may lead to pulses high in nitrate, whereas organic fertilizers release N more slowly and may supply ammonium for varying lengths of time, depending on the rates of nitrification. The root growth responses to these different forms of N are strongly influenced by spatial and temporal patterns of the N supply. Uniform increases in the N supply often reduce the root growth whereas localized increases in N supply may strongly stimulate root growth (reviewed by Robinson 1994, Hodge 2006). Unlike mineral fertilizers, application of compost may affect root growth not only by increasing inorganic ions in the soil but also by the presence of humic substances released by the decomposing OM. Humic substances may modify root morphology, inducing proliferation of lateral roots and root hairs and causing a higher differentiation rate of root cells (Concheri et al. 1996, Canellas et al. 2002). Indirect evidence suggests that this may be the result

of auxin-like effects in certain humic substances (Muscolo et al. 1998, Pizzeghello et al. 2001, Nardi et al. 2002).

The aim of the present study was to evaluate, in a commercial nectarine orchard, the effects of compost on root growth and turnover. In particular, we wished to separate just nutrient addition associated with mineral fertilizers from the addition of nutrient-rich OM. We hypothesized that trees grown in compost-amended soil would increase root growth and have a longer root lifespan than those of trees grown in mineral-fertilized soil and that variation in soil nitrate-N would not entirely account for the variability in root dynamics.

## Materials and methods

The study was conducted from 2003 to 2006 in a nectarine (*Prunus persica* Batsch var. *nectarina* (Ait) Maxim.) orchard, located in the southeastern part of the Po valley in northeastern Italy (44°27'N; 12°13'E). Trees of the variety 'Stark Red Gold', grafted on GF677 (*Prunus persica* × *Prunus amygdalus*) rootstock, were planted in late fall of 2001 at a distance of 5 m between the rows and 3.8 m between trees along the row on a Calcaric Cambisol soil (FAO 1990) characterized by 6.7% sand, 67% silt, 26.3% clay, pH 7.8, electrical conductivity of 200  $\mu\text{S cm}^{-1}$ , 1.1% total N and 1.7% OM. As typical of commercial practices in this region, soil was tilled three times a year to a 25-cm depth in the tree rows (the soil close to the tube was manually tilled at the same depth as the mechanical tillage), while the alleys were untilled and covered with grass. Tree canopies were trained in a 'delay-vase system' (Corelli-Grappadelli and Marini 2008). From June to September, trees were daily watered using drip irrigation calibrated to replenish daily evapotranspiration (based on pan evaporation at the farm meteorological station, 1 km from the field site). Average annual air temperature was 13.7 °C and average annual precipitation was 594 mm (1967–97; Geophysical Station of Modena University). Gravimetric soil moisture during the trial was determined in each plot at two depths, 0–40 and 40–80 cm, four times a year (before spring fertilization, 40 days after spring fertilization, mid-July and 40 days after late summer applications) and site averages ranged from 12 to 23% over the growing season.

After the orchard was planted, the three fertilization treatments (unfertilized control, mineral fertilized and composted) were compared in a randomized complete block design with four replicates. Mineral fertilizer included phosphorus (P, 100  $\text{kg ha}^{-1} \text{ year}^{-1}$ ) and potassium (K, 200  $\text{kg ha}^{-1} \text{ year}^{-1}$ ), which was applied at planting. Nitrogen was applied every year at an annual rate of 70–130  $\text{kg ha}^{-1} \text{ year}^{-1}$  (the rate of N applied was increased, according to the integrated production guidelines, to meet the increasing demand of plants), split into two applications, one at 40 days after full bloom (60%) and the other in September (40%). Compost was applied every year at 10 t dry weight (DW)  $\text{ha}^{-1} \text{ year}^{-1}$ , representing 240  $\text{kg N ha}^{-1} \text{ year}^{-1}$ , 100  $\text{kg P ha}^{-1} \text{ year}^{-1}$  and 200  $\text{kg K ha}^{-1} \text{ year}^{-1}$ .

Compost was split into two applications, one in spring and one in fall, similar to that for the mineral N fertilization. Compost was obtained from domestic organic wastes (50%) mixed with decayed (3 months) pruning materials from urban gardens and ornamental trees (50%) and was characterized by 2.4% DW N and 22.8% organic carbon, with a C/N ratio of 10.

