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Wood Chip Incorporation in Almond Orchard Planting Berms Increased Gravimetric Water Content, Soil CO_2 Efflux, and Fine Root Length Density

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Abstract. **Incorporation of chipped woody material into soil instead of burning or transporting wood chips (WCs) off-site is a practical solution to dispose of old orchard trees. In woody plants, the most external (fine) lateral roots are critical in acquiring water and nutrients and are the part of the root system that is most responsive to changes in the soil environment. Our objective was to measure the impact of pre-planting WC incorporation into the planting site on young almond tree root parameters such as root length density (root length per soil volume) and root architecture. We hypothesized that presence of decomposing WCs in soils in the years following planting leads to increased fine root length density and changes in root architecture that increase soil exploration per unit root biomass. Plum WCs were incorporated into the orchard soil 6 months before planting and three blocks were established with paired treatment and control (no WC) plots. Root traits, soil water content, soil bulk density, and soil CO_2 efflux were measured in both the berm and alleyways twice in years 2 and 3 after planting. We found significant increases in standing root length density in planting berms with WC incorporation 2 and 3 years after trees were planted. This was due to an increase in root mass per soil volume rather than an increase in specific root length or a change in proportion of fine roots produced. Thus, although root foraging was increased in planting berms with WCs incorporated, this was not due to a change in root architectural traits.**

Fine roots of woody plants are critical for foraging resources, and growth and architecture of fine roots are influenced by soil conditions such as water and nutrient availability, soil temperature, and soil strength (Coutts 1987; Giehl and von Wirén 2014; Giehl et al. 2014; Neilsen et al. 2001). Fine root system architecture is described in a functional way by root position (root order) within the network, counting from the most external root inward. First (first) order roots are the unbranched most external roots, second (second) order roots are the lateral roots that bear first order roots etc. (Lavely et al. 2020; McCormack et al. 2014, 2015). In general, lower-order roots (first and second) have higher absorptive capacity (Russell and Sanderson 1967), whereas higher-order fine roots (fourth and fifth) are supportive roots responsible for transport, anchorage, and storage (McCormack et al. 2015). If nutrients are distributed heterogeneously, there will be greater lateral branching when roots grow into the zone where resources are available (Drew et al. 1973; Hodge 2004, 2006; Jackson and Caldwell 1996). This plastic response to heterogeneous soil conditions helps acquire nutrients efficiently.

Restrictions on orchard waste burning and the decreasing number of California's biomass power generation plants have led to increased interest in processing tree biomass generated in orchard removal in other ways (San Joaquin Valley Unified Air Pollution Control District, SB 705 Air quality: agricultural burning). Whole orchard recycling (WOR) is the practice of grinding or chipping orchard trees and incorporating WCs (WCs) into the orchard soil before planting. WOR increases soil organic matter content and helps sequester carbon into the soil (Jahanzad et al. 2020). Holtz et al. (2004) found that almond WC incorporation increased soil organic carbon, soil cation exchange capacity, extractable soil ammonium (NH_4^+), soil phosphorus (P), soil potassium (K), and leaf P and K concentrations after 2 years. There is a concern that WC incorporation may inhibit initial tree growth because the high carbon to nitrogen ratio (C:N) in WCs can induce N immobilization (Holtz et al. 2004, 2018; Jahanzad et al. 2022). This response is transient, as turnover of the microbial population eventually releases N from the WCs into the soil solution, resulting in higher N availability compared with what was present before the addition of the organic material (Jahanzad et al. 2022). For almond orchards where almond WCs were incorporated in a loamy sand soil, Holtz et al. 2004 reported that leaf nitrogen concentration decreased during the first year of WC incorporation compared with the control field without WC incorporation; however, leaf N concentration in the WC treatment started to increase 2 years later, and exceeded the control treatment 3 years later.

Under nutrient limited conditions, trees can increase soil exploration in several, potentially complimentary, ways: 1) by increasing allocation of biomass to the fine root system; 2) by increasing the amount of root length produced per unit root biomass within each fine root order [increasing specific root length (SRL)]; and/or 3) by shifting biomass investment from higher-order roots to the more external lower-order roots that typically have a higher SRL.

The objective of this study was to measure the impact of pre-planting WC incorporation on young almond tree root parameters such as root length density (root length per soil volume) and root architecture. We hypothesize that if initial N immobilization occurs, WC incorporation will lead to increased root length density to uptake sufficient N to sustain tree growth. More specifically, we hypothesize that increased root length density in response to WC incorporation will be the result of increased SRL in the lower root orders rather than increased mass allocation as macropore presence is typically increased when organic matter is incorporated in the soil profile (Colombi et al. 2017; Valentine et al. 2012). As the berms are mostly undisturbed and receive direct irrigation from the drip emitters placed on each side of the berm, we expect to find greater effects of WC incorporation on root length density and root architectural traits in the planting berms vs. the often disturbed and compacted alleyways.

