Phosphorus Fertilization Can Improve Young Almond Tree Growth in Multiple Replant Settings

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KEYWORDS. fumigation, *Prunus amygdalus*, soil

ABSTRACT. Young almond (*Prunus amygdalus*) orchards replanted where old orchards of stone fruits (*Prunus* sp.) have been removed are subject to physical, chemical, and biotic stressors. Among biotic challenges, for example, is almond/stone fruit replant disease (ARD; formally known as Prunus replant disease), which specifically suppresses the growth and yields of successive almond and other stone fruit plantings and is caused, in part, by a soil microbial complex. During four orchard trials representing different almond replant practices and scenarios in the San Joaquin Valley in California, we examined the impacts of phosphorus (P) fertilization on the growth of replanted almond. During all trials, P was applied to tree root zones just after replanting, and the impact was assessed according to trunk cross-sectional area (TCSA) growth for 2 years. Expt. 1 was performed where a previous almond orchard was cleared using whole orchard recycling (i.e., the old orchard was "chipped" and then turned into the soil). The land was replanted without preplant soil fumigation. We tested separate fertilizer treatments based on various P, nitrogen, micronutrient, and "complete" formulations. Expt. 2 was also performed where an old almond orchard was recycled, but the soil was preplant-fumigated before replanting. Here, we tested only P fertilization. Expts. 3 and 4 were conducted where an old peach (*Prunus persica*) orchard was removed. Here, P and nitrogen fertilizer treatments were tested among additional factors, including preplant soil fumigation (Expts. 3, 4) and whole orchard recycling chips (Expt. 4). During all four trials, P fertilization (P at 2.2 to 2.6 oz/tree within a few weeks after planting) significantly increased TCSA growth. The growth benefit was nuanced, however, by almond cultivar, date of replanting, rootstock, and other site-specific factors. Although P fertilization did not match the benefit of preplant soil fumigation for the management of ARD, our data indicated that P fertilization can improve the growth of young almond orchards in diverse replant settings with or without preplant soil fumigation and should be considered by California almond producers as a general best management practice.

Phosphorus (P) has been studied widely in agriculture because of its critical role as a plant macronutrient and positive effect on the yield of many crops (Weeks and Hettiarachchi 2019). In plants, P is an integral component of nucleic acids and phospholipids, and it contributes essentially to many enzymatic reactions, including those involved in cellular energy transfer (Hawkesford et al. 2011). There is increasing concern regarding the contribution of P to eutrophication of water bodies (Weeks and Hettiarachchi 2019).

Deciduous fruit and nut tree responses to P fertilization have been mixed, especially in established orchards of crop-bearing age. Leaves displaying P deficiency symptoms were rare in commercial orchards (Brown and Uriu 1996; Cullinan and Batjer 1943; Overcash et al. 1960), suggesting that orchards were seldom P-deficient. The P fertilization trials in bearing orchards often demonstrated little to no response in yield (Klein et al. 1999; Polozola et al. 2019), although increased leaf P levels were sometimes measured (Ferreira et al. 2018; Leece 1976). It was stated that there is no reason to apply P fertilizer to almond (*Prunus amygdalus*) orchards other than to supply the needs of a cover crop (Carlson 1996). In established orchards, the common lack of response to applied P may be caused by the large, permanent root systems as well as mycorrhizal infections, which are known to aid trees with uptake of the element (Azcon-Aguilar and Barea 1997; Plassard and Dell 2010). Many deciduous tree fruit species grown in California export low rates of P in comparison with nitrogen (N) and potassium (K) (Muhammad et al. 2015), ranging from 1 lb/ton P in peaches (*Prunus persica*) to 18 lb/ton P in almond kernels (California Department of Food and Agriculture 2023).