New root production (growth) and lifespan were determined using the minirhizotron technique. One clear Plexiglas® tube (6 cm in diameter × 100 cm in length) per tree was inserted into the soil in October 2002, 50 cm from the trunk and at a 30° angle from vertical, to avoid any preferential water drainage and root growth along the tube walls (Bragg et al. 1983). Tubes were inclined toward the center of the row. The bottom of each minirhizotron was sealed to prevent water from entering the tube, whereas the top was closed with a rubber stopper and the portion of the tube above the ground was painted black to prevent light intrusion. Each tube was covered with a white can to prevent radiant heating. On the side of each tube, a green line was drawn and a progressive number was written at a 1.5-cm spacing. Images were collected with a video camera system (Bartz Technology, Santa Barbara, CA, USA) every 20 days during the growing season. During each growing season (2003, 2004, 2005 and 2006), videos were collected from March to November and later converted to digital images (Studio DC 10 Plus, Pinnacle Studio version 8, Mountain View, CA, USA) that were catalogued according to ICAP (Bartz) nomenclature in order to have a sequence of the same minirhizotron window positions over the time of investigation. Images were analyzed using specialized software (WinRHIZO Tron MF, Regent Instrument, Quebec, Canada) for number of roots and survivorship. Root birth was considered the date when a root was first observed, whereas root death was identified by disappearance from the window or evidence of root shriveling and decay. Root lifespan was calculated, in days, as the difference between date of death and of birth. The root survival probability was generated using the baseline statement of PROC PHREG in SAS with treatment or depth used as the stratifying variable.

To evaluate soil nitrate concentration, soil cores (1000 g fresh weight (FW) were collected at two depths, 0–40 and 40–80 cm, four times a year (before spring fertilization, mid-July and 40 days after spring and late summer applications) for each of the 4 years. Nitrate was extracted from 10 g FW of sieved (2 mm) soil in 100 ml of 2 M KCl solution, shaken at 90 rpm for 1 h. After soil sedimentation, the supernatant was collected and stored at –20 °C until analysis (Auto Analyzer AA-3, BRAN + LUEBBE, Norderstadt, Germany).

During the entire experiment, trunk diameter and fresh weight of pruning wood were measured in winter. Tree yields were measured at commercial harvest.

#### Statistical analysis

All data were statistically analyzed using a completely randomized block design with four replications (trees) using soil

fertilization (three levels: unfertilized control, mineral fertilized, composted) and depth (four levels: 0–20, 21–40, 41–60 and 61–80 cm) as factors. When analysis of variance showed statistical differences ( $P \leq 0.05$ ) and means were calculated by the Student–Newman–Keuls test. The effect of fertilization on the risk of root pigmentation and mortality was evaluated using a Cox proportional hazards regression approach (SAS Version 1996), where other covariates of depth, time of birth, root diameter and soil nitrate were included, depending on the model (Wells and Eissenstat 2001). In addition, correlation analyses were performed to evaluate the relationships between root responses and soil nitrate-N concentration.

## Results

### Soil nitrate and soil moisture

The fertilizer treatments did not affect soil moisture, with median gravimetric soil moisture varying from 17% in the mineral-fertilized treatment to 19% in the control treatment (Figure S1 available as Supplementary data at *Tree Physiology* Online). For 50% of the measurements, soil moisture content ranged from 14 to 23%. Soil nitrate was very variable, ranging from near zero to almost 25 p.p.m. in the soil solution. Although all treatments had a similar range, the compost treatment tended to have a higher median (10 p.p.m.) compared with the other two treatments (5 p.p.m.; Figure S1 available as Supplementary data at *Tree Physiology* Online).