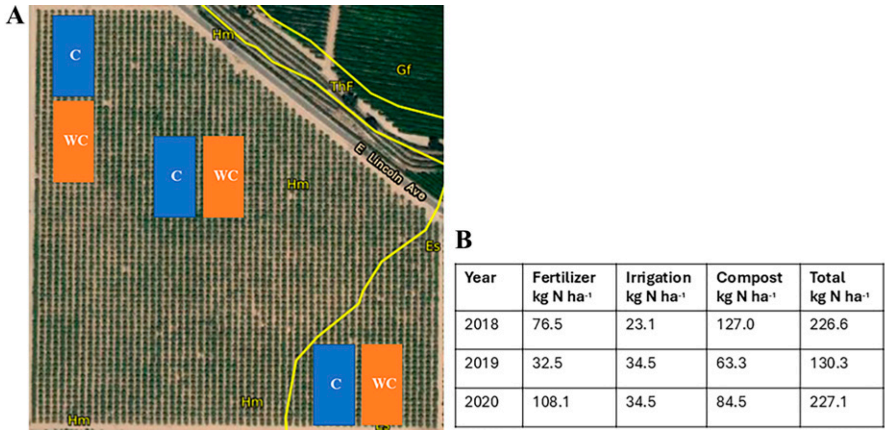
Methods

Site description. At an experimental orchard in Parlier, CA (36.644, 119.511), a 13-year-old plum (Japanese plum, *Prunus salicina*) orchard was recycled and chipped from Aug to Sep 2017, and 100,877 kg per hectare of WCs were spread and incorporated into the field soil to a depth of 0.3 m. A month after WC incorporation, a 0.6 m berm was created for tree planting. As a result, WC incorporation in the berm was in the top 0.9 m, while WC incorporation in the alleyway was to 0.3 m. There were three 0.4-ha blocks with both a 0.2-ha control (no WC) and a 0.2-ha WC-incorporated sub block within each block (Fig. 1). An orchard of Nonpareil and Monterey almond (*Prunus dulcis*) varieties grafted onto Viking rootstock (complex *Prunus* hybrid of *Prunus persica*, *P. dulcis*, *Prunus cerasifera*, and *Prunus mume*) was planted with and without WC incorporation in Jan 2018 at 5.2-m spacing within the row (berm) and 6.7-m spacing between rows (alleyway). A double-line drip irrigation system was installed with a single line on each side of the berm. In 2018, 226.6 kg total N per hectare was applied through fertilizer (76.5 kg·ha^{-1}), irrigation water (23.1 kg·ha^{-1}), and compost (127 kg·ha^{-1} N). In 2019 and 2020, 130.3 and 227.1 kg of total N per hectare was applied with fertilizer (32.5 and 108.1 kg·ha^{-1} N), irrigation water (34.5 and 34.5 kg·ha^{-1} N), and compost (63.3 and 84.5 kg·ha^{-1} N) (Fig. 1).

Nitrogen release from WCs. The amount of carbon (C) in the WCs was ~45,359 kg·ha^{-1} C (50% of mass, Culumber and Gao 2022). If soil microbes break down one-third of the WCs in the first year, the amount of C released from WCs is 14,968 kg·ha^{-1} C and using a carbon use efficiency of 0.3 (Sinsabaugh et al. 2013; Tao et al. 2023) an estimated 4490 kg·ha^{-1} C per year is used for microbial growth. With a microbial C:N ratio of 8:1 (Havlin et al. 2016), an estimated 561 kg·ha^{-1} N is needed to match the carbon used by microbes. If we assume a microbial turnover of 0.05 to 0.08 per day (Hagerty et al. 2014) where N is released from the microbial population and available for reuse, external N demand for microbial growth is 19.2 to 30.7 kg·ha^{-1} N per year. The recommended N application for a new almond orchard is 16.8 to 33.6 kg·ha^{-1} N per year, leading to an estimated total N demand to support microbes and tree growth between 36.0 and 64.3 kg·ha^{-1} N per year. The amount of N released from the decomposed WCs can be estimated using a C:N ratio of 160:1 (Jahanzad et al. 2022), which yields 28 kg·ha^{-1} N. The WC-incorporated orchard received 226.6, 130.3, and 227.1 kg·ha^{-1} N per year in 2018, 2019, and 2020, respectively (Culumber and Gao 2022) and thus, according to our calculations, the applied amounts of N combined with the N released from the WCs were easily sufficient to meet the seasonal N requirements for both trees and microbes combined, even if substantial leaching may have occurred.

Soil bulk density and gravimetric water content. Soil bulk density samples were collected at two locations: in between two trees on the berm and 1.5 m away from the tree in the alleyway with a 15-cm-long and 5-cm-diameter cylindrical soil auger (AMS Inc, American Falls, ID, USA). Samples were collected once in Aug 2019. Samples were dried at 105 °C for 48 h and the bulk density was calculated by dividing dry mass by core volume. To find gravimetric soil water content, fresh soil was collected at the same locations as soil bulk density and weighed on site using a portable scale. The samples were dried at 105 °C and gravimetric water content was calculated by subtracting dry mass from fresh mass and dividing by the dry mass ($g_{water}·g^{-1}{}_{dry\ soil}$).

Root length density and SRL. Four soil cores were collected from 0–20, 20–40, 40–60,



Year	Fertilizer kg N ha⁻¹	Irrigation kg N ha⁻¹	Compost kg N ha⁻¹	Total kg N ha⁻¹
2018	76.5	23.1	127.0	226.6
2019	32.5	34.5	63.3	130.3
2020	108.1	34.5	84.5	227.1

Fig. 1. (**A**) Experimental layout, each block = 0.4 ha, with two 0.2-ha sub-blocks. Wood chips (WCs) were incorporated in the soil in Sep 2017 and almond trees were planted in Jan 2018. At each sampling date soil cores to 80-cm depth were collected at 0.6 m away from two randomly selected trees in each sub-block, one in the berm and one in the alleyway. Root architecture samples were collected in the berm only. (**B**) Amount of N applied per hectare as fertilizer, irrigation, and compost, respectively, in the year preceding root sampling (2018) and the sampling years 2019 and 2020.

Table 1. Soil bulk density and gravimetric water content in the berm and alleyway in the wood chip (WC)-amended and nonamended almond orchard soil on 1 Aug 2019, WCs were incorporated into the soil in Sep 2017. Values in each column are the means of three replications ± standard error. Differences between control and WC treatment at each depth were tested using estimated marginal means pairwise comparison within each location. Bold numbers indicate a statistically significant effect of WC incorporation, *$P < 0.05$, **$P < 0.01$, and ***$P < 0.001$. Different letters indicate significant differences between depths within a site and WC treatment at $P < 0.05$, lowercase letters indicate differences within the berm, while uppercase letters indicate differences within the alleyway.