However, positive responses of orchards to P fertilization were documented in soils prone to P deficiency (Cripps 1987), in young fruit trees (Balal et al. 2011; Ferreira et al. 2018; Keatley et al. 1968; Neilsen et al. 1993, 1994; Overcash et al. 1960; Taylor 1975; van den Ende and Taylor 1969), and, sometimes, in bearing orchards (Crane 1924; Keatley et al. 1968; Overcash et al. 1960), although results reported by Crane (1924) and Overcash et al. (1960) varied by location. Additionally, P fertilization was investigated in the context of apple (*Malus domestica*) replant disease; in a replant setting, combining P fertilization and preplant soil biocidal treatments increased apple tree growth and early fruit yield, but P fertilization alone was less effective (Neilsen and Yorston 1991). Sewell et al. (1988) reported that in apple replant soil, potted apple seedlings grew better after P applications, but the response occurred only in soils that had been fumigated. They observed that none of the seedlings growing in fumigated soil had

Units

To convert U.S. to SI, multiply by	U.S. unit	SI unit	To convert SI to U.S., multiply by
0.4047	acre(s)	ha	2.4711
0.3048	ft	m	3.2808
2.54	inch(es)	cm	0.3937
6.4516	$inch^2$	cm^2	0.1550
1.1209	lb/acre	$kg\cdot ha^{-1}$	0.8922
0.5	lb/ton	$kg\cdot t^{-1}$	2
1	mEq/100 g	$cmol\cdot kg^{-1}$	1
1	mmho/cm	$dS\cdot m^{-1}$	1
28.3495	oz	g	0.0353
1	ppm	$mg\cdot kg^{-1}$	1
2.2417	ton(s)/acre	$t\cdot ha^{-1}$	0.4461

mycorrhizae infections, whereas all the seedlings growing in unfumigated soil had mycorrhizae (Sewell et al. 1988). The authors concluded that trees growing in unfumigated soil were able to obtain sufficient P through mycorrhizae. Many of the cited orchard studies involved trees planted in pots (Ferreira et al. 2018; Neilsen et al. 1993, 1994; van den Ende and Taylor 1969) and may not adequately reflect in-field responses to P fertilization.

Although P fertilization is not generally recommended for almond in California, there are reasons to re-examine the stance, particularly in replant settings. California has hosted 1,350,000 acres of harvested almonds (US Department of Agriculture, National Agricultural Statistics Service 2022). Each year, tens of thousands of acres of the oldest orchards must be replanted to remain economically productive. It is these replant settings in which growers are most likely to consider and inquire about potential benefits P fertilization, especially as they adapt to environmentally minded and state-mandated changes in soil management practices.

Two of the most important soil management practices used in California almond production are whole orchard recycling (WOR), which involves "chipping" or grinding old orchard residues and returning them to the soil instead of burning them (Holtz 2017), and preplant soil fumigation, which is often used after orchard removal to prevent biological replant problems such as almond/stone fruit replant disease (ARD; formally referred to as Prunus replant disease) (Browne et al. 2006, 2013). In the San Joaquin Valley, burning of old removed orchards is not generally permitted, and WOR has become widespread. During one study, WOR added ~74 t·ha^{-1} organic matter and increased almond yields, soil organic matter, soil water retention, and soil water infiltration (Jahanzad et al. 2020). Nevertheless, it was concluded that, for adequate performance, trees planted in soil after WOR may require greater amounts of N fertilizer during their first year compared with plantings in soil without WOR because of the potential temporary N immobilization by the high carbon:N ratio of WOR residues (Jahanzad et al. 2020). N is the only macronutrient recommended for fertilization of nonbearing almond trees (Jarvis-Shean et al. 2018), but it is reasonable to consider whether P fertilization may also be needed, and whether WOR recycling residues may affect this need. The micronutrient zinc is commonly deficient in young orchards of California, and it is often applied in foliar treatments. ARD specifically suppresses growth and yields of successive almond and other stone fruit plantings and is induced, in part, by a soilborne microbial complex (Browne et al. 2006, 2013). Preplant soil fumigation is increasingly regulated in the San Joaquin Valley, and the almond industry is exploring amendment and fertilizer-based approaches, in which P fertilization could be a component, to supplant reliance on fumigation.