### Aboveground vegetative and reproductive production

The fertilizer treatments did not influence trunk circumference during the entire duration of the trial (Table 1). By the end of the study (2006), pruning wood was increased by the

Table 1. Effect of fertilization practice on plant trunk circumference, pruning wood (FW) and fruit production (FW) in a nectarine orchard in northeastern Italy.

| Treatment                                  | 2003 | 2004 | 2005 | 2006   |
|--|------|------|------|--------|
| Trunk circumference (cm)                   |      |      |      |        |
| Control                                    | 16.0 | 29.9 | 37.9 | 40.3   |
| Mineral                                    | 15.4 | 29.9 | 37.7 | 39.6   |
| Compost                                    | 15.3 | 30.8 | 38.2 | 39.6   |
| <i>P</i> -values                           | 0.35 | 0.31 | 0.81 | 0.59   |
| Pruning wood (kg)                          |      |      |      |        |
| Control                                    | 2.9  | 9.8  | 7.0  | 6.1b   |
| Mineral                                    | 2.6  | 9.1  | 6.9  | 6.8ab  |
| Compost                                    | 2.5  | 9.7  | 7.6  | 7.6a   |
| <i>P</i> -values                           | 0.48 | 0.55 | 0.58 | 0.04   |
| Fruit production (kg plant <sup>-1</sup> ) |      |      |      |        |
| Control                                    | –    | 31.8 | 46.3 | 56.4b  |
| Mineral                                    | –    | 32.4 | 48.1 | 68.8a  |
| Compost                                    | –    | 31.9 | 50.5 | 66.6a  |
| <i>P</i> -values                           | –    | 0.94 | 0.13 | 0.0002 |

Means followed by the same letter are not statistically different ( $P \leq 0.05$ ).

application of compost over that of the unfertilized trees ( $P < 0.04$ ), with mineral-fertilized trees intermediate (Table 1). In early years of the study (2003–2005), no significant differences in pruning weights were observed. Fruit production began in 2004, and by 2006 significant differences were observed among the treatments ( $P < 0.001$ ), with compost- and mineral-fertilized trees showing very similar yields that were 18–22% higher than that of the unfertilized trees (Table 1).

### Root production

We did not observe any significant interactions of year or depth on cumulative root production in the three fertilizer treatments. Compost-treated trees had higher total cumulative root production than the unfertilized controls during the 4-year investigation period, with mineral-fertilized plots intermediate (Figure 1). Annual root production was highest in the first year of the study and decreased with time, becoming stable in 2005 and 2006. Root populations observed at depths between 40 and 80 cm were higher than those in the shallowest layer (0–20 cm) where fewer roots were found (Figure 1).

Seasonal patterns of root production varied from year to year (Figure 2), and the fertilizer treatment did not significantly shift the seasonal patterns in any year (time  $\times$  treatment interaction,  $P > 0.536$  for any year). Compared with unfertilized control trees, compost-treated trees exhibited greater white root production in June 2003, August 2003 and May 2004; mineral-fertilized trees were intermediate (Figure 2a and b). These differences in root production among fertilizer treatments were not evident in the latter 2 years of the study (2005 and 2006).

The only reasonably consistent seasonal pattern of root production in the study was that few roots tended to be produced in mid- to late July (except in 2005 for mineral-fertilized trees). In some years, there was little root production before May (2003 and 2004), while in other years a substantial fraction of yearly root production was produced in March and April (2005 and 2006). A bimodal pattern of root production often reported in fruit crops (Glenn and Welker 1993) was

only observed in this study for all treatments in 2003 and 2006 and for the unfertilized control trees in 2005.

### Root pigmentation and lifespan

Root pigmentation is linked to loss of respiratory activity and reduced capacity to absorb nutrients (Comas et al. 2000, Volder et al. 2005, 2009, Baldi et al. 2010). Overall, nectarine roots in the unfertilized and mineral-fertilized treatments took  $\sim 31$  days (median) to become pigmented, and the compost treatment delayed pigmentation by an additional 32 days (median), suggesting that compost extended the period when roots were most absorptive. However, there was a strong treatment–depth interaction: roots of composted trees became pigmented in a shorter time than in the other treatments in the shallower soil layer, while they took a much longer period than the other treatments in the deeper 60 and 80 cm depth layer (Figure 3).

Root survivorship in trees treated with compost was significantly longer than that of untreated control and mineral-fertilized trees (Figure 4, top). Differences in treatments were greatest for roots  $< 300$  days old, with  $\sim 16\%$  shorter median lifespan in the mineral-fertilized and unfertilized trees (227 and 226 days, respectively) than in the compost-treated trees (269 days) over all 4 years.