		Bulk density (g·cm^{-3})		Gravimetric water content (g·g^{-1})	
Soil depth (cm)		C	WC	C	WC
Berm	0–20	1.47 ± 0.11 a	1.32 ± 0.15 a	**0.047 ± 0.012** a	**0.100 ± 0.020** a***
	20–40	1.81 ± 0.17 ab	1.81 ± 0.11 b	**0.033 ± 0.005** a	**0.071 ± 0.006** ab**
	40–60	1.90 ± 0.15 b	1.88 ± 0.13 b	**0.040 ± 0.006** a	**0.069 ± 0.010** ab*
	60–80	1.98 ± 0.18 b	1.91 ± 0.18 b	0.048 ± 0.008 a	0.050 ± 0.013 b
Alleyway	0–20	1.67 ± 0.07 A	1.61 ± 0.08 A	0.036 ± 0.010 A	0.035 ± 0.003 A
	20–40	1.81 ± 0.05 A	1.81 ± 0.02 A	0.043 ± 0.009 A	0.041 ± 0.002 A

Table 2. Effects of wood chip incorporation on soil bulk density and gravimetric water content at different sampling locations (planting berm and alleyway) in the 0–20 and 20–40-cm soil depth. Soil samples were collected on 1 Aug 2019, wood chips were incorporated into the soil in Sep 2017. Bold numbers indicate statistically significant differences at $P < 0.05$ and italicized numbers indicate differences at $P < 0.010$.

	Bulk density		Gravimetric water content	
	F	*P*	F	*P*
Treatment	0.563	0.465	10.1	**0.007**
Soil depth	19.5	**<0.001**	1.30	0.274
Location	3.57	*0.080*	12.3	**0.004**
Treatment × Soil depth	0.673	0.426	0.376	0.549
Treatment × Location	0.100	0.756	12.0	**0.004**
Soil depth × Location	3.64	*0.077*	4.14	*0.061*
Treatment × Soil depth × Location	0.145	0.709	0.259	0.618

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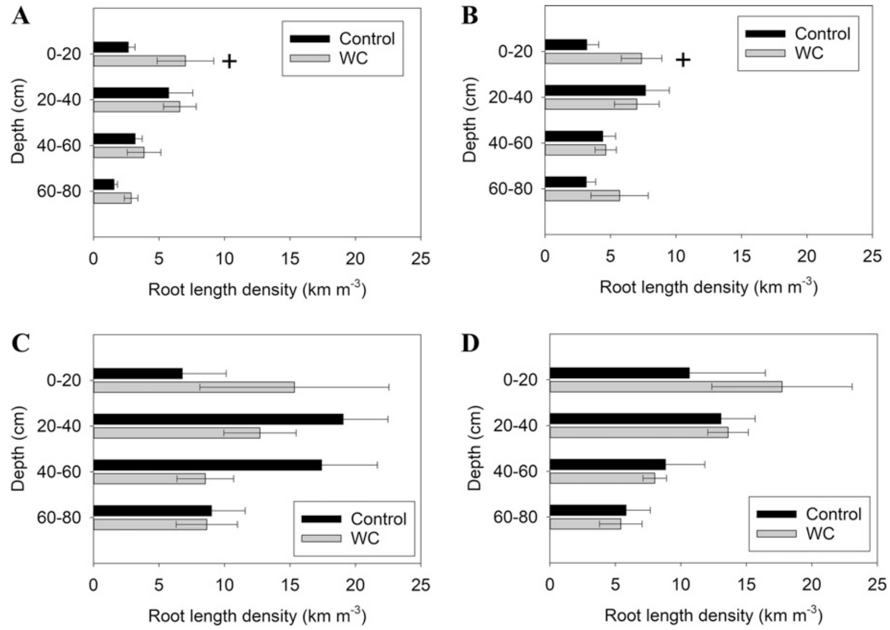

Fig. 2. Standing root length density ($km_{root\ length} \cdot m_{soil}^{-3}$) in the planting berm at different soil depths (0–20, 20–40, 40–60, and 60–80 cm) in (**A**) Jun 2019, (**B**) Sep 2019, (**C**) Jun 2020, and (**D**) Oct 2020 for almond trees on Viking rootstock. Wood chips (WCs) were incorporated in the soil in Sep 2017, and almond trees were planted in Jan 2018. + indicates a statistically significant difference at $0.05 < P < 0.1$ between control and WC incorporation treatment.

and 60–80 cm depth at two locations per treatment per block in Jun and Sep 2019 and Jun and Oct 2020 to measure standing root length density (RLD, root length per volume of soil). Soil cores were stored at 4 °C until each soil sample was washed through three soil sieves consisting of a 5 mesh (4000 μm), 10 mesh (2000 μm), and 35 mesh (500 μm), and gently washed with deionized water. Roots on each sieve were collected using tweezers and scanned using WinRhizo Pro (v. 2013a, Regent Instruments, Quebec City, Quebec, Canada) to measure total root length and average root diameter. Roots were then dried at 60 °C and weighed. RLD and root mass density (RMD, dry mass per soil volume) were calculated by dividing the recovered root length/mass by the core volume. SRL (root length per root mass) was calculated by dividing total root length by total root dry mass.