We report the first-year and second-year responses to P fertilizer treatments during four almond replant experiments. The experiments were designed to test a hypothesis that fertilization with P can improve tree growth in young replanted almond orchards and were a response to growers and industry consultants who strongly believed that such orchards benefit from P fertilization, despite the lack of research on the topic. Replant settings were chosen for our P experiments because they may limit P uptake potential of the tree; the young root systems have not thoroughly explored the soil to access the relatively nonmobile nutrient, and, where present, ARD may additionally compromise P access because the disease reduces root length density (Browne et al. 2006). Collectively, our trials tested P fertilization treatments in the following contexts: with and/or without WOR involved, with and/or without preplant soil fumigation involved, and in comparison with other fertilizer treatments or combinations involving N, K, micronutrients, and complete fertilizer formulations.

Materials and methods

Trials overview. Trials are outlined in Tables 1 and 2. They included two grower-hosted experiments, Expt. 1, planted in 2019, west of Chowchilla, CA, USA (lat. 37°3′15.27″N, long. 120°17′48.90″W), and Expt. 2, planted in 2021, east of Chowchilla (lat. 37°06′55.65″N, long. 120°05′31.48″W); additionally, two experiment station trials, Expts. 3 and 4, were planted in 2021 adjacent to one another at the University of California Kearney Agricultural Research and Extension Center near Parlier, CA, USA (lat. 36°35′54.09″N, long. 119°31′3.95″W). The trials collectively tested P fertilization treatments under multiple replant scenarios that are commonly encountered by almond growers in the San Joaquin Valley.

Soils and preplant management practices. Multiple sandy loam soils were represented among the trials. Pachappa fine sandy loam predominated in Expt. 1, with a streak of Tujunga loamy sand running through approximately one-third of the area. San Joaquin sandy loam and Ramona sandy loam were represented in similar proportions in Expt. 2. Hanford sandy loam and Hanford fine sandy loam soil were represented in both Expts. 3 and 4. In Expt. 1, soil samples were obtained before experimental fertilizer treatments were applied from 15 to 45 cm below the soil surface to avoid a recently tilled layer. In Expts. 2 to 4, soil samples were collected before fertilization treatments from depths of 0 to 30 cm and 30 to 60 cm. Physicochemical properties of the samples were determined by Ward Laboratories (Kearney, NE, USA) for Expts. 1, 3, and 4, and by Delavalle Laboratories (Fresno, CA, USA) for Expt. 2 (Table 3).

All four experiments occurred in orchards that were replanted after removal of a preceding stone fruit or nut orchard (almond in Expts. 1 and

Received for publication 4 Oct 2022. Accepted for publication 27 Sep 2023.

Published online 16 Feb 2024.

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This project was partially funded by the Almond Board of California. We are grateful to Dan Spalding and Vincent Silva for infrastructure support at the University of California Kearney Agricultural Research and Extension Center, and to Gary Cornaggia and Daniel Hui for hosting grower trials. Mention of a trade name or trademark does not constitute a recommendation or endorsement by the authors or their institution and is mentioned solely to report research results.

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https://doi.org/10.21273/HORTTECH05143-22

Table 1. Features of orchard replant Expts. 1 to 4.

Expt.	Soil management before replanting	Replanted cultivars (and rootstock)	Orchard replanting date(s)
1	Whole orchard recycling (WOR)	'Butte', 'Padre' ('Nemaguard')	Mar 2019
2	WOR, shank fumigation	'Nonpareil', 'Monterey' ('Viking')	Nov 2020 ('Monterey'), Feb 2021 ('Nonpareil')
3	Burned old orchard residues in place, shank fumigation and control treatments applied in mainplots	'Nonpareil', 'Monterey' ('Nemaguard')	May 2021
4	Burned old orchard residues in place, WOR and control treatments in mainplots, shank fumigation and control treatments applied in subplots	'Nonpareil', 'Monterey' ('Nemaguard')	May 2021