In addition to the fertilizer treatment, the root survivorship was also affected by other environmental factors. The root survivorship increased with an increase in soil depth (Figure 4, bottom;  $P < 0.001$ ) and was similar at 41–60 and 61–80 cm depths. The median lifespan of roots at 60–80 cm depth was 254 days, 156 days longer than those at the 0–20 cm depth. Root survival was also affected by the date of first appearance: roots that appeared late in the summer showed a longer survivorship than those born earlier or later in the season (Figure S2 available as Supplementary data at *Tree Physiology* Online).

### Root standing crop

Root standing crop or the total population of roots at any point in time is the net effect of the roots produced and those that had died. Because trees in the compost treatment

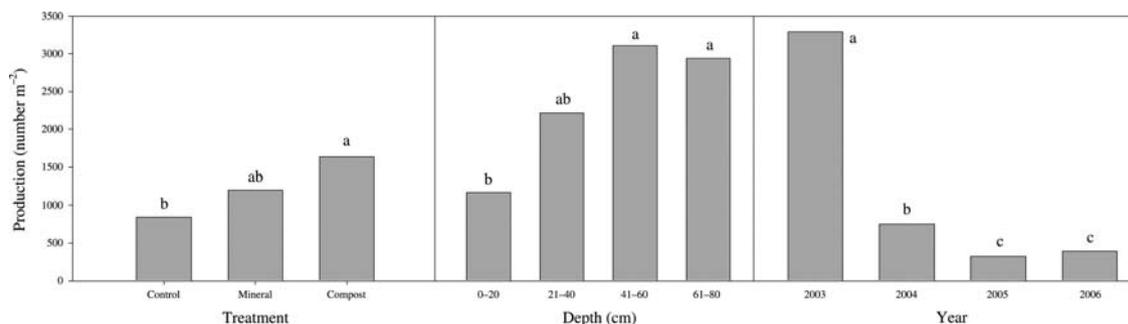


Figure 1. Effect of fertilization practice on the number of roots produced over the entire experiment in a nectarine orchard in northeastern Italy (2003–2006). Root production is expressed per square meter of viewing surface on the minirhizotron tube. Means represent averages of main effects.