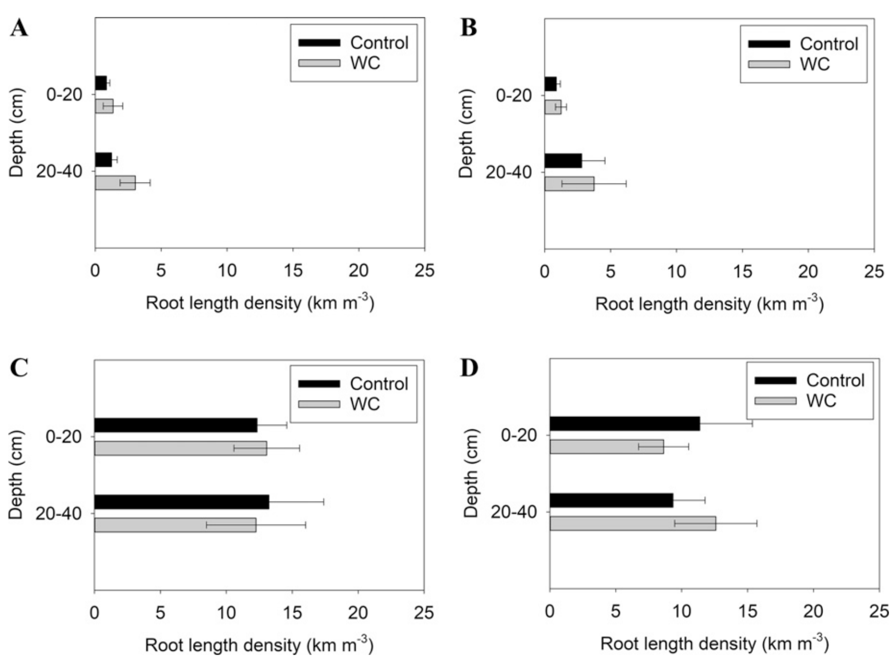

Fig. 3. Standing root length density ($km_{root\ length} \cdot m_{soil}^{-3}$) in the alleyway at 0–20 and 20–40 cm soil depth in (**A**) Jun 2019, (**B**) Sep 2019, (**C**) Jun 2020, and (**D**) Oct 2020 for almond trees on Viking rootstock. Wood chips (WCs) were incorporated in the soil in Sep 2017 and almond trees were planted in Jan 2018.

Six root architecture samples per treatment per block were collected from the berm 0.6 m away from the tree by lifting a large soil sample with a shovel (~0.30 m deep) in Feb and Sep 2019, and Jun and Oct 2020. From each sample we selected entire root branches that included at least five fine root orders. Each root branch was washed carefully with deionized water. The washed root branch was placed in a tray with deionized water and roots on each branch were separated by root order. All roots in each root order were scanned using WinRhizo Pro to measure length within each root order. We calculated proportional length and mass distribution (Lavely et al. 2020). Roots were dried at 70 °C to m dry mass and SRL (root length per root mass) was calculated for each root order.

Soil CO_2 efflux. Soil CO_2 efflux was measured with an LI8100A soil CO_2 flux survey chamber (LI-COR Biosciences, Lincoln, NE, USA) in May, Aug, Sep, and Oct in 2019 and Mar, Jun, and Oct in 2020. Soil collars (0.2 m diameter) were inserted 5 cm into the soil at 1.5 m from the tree trunk in both the berm and the alleyway at least 3 h before the flux measurement. Three replicate flux measurements each were conducted near three different trees in each experimental block between 9:00 AM and noon with rotation of control and WC block to minimize biasing treatments. Each replicate measurement cycle consisted of 90 s of observation, 30 s of dead ban, and 30 s of pre-purge period. Soil temperature was collected at the same time as the CO_2 flux measurement using a LI6000-09TC soil temperature probe at 15 cm depth.

Statistical analysis. For bulk density and gravimetric water content, we used a three-way analysis of variance (ANOVA) test with WC treatment, soil depth (0–20 and 20–40 cm), and sampling location (berm vs alleyway) as the main factors. As we sampled deeper in the berm location, we also conducted a two-way ANOVA for each location with WC treatment and soil depth as main factors.

To compare effects on root length and mass density across sampling locations we calculated RLD and RMD for the top 40 cm before statistical analysis and used a two-way ANOVA analysis using WC treatment and sampling location as the main factors. As we sampled deeper in the berm location, we also conducted a two-way ANOVA for each date with WC treatment and soil depth as main factors. For analysis of root architecture samples, we used a two-way ANOVA with WC treatment and root order as the main factors. We used a three-way ANOVA analysis using WC treatment, sampling location, and sampling time as the main factors to evaluate their effect on CO_2 efflux. A linear mixed model with block as a random effect was used to analyze the complete randomized block design. We used pairwise comparison of estimated marginal means to assess differences between treatment combinations at each sampling time point. A Pearson's correlation test was used to examine the relationships between gravimetric water contents and root

Table 3. Effects of wood chip treatment on root length density and root mass density averaged across 0–40-cm sampling depth at different sampling times (Jun 2019, Sep 2019, Jun 2020, and Oct 2020), and locations (planting berm and alleyway). Wood chips were incorporated into the soil in Sep 2017, and young almond trees were planted in Jan 2018. Bold numbers indicate statistically significant differences at $P < 0.05$ and italicized numbers indicate differences at $P < 0.010$.

		Root length density		Root mass density	
Year	Factors	F	*P*	F	*P*
Jun 2019	Treatment	1.20	0.333	3.98	0.116
	Location	22.20	**<0.001**	12.69	**0.002**
	Treatment × Location	0.78	0.387	1.81	0.196
Sep 2019	Treatment	0.49	0.520	0.03	0.859
	Location	14.19	**0.001**	3.55	*0.075*
	Treatment × Location	0.44	0.515	1.49	0.236
Jun 2020	Treatment	0.01	0.891	0.52	0.479
	Location	0.04	0.835	0.05	0.813
	Treatment × Location	0.02	0.865	0.64	0.430
Oct 2020	Treatment	0.46	0.505	0.19	0.679
	Location	1.19	0.289	0.64	0.434
	Treatment × Location	0.35	0.559	0.96	0.340

Table 4. Effects of wood chip treatment on root length density and root mass density in the planting berm at different sampling times (Jun 2019, Sep 2019, Jun 2020, and Oct 2020), and soil depths (0–20, 20–40, 40–60, and 60–80 cm). Wood chips were incorporated into the soil in Sep 2017, and young almond trees were planted in Jan 2018. Bold numbers indicate statistically significant differences at $P < 0.05$ and italicized numbers indicate differences at $P < 0.010$.