2, peach in Expts. 3 and 4). In all cases, the preceding rootstock was 'Nemaguard' (*P. persica*). Management practices used for old orchard removal and soil remediation before replanting varied by experiment (Table 1). Before orchards used for Expts. 1 and 2 were planted, the hosting growers had implemented WOR for removal of the old orchards; therefore, WOR was an existing condition in these trials, not an experimental variable. Before planting trees used for Expts. 3 and 4, the old orchard trees had been excavated and burned in place. In addition, for Expt. 4, simulated WOR was included as an experimental variable by adding almond orchard chips from an external source to replicated plots as detailed below (fertilizer treatments and experimental designs). Preplant soil fumigation was not used for Expt. 1, but it was included throughout land used for Expt. 2; a conventional fumigant mixture was shank-applied to soil in 11.7-ft-wide strips centered over future tree rows (332 lb/acre 1,3-dichloropropene + 200 lb/acre chloropicrin) by TriCal Inc. (Hollister, CA, USA). In Expts. 3 and 4, the same preplant soil fumigation treatment was included as an experimental factor as detailed here (Fertilizer treatments and experimental designs).

Orchard designs and planting. The trials generally represented cultivars, rootstocks, and other features commonly used for almonds in the San Joaquin Valley (Table 1). In Expt. 1, bare-root trees were planted in Mar 2019; single trees of 'Butte' and 'Padre', both on Nemaguard rootstock, were alternated in each tree row. The rows and trees were spaced 20 ft and 14 ft apart, respectively (156 trees/acre), and microsprinkler irrigation was used (one emitter per tree, between trees, down rows). In Expt. 2, alternating rows of 'Monterey' and 'Nonpareil' potted trees on Viking rootstock {*P. persica* × [*Prunus dulcis* × (*Prunus cerasifera* × *Prunus mume*)]} were planted in Nov 2020 and Feb 2021, respectively. Expt. 2 rows and trees were 21 ft and 16 ft apart, respectively (130 trees/acre), and tree rows were irrigated with dual drip lines. In Expts. 3 and 4, potted trees of 'Nonpareil' and 'Monterey' on Nemaguard rootstock were planted alternately in each row in May 2021; the rows and trees were 19 ft and 10 ft apart, respectively (229 trees/acre), and rows were irrigated with dual drip lines.

Fertilizer treatments and experimental designs. The P fertilizer formulation common to all experiments was granular triple super phosphate (0N–19.6P–0K; TSI; The Tremont Group Inc., Woodland, CA, USA) (Table 2). Additionally, granular urea (46N–0P–0K; UMaxx; Koch Agronomic Services, Wichita, KS, USA) was used in Expts. 1, 3, and 4. Triple 15 (15N–6.5P–15K; YaraMila 15–15–15; Yara North America, Tampa, FL, USA), a complete slow-release fertilizer with micronutrients (15N–3.9P–10K; Osmocote Plus; The Scotts Company, Marysville, OH, USA), and a slow-release micronutrient fertilizer (MEG-IRON V Micro Nutrient Mix; Florikan, Sarasota, FL, USA) were used in Expt. 1. The amounts, application schedules, and treatment abbreviations used for each formulation treatment are outlined (Table 2).

In Expt. 1, fertilizer treatments, including a control ("Ctl"), were assigned randomly to four-tree plots (continuous sections of tree row including two 'Butte' and two 'Padre' trees) in a randomized complete block design. There were four replicate blocks, each within a different tree row, for a total of 16 trees per fertilizer treatment. The control in Expt. 1, applied by the grower to all trees, included 10.5 lb/acre N in 32N–0P–0K through the irrigation system and 1 lb/acre N, 2.1 lb/acre P, and 4.3 lb/acre K split into two foliar spray applications. A substantial proportion of the grower-applied fertilizer nutrients was not considered to be accessible to the trees because of the application methods and small size of the trees and their root systems. All the experimental fertilizer treatments were applied within the expanding root zone in soil wetted by microsprinklers, evenly on both sides of each tree, 30 cm from the tree trunk, and in the soil at a depth of 15 cm. The "+P", "+NPK", and "+N" applications were divided into five portions applied ~1 month apart (Table 2). The "+NPK, +micros" and "+Micros" treatments were administered as a single application in Apr 2019. Effects of the Expt. 1 treatments were assessed according to tree trunk growth measurements taken at ~50 cm above the soil line; trunk diameters measured