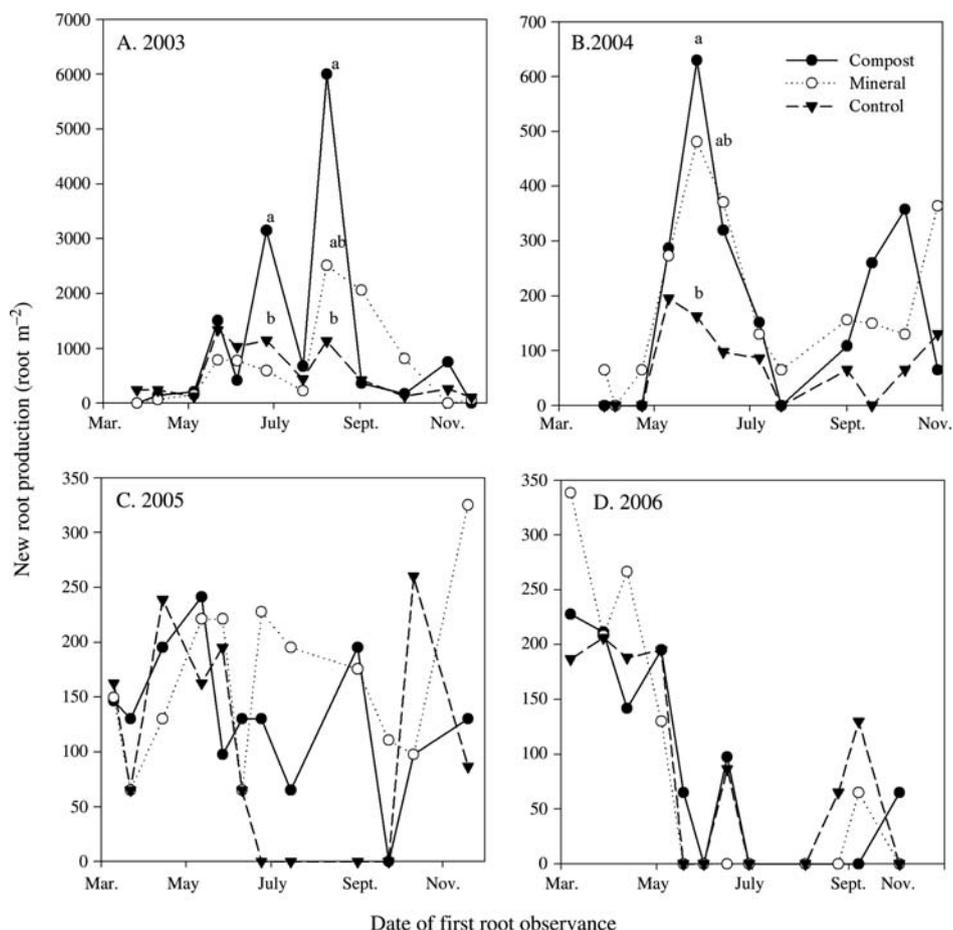


Figure 2. Effects of fertilization practice on new root production in a nectarine orchard in northeastern Italy (2003–2006). Data are expressed as new roots observed since the last observation date per square meter of minirhizotron tube surface examined and are an average value over all depths. Note change in scale of y-axes. A tick mark on the x-axis represents the first day of each month. Within an observation date, means followed by a different letter are statistically different ( $P \leq 0.05$ ); means with no letters are not statistically different.

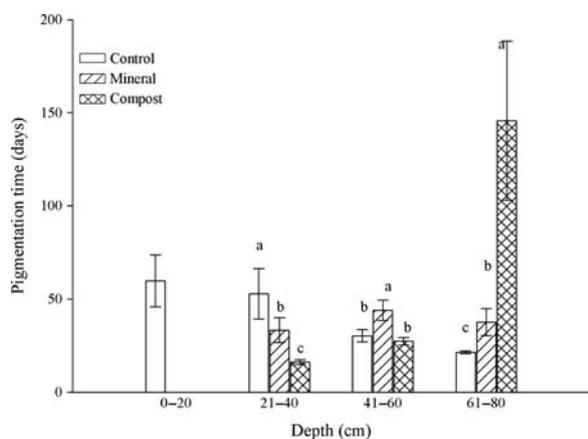


Figure 3. Effects of fertilization practice and soil depth on the period of time until a root became pigmented. Data are based on all roots produced over the 4-year experiment. Bars indicate mean  $\pm$  standard error. Data were analyzed with TPHREG (SAS Institute); the interaction of treatment and depth was statistically significant ( $P = 0.001$ ). At 0–20 cm soil depth, roots in compost and mineral treatments did not become pigmented but directly died.

had higher root production and longer root lifespan, they had much higher peak standing crops in every year of the study than the other fertilizer treatments ( $P \leq 0.01$ ; Figure 5).

#### Variation attributed to soil nitrate supply

We examined whether variation in soil nitrate among soil locations across treatments (Figure S1 available as Supplementary data at *Tree Physiology* Online) could fully account for the effects of fertilizer treatment on root production, duration the roots remained unpigmented, root lifespan and root standing crop. As reported previously, an analysis of variance indicated that the mean soil nitrate concentration was not influenced by fertilization treatments. However, inclusion of soil nitrate as a covariate in the proportional hazards regression model of root survivorship indicated that the effects of fertilizer treatment on root survivorship were mainly due to variation in soil nitrate ( $P \leq 0.001$ ). The positive correlation of nitrate-N concentration with the median lifespan was significant ( $r = 0.48$ ;  $P \leq$