		Root length density		Root mass density	
Year	Factors	F	*P*	F	*P*
Jun 2019	Treatment	1.17	0.390	5.65	0.140
	Soil depth	5.35	**0.003**	7.37	**<0.001**
	Treatment × Soil depth	1.38	0.264	0.72	0.542
Sep 2019	Treatment	1.75	0.255	4.04	*0.051*
	Soil depth	1.90	0.146	3.83	**0.016**
	Treatment × Soil depth	1.25	0.302	1.04	0.381
Jun 2020	Treatment	0.41	0.521	0.15	0.700
	Soil depth	1.21	0.315	2.65	*0.061*
	Treatment × Soil depth	2.04	0.124	1.02	0.392
Oct 2020	Treatment	0.49	0.555	1.38	0.304
	Soil depth	3.28	**0.031**	4.57	**0.008**
	Treatment × Soil depth	0.67	0.571	0.46	0.708

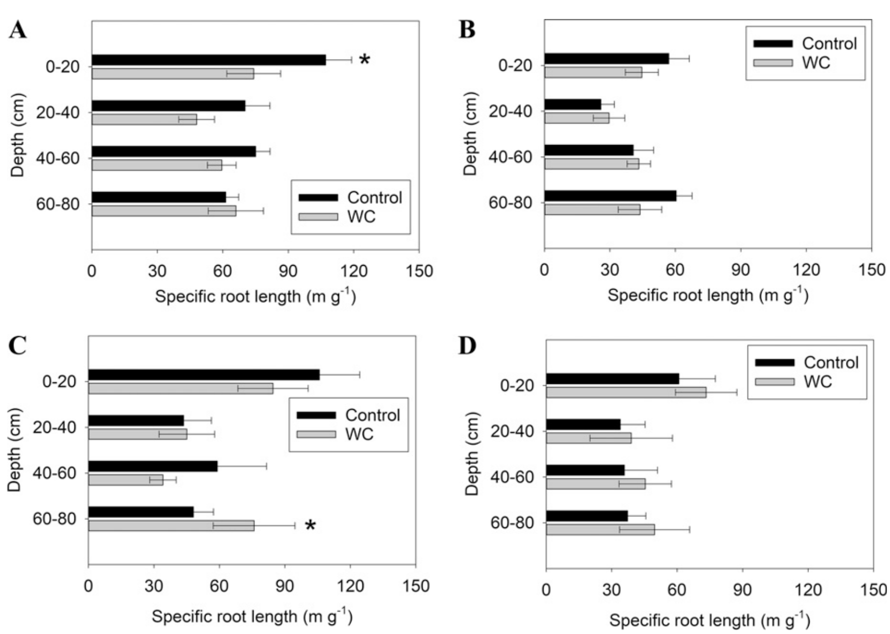

Fig. 4. Specific root length as affected by soil depth (0–20, 20–40, 40–60, and 60–80 cm) and treatment (control = no wood chips, WC = wood chips incorporated) in the berm in (**A**) Jun 2019, (**B**) Sep 2019, (**C**) Jun 2020, and (**D**) Oct 2020 for almond trees on Viking rootstock. WCs were incorporated in the soil in Sep 2017 and almond trees were planted in Jan 2018. *Indicates a significant effect of WC treatment at $P < 0.05$; + shows a significant effect of WC treatment at $P < 0.10$.

length/mass density. Statistical analyses were conducted using the R statistical package (version 4.0.2) and figures were created using Sigmaplot v.15 (Grafiti, Palo Alto, CA, USA).

Results

WC incorporation increased gravimetric water content in the top 40 cm of soil in the drip-irrigated berm (Tables 1 and 2), but not statistically significantly so in the nonirrigated alleyway ($P_{\mathrm{treatment} \times \mathrm{location}} = 0.004$, Table 2). Incorporation of WCs in the berm led to a 113%, 115%, and 72.5% increase in gravimetric water content in 0–20, 20–40, and 40–60-cm soil depths, respectively (Table 1). We did not find a statistically significant effect of WC incorporation on soil bulk density and there was no interaction effect of WC treatment, soil depth, and location (Tables 1 and 2).

In 2020, RLD was twice that of 2019 in both the berm (Fig. 2) and alleyway (Fig. 3). Averaged across all dates, both RLD and RMD in the top 40 cm of soil were greater in the berm than in the alleyway ($P = 0.014$, Table 3). In the berm, we found a marginally significant overall effect of WC incorporation in the topsoil (0 to 20) where RLD was more than doubled in Jun 2019, Sep 2019, and Jun 2020, and was increased by 60% in Oct 2020 ($P_{\mathrm{treatment} \times \mathrm{soil\ depth}} = 0.008$, Fig. 2, Table 4). Like RLD, RMD was greater in the berm than in the alleyway and RMD was significantly greater in 2020 than that in 2019 (Table 3, Supplemental Figs. 1 and 2). In the alleyway there were no significant effects of WC treatment and soil depth on RLD (Fig. 3, Table 4) or RMD (Supplemental Fig. 2, Table 4).