Table 2. Experimental fertilizer treatments tested in orchard replant Expts. 1 to 4. Depending on the experiment, the fertilizer treatments were applied to replicate plots (Expts. 1 and 2), sub-plots (Expt. 3), or sub-sub plots (Expt. 4) within weeks after orchard replanting.[i]

Expt.	Formulation(s) (and treatment abbreviation)	Oz of formulation per tree per application[ii]	Number of applications	Total treatment nutrient amount applied per tree (oz) [iii]			
				N	P	K	Other
1	None (Ctl)	None	0	0.0	0.0	0.0	0.0
	0N–19.6P–0K (+P)	2.2	5	0.0	2.2	0.0	0.0
	15N–6.5P–12.4K (+NPK)	6.7	5	5.0	2.2	4.1	0.0
	15N–3.9P–10K + micronutrients (+NPK, +micros)	40.0	1	6.0	1.6	4.0	0.5 Mg, 2.4 S, 0.007 B, 0.02 Cu, 0.18 Fe, 0.02 Mn, 0.007 Mo, 0.02 Zn
	46N–0P–0K (+N)	2.2	5	5.0	0.0	0.0	0.0
	Micronutrients (+Micros)	2.7	1	0.0	0.0	0.0	0.1 Ca, 0.3 Mg, 0.01 Cu, 0.1 Fe, 0.03 Mn, 0.02 Zn, <0.001 B
2	Control (Ctl)	None	0	0.0	0.0	0.0	0.0
	0N–19.6P–0K (+P)	13.3	1	0.0	2.6	0.0	0.0
3	46N–0P–0K (Std_N)	0.5	14	3.5	0.0	0.0	0.0
	46N–0P–0K + 0N–19.6P–0K (Std_N+P)	0.5 +2.2, 11.0	14 +1, 1	3.5	2.6	0.0	0.0
	46N–0P–0K (High_N)	0.5, 1.1	6, 8	5.5	0.0	0.0	0.0
4	46N–0P–0K (Std_N)	0.5	14	3.5	0	0	0.0
	46N–0P–0K + 0N–19.6P–0K (Std_N+P)	0.5 +2.2, 11.0	14 +1, 1	3.5	2.6	0	0.0
	46N–0P–0K (High_N)	0.5, 1.1	6, 8	5.5	0	0	0.0

[i] The fertilizer treatments were applied to soil within 30 cm (11.8 inches) of the tree trunks, split evenly between two sides of each tree. All fertilizer treatments used uncoated dry granular formulations, except "NPK+micros", which had a coated slow-release formulation. Expt. 1 and 2 fertilizer treatments were applied in addition to standard grower fertilization practices. In Expt. 1, the grower applied irrigation fertilizer applications that supplied nitrogen (N) at a total of 10.5 lbs/acre and two foliar sprays that supplied a total of: N at 1 lb/acre, phophours (P) at 2.1 lb/acre, and potassium (K) at 4.3 lb/acre. In Expt. 2 the grower incorporated chicken manure [6500 lb/acre; approximately 65 lb/acre nitrogen (N), 30 lb/acre phosphorus (P), and 70 lb/acre potassium (K)] into the soil in fall 2020 and applied calcium ammonium nitrate (20 lb/acre N and 7.5 lb/acre calcium) through the drip irrigation system during the 2021 growing season. Expts. 3 and 4 received only the fertilizer treatments in the table. 1 lb/ac = 1.12 $kg\cdot ha^{-1}$.

[ii] When two different application amounts are indicated for a formulation component of a treatment, the order of application amounts corresponds to the order of the number of applications indicated in the next column. 1 oz = 28.3 g.

[iii] Abbreviations used as follows: nitrogen (N), phosphorus (P), and potassium (K). 1 oz = 28.3 g.