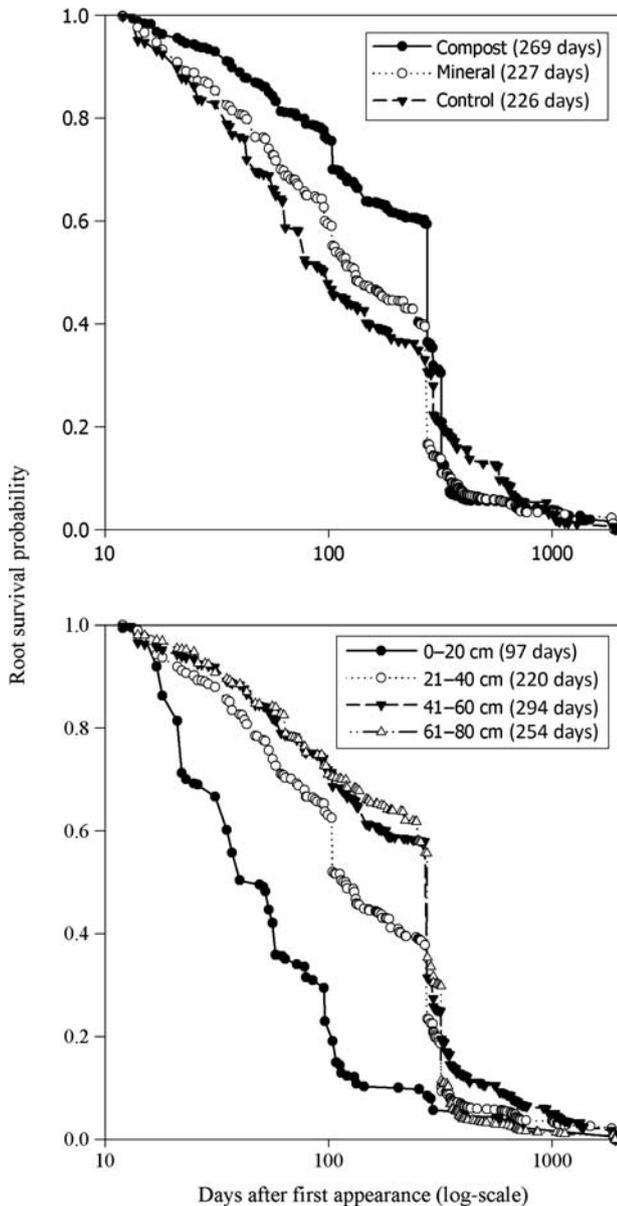


Figure 4. Survival probability of roots observed from 2002 until 2006. Survival probabilities were generated using the baseline statement of PROC PHREG in SAS with treatment (top) or depth (in cm, bottom) as the stratifying variable. Median lifespans (in days, in parenthesis) are also shown.

0.001), with a stronger relation at a soil depth of 40–80 cm (where most of the roots were; Figure 6), than at 0–40 cm ( $r = 0.36$ ;  $P \leq 0.02$ ; data not shown).

## Discussion

The positive effect of organic fertilizers on the number of new roots observed, extended period of absorptive activity (as indicated by delayed pigmentation) and extended lifespan during the 4-year-long investigation is probably related to the positive effect of this fertilization strategy on soil

chemical (nitrate concentration, humic substances) and physical properties. These results were most strongly expressed in the first 2 years of the study when the trees were first becoming established. Overall, these results indicate that root systems may strongly benefit from this fertilization practice in establishing trees, even if it is not reflected in fruit production or trunk growth.

There was a strong *positive* relationship between the soil nitrate concentration and root lifespan. Indeed, the results of the Cox proportional hazards regression indicated that most of the variations in root lifespan associated with fertilization practices could be explained by variation in the soil nitrate concentration as indicated by non-significant treatment effects with soil nitrate included as a covariate. This may seem counter-intuitive, because variation in the root nitrogen concentration among different species has been shown to be *negatively* correlated with root lifespan (Tjoelker et al. 2005, Withington et al. 2006). Even though we measured only nitrate pools and not the total N fluxes, as a first approximation N availability was probably correlated with extractable soil nitrate, as extractable ammonium is generally low in these alkaline soils (Martin and Chapman 1951). On the basis of this assumption, root efficiency in terms of nitrogen uptake per unit carbon expended should be positively correlated with soil nitrate concentration. Because increased nitrate availability presumably led to higher efficiency and also an extended period of high uptake as indicated by the delayed pigmentation of the roots in the deepest soil layer (Figure 3), this should lead to longer root lifespan based on resource optimization in organ deployment (Eissenstat and Yanai 1997).

Unlike root lifespan, the increase in root production caused by compost could not be explained just by increases in soil nitrate, as indicated by significant treatment effects even when soil nitrate was used as a covariate. Several studies have reported on important benefits to root growth from organic substances that might result from decomposing compost. In controlled environments, humic acids increased root biomass in corn and oat (Lee and Bartlett 1976) and root number and length in tobacco (Mylonas and McCants 1980) with a stronger effect on roots than on shoot growth (Mylonas and McCants 1980, Chen and Solovitch 1987). Factors include both improved root apex formation (Marschner 1986) and stimulation of root elongation by high-molecular-weight components, such as fulvic acids (Mylonas and McCants 1980) and phenols (Wilson and Staden 1990).