There were no consistent effects of WC treatment on SRL (root length per unit root mass, Figs. 4 and 5) or root diameter (Supplemental Figs. 3 and 4) in either the alleyway or the berm. More detailed architectural analysis of root branch samples collected from the berm showed that SRL within each root order was unaffected by WC treatment except in Sep 2019 where first order roots had a greater SRL in the WC treatment (127.7 $m \cdot g^{-1}$) than in the control treatment (112.6 $m \cdot g^{-1}$) (Fig. 6). We also did not find a consistent effect of WC on the diameter of roots within each order throughout the experimental period (Supplemental Fig. 5). Proportional root length/mass allocation to each root order was significantly different by root order ($P < 0.001$) and date (Fig. 7, Supplemental Fig. 6). Length allocation to the different orders was unaffected by incorporating WCs (Fig. 7), whereas on three out of four dates the allocation to the coarsest root order (fifth order) roots was significantly increased by incorporating WCs (Supplemental Fig. 6).

Soil CO_2 efflux in the berm was significantly greater in the WC-amended soil compared with nonamended soil ($P_{\mathrm{treatment} \times \mathrm{location}} = 0.002$, Fig. 8A, Table 5). In the berm, which received three times more WCs compared with the alleyway, the higher CO_2 flux in the WC-amended soil compared with the

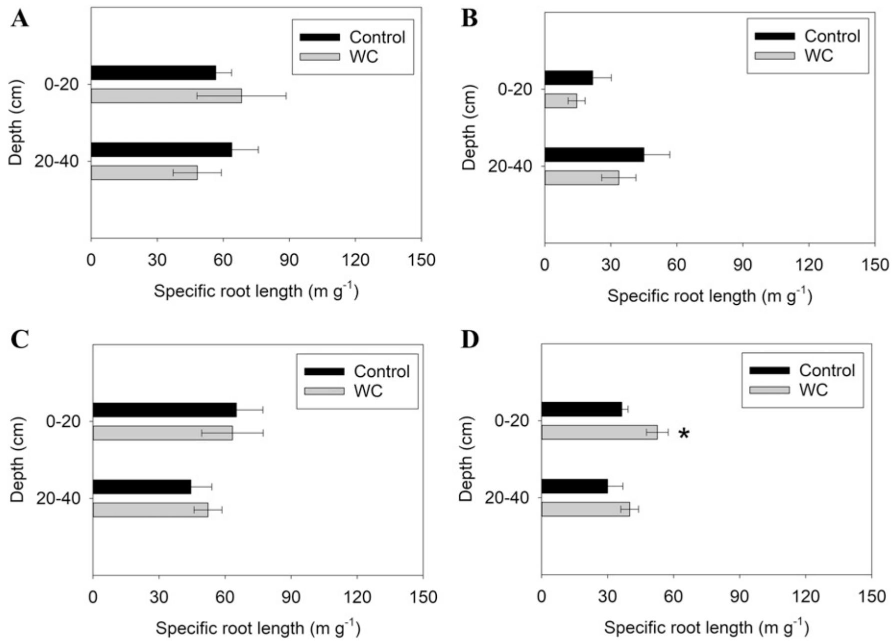

Fig. 5. Specific root length in alleyway at different soil depth (0–20 and 20–40 cm) in (**A**) Jun 2019, (**B**) Sep 2019, (**C**) Jun 2020, and (**D**) Oct 2020 for almond trees on Viking rootstock. Wood chips (WCs) were incorporated in the soil in Sep 2017 and almond trees were planted in Jan 2018. *Indicates a significant effect of WC treatment at $P < 0.05$; + shows a significant effect of WC treatment at $P < 0.10$.

nonamended soil remained for at least 3 years after WC incorporation (Fig. 8A). In the alleyway there was only a greater soil CO_2 efflux in the WC treatment in May 2019 and this difference was not found at later dates (Fig. 8B). For the dates where we also have standing RLD in the top 40 cm we found a correlation between RLD and soil CO_2 efflux in Jun and Oct 2020 (Supplemental Fig. 8, Supplemental Table 1), whereas CO_2 efflux was more strongly driven by soil temperature in Jun and Sep 2019. On both June dates, incorporating WCs led to higher CO_2 fluxes, independent of RLD and soil temperature (Supplemental Table 1, Supplemental Fig. 7).

Discussion

Standing RLD was unaffected by WC incorporation in the alleyways, whereas in the berm, standing RLD was on average 53% greater in the top 20 cm when WCs were incorporated into the soil. This increase in standing RLD is consistent with increased nutrient foraging as production of new fine lateral roots increases nutrient uptake capacity (McCormack et al. 2015; Volder et al. 2005). Increased root production is likely the result of both increased nitrogen demand and increased gravimetric water content in the WC-amended berm soil, as greater water availability in the soil system stimulates localized fine root length proliferation (Supplemental Table 2) (Eissenstat et al. 2015; Gloser et al. 2007, 2008; Pregitzer et al. 1993; Pritchard et al. 2010). Contrary to our expectations, we did not find that WC incorporation altered architectural traits of fine root branches growing in the berm. Incorporation of WCs did not alter SRL, fine root diameter, or proportional length allocation to fine root orders. Thus, we conclude that WC incorporation increased RLD solely through increased allocation of root mass per soil volume.

Jahanzad et al. (2022) found that WC incorporation increased nutrient immobilization, especially in the topsoil (0–15 cm). If not matched by adding external N, increased N immobilization can create temporary N limited conditions for plant growth, and these low N conditions can affect root system architecture (Kiba and Krapp 2016; Poirier et al. 2018; Postma and Lynch 2012). However, in our study, enough external N was applied in the first 3 years to compensate for potential N immobilization, and, when our samples were collected, soil N availability was increased by WC incorporation (Culumber and Gao 2022). The observed increase in fine RLD may have been driven by localized greater water and N availability and reduced localized soil strength from incorporating WCs. Many roots grew through the WC debris in our experiment (Fig. 9). As WCs decompose, the decomposing chips provide localized water retention and nutrient availability (Fahey et al. 1991) and a zone of decreased resistance to root expansion. We propose that adding WCs increases opportunities for roots to expand, even if overall bulk density of the larger soil sample was not statistically significantly decreased compared with samples without WCs. Other studies have also reported similar findings when they compared the effect of adding organic materials vs. adding the equivalent in nutrients on new root production. For example, Baldi et al. (2010) reported that adding organic fertilizer (compost from mixture of half domestic organic waste and half pruning materials) increased new root production and root life span in a nectarine (*Prunus dulcis* L.) orchard compared with adding mineral fertilizer.