Table 3. Properties of soils at sites in California used for almond orchard replant experiments.[i]

Expt.	Soil series	Sampling depth (cm)[ii]	pH	EC ($dS\cdot m^{-1}$)[ii]	Total N (ppm)[ii]	NO_3^- (ppm)[ii]	NH_4^+ (ppm)[ii]	Olsen P (ppm)[ii]	Exch. K (ppm)[ii]	Exch. Ca (ppm)[ii]	Exch. Mg (ppm)[ii]	Exch. Na (ppm)[ii]	CEC (mEq/L00 g)[ii]	Org. C (%)[ii]
1	Composite[iii]	15–45	6.6	0.08	440	3	0.6	11	65	1001	125	82	7	0.49
2	San Joaquin	0–30	7.3	1.71	NA	2	NA	18	95	1810	113	43	10	NA
		30–60	7.2	2.27	NA	2	NA	17	85	1650	125	51	10	NA
	Ramona	0–30	7.2	3.25	NA	7	NA	31	220	1880	198	41	12	NA
		30–60	7.2	2.37	NA	8	NA	22	153	1840	238	48	12	NA
3	Hanford	0–30	7.7	0.26	598	11	1.4	16	93	1440	237	41	10	0.73
		30–60	7.9	0.21	195	14	0.5	9	61	1467	244	52	10	0.19
4	Hanford	0–30	7.5	0.16	611	12	2.9	13	92	1051	181	31	7	0.60
		30–60	7.8	0.11	227	12	4.3	12	61	896	161	32	6	0.18

[i] For each experiment, soil samples were collected from indicated depths before fertilizer treatments were applied. Results were averages from three composited soil samples per block for Expt. 1, five composited soil samples per soil series and depth for Expt. 2, and two composited subsamples per main plot and soil depth in Expts. 3 and 4. Soil analyses for Expts. 1, 3, and 4 were conducted by Ward Laboratories (Kearney, NE, USA). Soil analyses for Expt. 2 were conducted by Delevale Laboratories (Fresno, CA, USA).

[ii] Ca = calcium; CEC = cation exchange capacity; EC = electrical conductivity; Exch. = exchangeable; K = potassium; Mg = magnesium; N = nitrogen; Na = sodium; NA = not available; NH_4^+, ammonium; NO_3^- = nitrate; Org. C = organic carbon; P = phosphorus; 1 cm = 0.3937 inch, 1 $dS\cdot m^{-1}$ = 1 mmho/cm, 1 ppm = 1 $mg\cdot kg^{-1}$, 1 mEq/100 g = 1 $cmol\cdot kg^{-1}$.

[iii] Pooled from Pachappa and Tujunga series soils.

just before fertilizer treatments in Apr 2019 and trunk circumferences measured in Oct 2019, Jan 2021, and Aug 2022 were used to calculate corresponding increases in the trunk cross-sectional area (TCSA). TCSA was chosen as a measure of tree growth because of its correlation with aboveground biomass (Westwood and Roberts 1970) and the relative ease of collecting the data compared with leaf area or light interception data. Additionally, much of the work involving P fertilization examined trunk parameters (Ferreira et al. 2018; Keatley et al. 1968; Taylor 1975; van den Ende and Taylor 1969). Leaves were sampled from both scion cultivars in all replicate fertilizer plots in Jul and Sep 2019. The leaves from both cultivars were combined to analyze the nutrient content by Delavalle Laboratories using the automated combustion method for total N and the nitric/perchloric acid digestion method for other macronutrients and micronutrients (Miller et al. 2013).

In Expt. 2, "Ctl" and "+P" treatments were assigned to three-tree plots within two rows of 'Monterey' and two rows of 'Nonpareil' trees using a randomized complete block design for each cultivar (Table 2). Each of the rows contained four blocks of the fertilizer treatment plots, with two situated on the Ramona series soil and two on the San Joaquin series soil. For each cultivar, there were 24 trees assigned per fertilizer treatment (12 in each soil series). The "Ctl" and "+P" plots had both received grower-applied and incorporated composted chicken manure in Fall 2020 before planting (6500 lb/acre, which included ~65 lb/acre N, 30 lb/acre P, and 70 lb/acre K). Additionally, over the 2021 growing season, "Ctl" and "+P" plots received grower-applied calcium (Ca) ammonium nitrate formulation (17N–0P–0K) that contained ~20 lb/acre N and ~7.5 lb/acre Ca). The experimental P treatment was applied once in Mar 2021 using the same formulation and placement as in Expt. 1; it provided 2.6 oz/tree P (Table 2). Effects of the Expt. 2 treatments were assessed according to increases in TCSA, calculated using trunk diameter measurements just before P treatments were applied, trunk diameter measurements in Jan 2022, and trunk circumference measurements in Aug 2022. The leaf nutrient content was not assessed during this experiment.