Other studies have shown the important benefits of compost to soil physical properties particularly by increasing soil porosity and reducing soil bulk density, both of which are generally favorable to root growth and function (Passioura 2002). Studies on soil porosity in the same experimental orchard showed that the application of compost increased the number of transmission pores (50–500  $\mu\text{m}$ ) and decreased soil density from 1.25  $\text{mg m}^{-3}$  in untreated control to 1.20  $\text{mg m}^{-3}$  after compost application (Calzolari et al. 2005, Vignozzi et al. 2005). These results are in agreement with

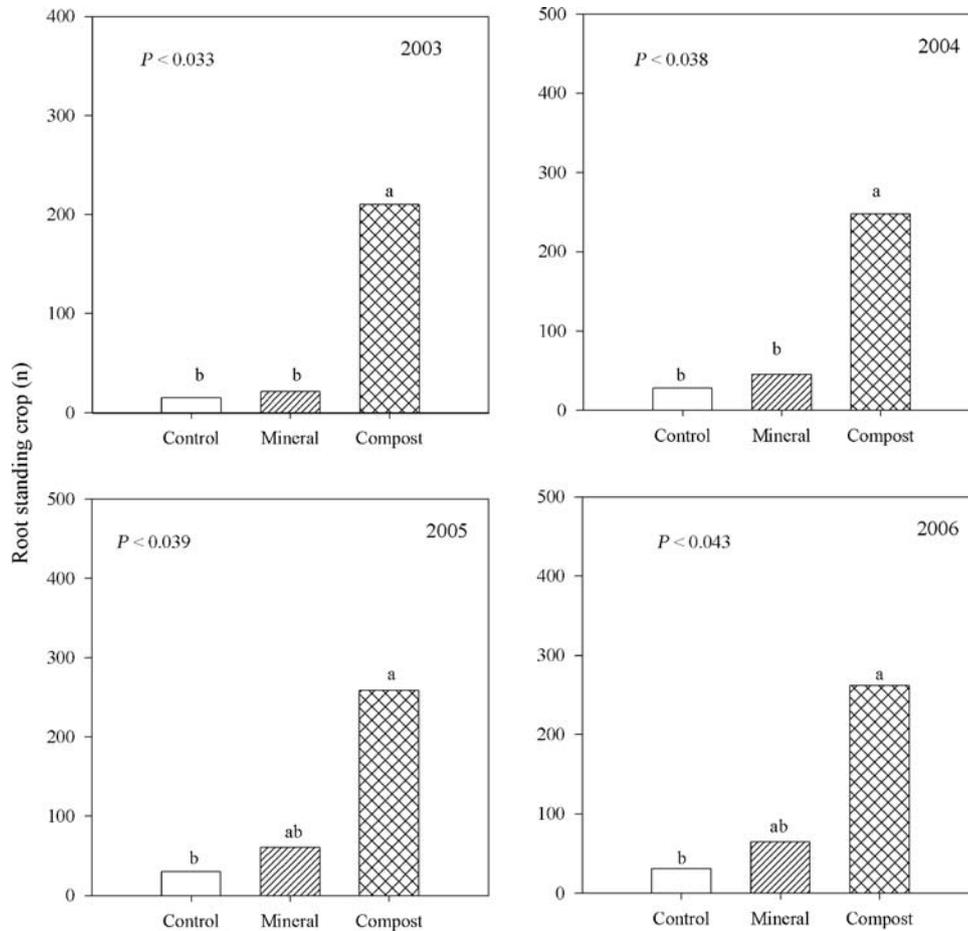


Figure 5. Effect of fertilization treatment on root standing crop, calculated as net effect of the roots produced less those that had died at the end of each year. Values are average of all the depths. Means followed by a different letter were significantly different (data log-transformed prior to analysis;  $P = 0.05$ ).