Soil CO_2 flux is influenced by many different environmental factors such as soil temperature, soil moisture, substrate availability, and substrate quality, all of which affect the ability of microbes to break down organic matter (Conant et al. 2004). WC incorporation provides a great amount of C, which, when adequate soil moisture is available, is

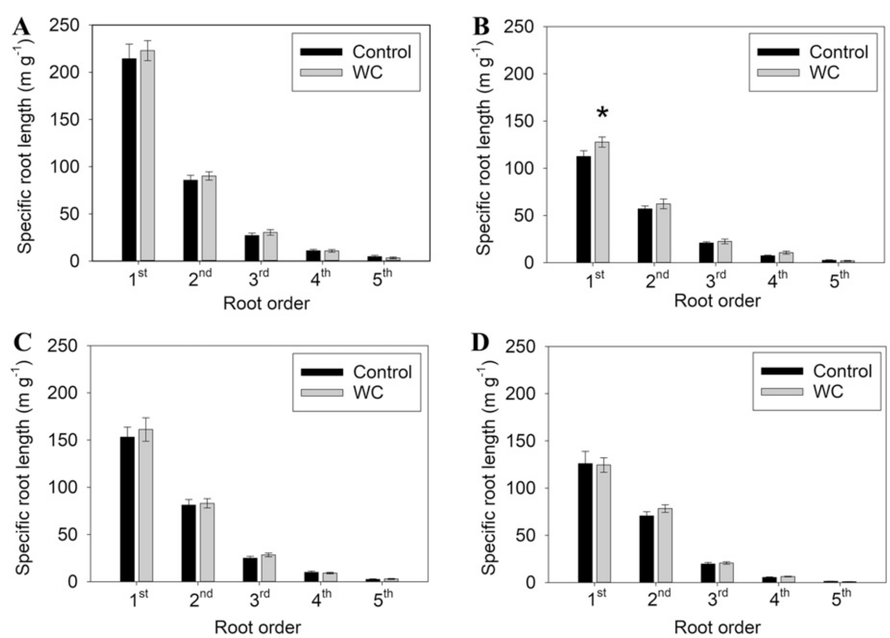

Fig. 6. Specific root length ($m_{root} \cdot g_{root}^{-1}$) for each root order for root branches with at least five root orders collected in the berm soil in (**A**) Feb 2019, (**B**) Sep 2019, (**C**) Jun 2020, and (**D**) Oct 2020 for almond trees on Viking rootstock. Wood chips (WCs) were incorporated in the soil in Sep 2017 and almond trees were planted in Jan 2018. *Indicates a statistically significant difference between WC treatment and control treatment at $P < 0.05$.

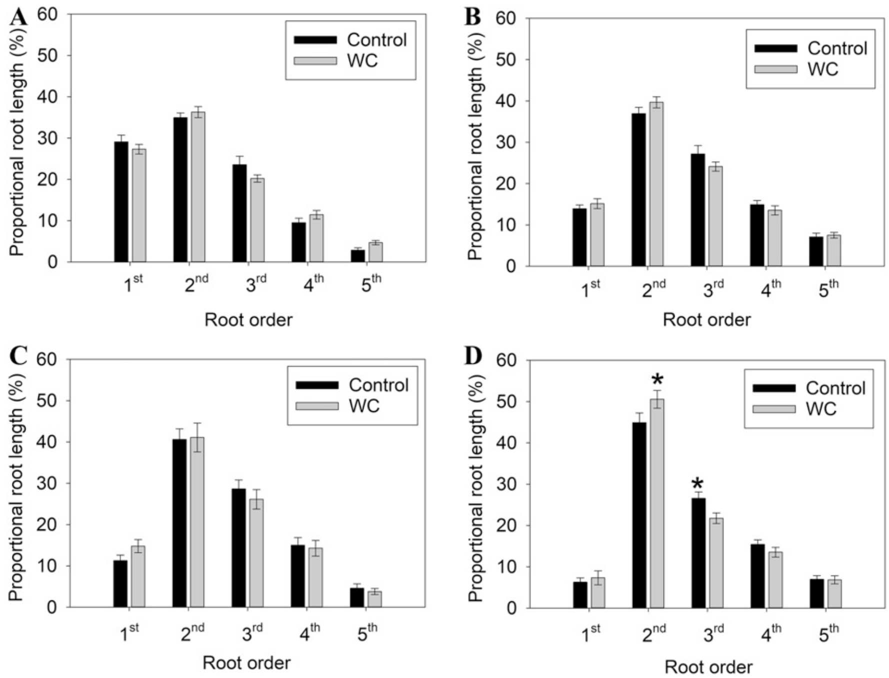

Fig. 7. The proportion of length allocated to each root order in either the control or wood chip (WC)-incorporated treatments in the berm in (**A**) Feb 2019, (**B**) Sep 2019, (**C**) Jun 2020, and (**D**) Oct 2020 for almond trees on Viking rootstock. WCs were incorporated in the soil in Sep 2017 and almond trees were planted in Jan 2018. Note that the scale is increased in (**D**). *Indicates a statistically significant difference between WC treatment and control treatment at $P < 0.05$.