In Expt. 3, N and P fertilizer treatments were incorporated into subplots of a split plot design. Main plots consisting of 15-tree sections of tree rows were allocated to fumigation treatments (a control that was shanked but nonfumigated and a preplant shank fumigation treatment) that were arranged in four randomized complete blocks. Details of the shank fumigation treatment were listed previously (Soils and preplant management practices). Three fertilizer treatments, "Std N," "Std N+P," and "High N," as detailed in Table 2, were assigned randomly to four-tree subplots (two trees of 'Monterey' and two of 'Nonpareil') within each nonfumigated (control) and fumigated main plot. Fertilizer treatments began in early June and included 14 applications of N (applied weekly during the 2021 growing season) and two applications of P (both applied during the first half of Jun 2021). Fertilizer formulations and placement (i.e., on each side of each tree) were as described for Expts. 1 and 2, except that applications of N were applied on the soil surface and followed immediately by irrigation. Fertilizer application zones were straddled and wetted by the dual drip line irrigation system. Impacts of the fertilizer treatments on tree growth were assessed according to measurements on tree trunks at 50 cm above the soil line; stem diameters in May and Oct 2021 and circumferences in Aug 2022 were used to calculate increases in TCSA from the time of planting. The leaf nutrient content was not assessed during this experiment.

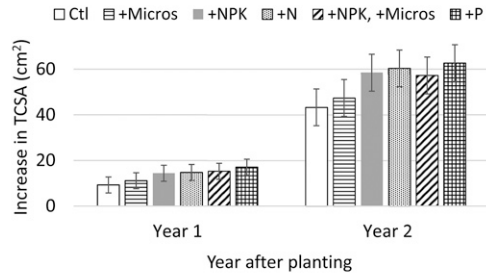

Fig. 1. 'Padre' almond trunk cross-sectional area (TCSA) gain in years 1 and 2 after planting as a function of fertilization treatment during the first year after planting (Expt. 1). The treatments, in order of abbreviations in the legend, were as follows: no fertilizer control (Ctl); 2.7 oz/tree of a micronutrient-only treatment (+Micros); 33.5 oz/tree of 15N–6.5P–12.4K (+NPK); 11 oz/tree of 46N–0P–0K (+N); 40 oz/tree of slow-release 15N–3.9P–10K plus micronutrient blend (+NPK, +micros); and 11 oz/tree of 0N–19.6P–0K (+P). The treatments were split evenly between two sides of each tree and applied within 30 cm (11.8 inches) of the tree trunk and at a depth of 15 cm (5.9 inches) in soil. All treatments were applied in addition to the resident grower fertilization practice, which included: 10.5 lb/acre nitrogen (N) in the form of 32N–0P–0K fertilizer through the irrigation system and 1 lb/acre N, 2.1 lb/acre phosphorus, and 4.3 lb/acre potassium split into two foliar sprays. Error bars are 95% confidence intervals. 1 oz = 28.3495 g; 1 lb/acre = 1.1209 kg·ha^{-1}; 1 cm^2 = 0.1550 inch^2.

In Expt. 4, the same fertilizer treatments as used in Expt. 3 were incorporated into a split-split plot design that included WOR treatment main plots and fumigation treatment subplots (Table 2). The main plot treatments (nontreated control vs. WOR chips applied at ~61 tons/acre incorporated to a soil depth of 4 inches) were assigned randomly to 30-tree rows randomized in four complete blocks. The subplot treatments (nonfumigated control vs. preplant fumigation applied as specified for Expt. 3) were assigned randomly to contiguous 15-tree halves of each main plot. Within each subplot, four-tree sub-subplots were randomly assigned to the fertilizer treatments (Table 2). Fertilizer application methods, irrigation, and tree growth response assessments were as described for Expt. 3. The leaf nutrient content was not assessed in this experiment.