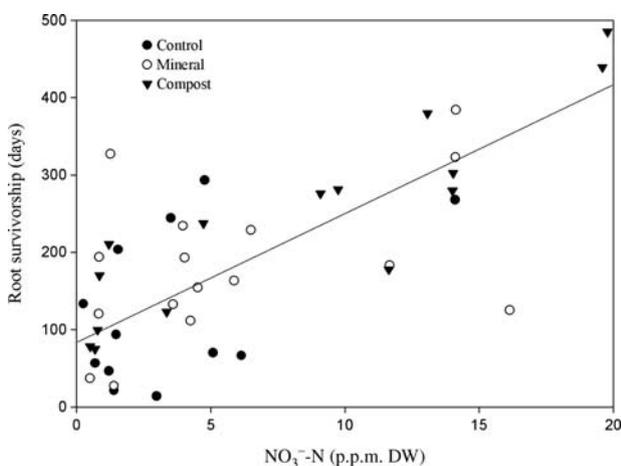


Figure 6. Relationship of soil nitrate-N concentration to median root lifespan over the entire experiment at the depth of 40–80 cm in a nectarine orchard in northeastern Italy ( $r = 0.60$ ;  $P \leq 0.001$ ). A similar, but weaker relationship was observed at 0–40 cm depth (data not shown;  $r = 0.36$ ;  $P \leq 0.02$ ).

Celik et al. (2004) who found an improvement in the soil porosity after the application of OM. The root growth is generally stimulated in soils of lower bulk density and porosity.

The variable patterns of seasonal root production from year to year seen in this study have also been observed in both grape and apple (Eissenstat et al. 2005) and are in contrast to many textbook depictions of patterns of root growth (Atkinson and Wilson 1979, Mullins et al. 1992, Fallahi 1994). In 2 years (2004 and 2006), a bimodal pattern of root production occurred in all treatments and, in 2005, the unfertilized trees also exhibited a bimodal pattern. Thus, our data indicate that a bimodal pattern of root growth may or may not occur in peach, consistent with studies in other fruit crops. Thus, strong competition with fruit for photosynthate may occur, but it is clearly not an overriding factor controlling the root growth in every year. We did, however, see very limited root growth in parts of July quite consistently over the study, which may be partly associated with fruit competition.

Unlike many studies where most root growth occurred near the soil surface, in this study the root growth was

mainly observed in the deeper soil layers, with the most root production observed at depths of 40–80 cm (Figure 1). The limited root growth and very short lifespan of roots at the surface soil layers was probably associated with high soil temperatures and tillage practices. The optimal range of temperature for peach root growth is between 12 and 22 °C (Tamási 1986), values that in summer are usually found in deeper soil layers in this region. In this experiment, the orchard floor management of the tree row included weed tillage and, as a result, the bare soil surface was fully exposed to solar radiation. The mechanical damage and heat may have negatively impacted root number, function and survival, especially during summer periods of high temperatures. Moreover, the reduced number of roots and very low survival of roots in the shallower layer of the compost treatment could be a result of chemicals leaching from the decaying compost being toxic at high concentrations but beneficial in the deeper layers where these chemicals are diluted (Lopez-Bucio et al. 2003, Giorgi et al. 2008). During this study, the trend of a yearly decrease in root growth was probably a consequence of several factors. In 2003, the expanding root system of the young trees of the relatively vigorous hybrid (peach × almond) rootstock during the non-fruiting stage may have been a major cause of the very high root production in that year. Fruit production began in 2004, and this process may limit root production because of strong competition for carbohydrates (Atkinson 1985). Increasing yields from 2004 to 2006 (Table 1) may have continued to inhibit high root production. In addition, a possible disturbance of soil and root system by minirhizotron installation may have also promoted root growth (Joslin and Wolfe 1999), although this disturbance effect would likely be smaller in a newly planted orchard, as occurred in this study.

In conclusion, organic fertilization practices can have strong influences on root production, the time a root remains unpigmented and root lifespan that might not be expressed immediately in terms of aboveground growth or fruit production. The effects of fertilization practice on lifespan could be largely accounted for by variation in soil nitrate concentration. In contrast, root production was stimulated by compost in ways that could not readily be explained by nitrate availability. This work helps to clarify the complex ways the shifts in fertilization practices may affect fruit tree root function and dynamics.

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#### Supplementary data

Supplementary data for this article are available at *Tree Physiology* Online.

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