Table 5. Results for effects of wood chip treatment on soil CO_2 efflux in the planting berm and alleyway (location) and at different dates (time) (May 2019, Aug 2019, Sep 2019, Oct 2019, Mar 2020, Jun 2020, and Oct 2020). Wood chips were incorporated into the soil in Sep 2017, and young almond trees were planted in Jan 2018. Bold numbers indicate statistically significant differences at $P < 0.05$, $*P < 0.05$, $**P < 0.01$, and $***P < 0.001$.

	Soil CO_2 flux	
	χ^2	P value
Treatment	3.15	0.076
Location	0.229	0.632
Time	37.9	**<0.001*****
Treatment × Location	9.58	**0.002****
Treatment × Time	13.0	**0.042***
Location × Time	17.3	**0.008****
Treatment × Location × Time	5.92	0.432

the most limiting factor for microbial growth in many arid and semiarid regions such as California (Fontaine and Barot 2005; Johnston et al. 2004; Yazdanpanah et al. 2016). Thus, we expected that WC incorporation would have a particularly strong impact in the berm where WCs were incorporated in the top 0.9 m of soil, and drip irrigation was applied. The differences in soil CO_2 flux between the control and WC-incorporated soil in the berm decreased over time as the WCs decomposed. Root respiration also releases substantial amounts of CO_2, depending on root density, soil temperature, and root nitrogen concentration (Burton et al. 2002; Ceccon et al. 2016; Kelting et al. 1998; Pregitzer et al. 1998) In our study, we found that even with RLD significantly greater in the WC treatment, there was no difference in soil CO_2 flux between the control and WC treatment at the end of the observation period, suggesting that root respiration was only a minor component of soil CO_2 efflux in our system at the times we measured CO_2 flux, which may have missed the times when roots are most active. For example, Buchmann (2000) reported that significant root respiration in *Picea abies* stands was only detectable at times of peak root production when a larger proportion of the root system is young and metabolically active (Volder et al. 2005). However, we had still expected greater soil CO_2 flux in the WC treatments as large fragments of WCs were still visible at the end of 2020, and thus more substrates would have been available for microbial breakdown. One explanation could be that the microbial community composition changed in response to adding substrate with a high C:N ratio. Adding organic amendments with a high C:N ratio can increase fungi-to-bacteria ratio (Faust et al. 2017), which may have also led to a relative slowdown in CO_2 efflux rate in the WC treatment compared with the control as fungi are less metabolically active than bacteria.

Conclusion

Following our hypothesis, we found that WC incorporation in the planting berms induced greater root length and root mass production in the topsoil, increased gravimetric soil water content, and increased soil CO_2 flux. However, we did not find similar responses in the alleyway. Contrary to our expectations, incorporating WCs into the orchard soil (berm or alleyway) did not alter root architectural traits. We did not find an increase in SRL or a shift in biomass allocation to the

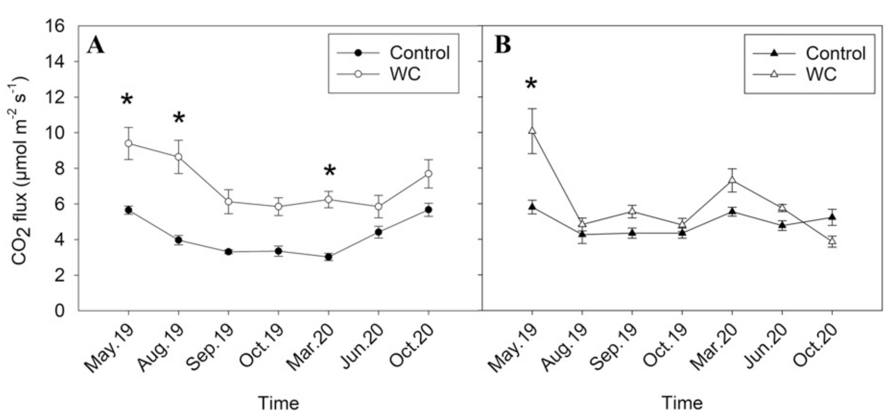

Fig. 8. Soil CO_2 efflux from wood chip (WC)-incorporated soils (opened symbol) and control/no WC soils (closed symbols) in (**A**) planting berm and (**B**) alleyway through time in 2019 and 2020. WCs were incorporated in the soil in Sep 2017 and almond trees were planted in Jan 2018. *Indicates a significant effect of WC treatment at $P < 0.05$.

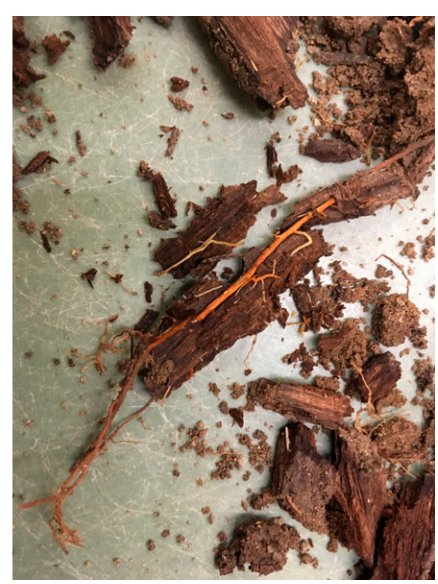

Fig. 9. Fine roots growing through the wood chip debris.

production of first and second order roots. The positive effects of incorporating WCs on soil bulk density, soil gravimetric water content, and root production in this orchard show that incorporating WCs before planting is a practical solution to recycle old orchards and reduce the greenhouse gas emissions associated with burning. As positive effects of WC incorporation on root growth were linked to increased gravimetric water content, the method of irrigation (drip line) was likely strongly impacting our lack of findings in the alleyway. The drip irrigation was limited to the berm only, and future studies on maximizing the beneficial impact of WC incorporation should include irrigation practices that wet a larger area, for example, (micro)sprinkler irrigation or even flood irrigation.

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