Data analyses. Increases in TCSA were subjected to an analysis of variance (ANOVA) using PROC MIXED of SAS/STAT software (version 9.4 for Windows; SAS Institute Inc., Cary, NC, USA). When *P* values indicated significant effects of treatments ($P \leq 0.05$), means were separated according to the 95% confidence intervals generated by PROC MIXED. Before the ANOVA, PROC MEANS of the SAS software was used to average data over the subsamples (i.e., the individual trees within experimental units). PROC MIXED was performed for each almond cultivar separately; the model statements

Table 4. Response of leaf nutrient levels to fertilizer treatments in almond replant Expt. 1 based on the analysis of leaf samples collected in Jul and Sep 2019 from replicate plots of 'Butte' and 'Padre' trees.

	July			September
Fertilizer treatment formulation (code)[i]	Potassium (%)	Calcium (%)	Manganese (ppm)[ii]	Manganese (ppm)
None (Ctl)	1.61 a[iii]	1.17 a	69 Bc	51 b
0N–19.6P–0K (+P)	1.49 abc	0.88 ab	56 c	53 b
15N–6.5P–12.4K (+NPK)	1.29 bc	0.76 b	93 ab	57 b
15N–3.9P–10K + micronutrients (+NPK, +micros)	1.69 a	1.09 a	116 a	72 a
46N–0P–0K (+N)	1.20 c	0.77 b	59 c	56 b
Micronutrients (+Micros)	1.55 ab	0.94 ab	57 c	47 b
Significance of treatment effect[iii]	$P = 0.041$	$P = 0.056$	$P = 0.008$	$P = 0.007$

[i] All fertilizer treatments were applied in addition to standard grower practices, which included the following: 10.5 lb/acre 32N–0P–0K formulation through the irrigation system and two foliar sprays that applied 1 lb/acre nitrogen (N), 2.1 lb/acre phosphorus (P), and 4.3 lb/acre potassium (K). Samples were analyzed by Delavalle Laboratories (Fresno, CA, USA); 1 lb/acre = 1.1209 kg·ha^{-1}.

[ii] 1 ppm = 1 mg·kg^{-1}.

[iii] Data were subjected to analysis of variance using JMP (SAS Institute Inc., Cary, NC, USA). Means without letters in common were significantly different according to Fisher's least significant difference at $P < 0.05$.

specified increases in TCSA as a function of fertilizer treatments (Expts. 1 and 2) or the factorial treatments (Expts. 3 and 4). Using PROC MIXED, "block" was specified as a random effect for Expts. 1 and 2. Block and block × fumigation were specified as random effects in Expt. 3, and block, block × WOR, and block × fumigation were specified as random effects for Expt. 4. The leaf analysis results for Expt. 1 were subjected to ANOVA using JMP (SAS Institute Inc.), and the means were separated according to Fisher's least significant difference test with an α of 0.05.

Results

Expt. 1. There was no significant effect of fertilizer treatment on TCSA increases of 'Butte' trees by year 1 ($P = 0.17$) or year 2 ($P = 0.22$) after planting, but the growth of 'Padre' was increased by some of the fertilizer treatments through the second year of growth (year 1, $P = 0.04$; year 2, $P = 0.015$) (Fig. 1). By year 4, there was no strong effect of fertilization treatment on growth with either 'Butte' or 'Padre' ($P = 0.74$ and 0.09, respectively). Each of the fertilizer treatments, except for micronutrients alone ("+Micros"), increased 'Padre' growth during years 1 and 2 compared with the control (Fig. 1). There were no significant differences in growth among "+P", "+N", "+NPK", or "+NPK+micros" treatments based on 95% confidence intervals.

Regarding leaf samples collected during July of year 1, there were no significant differences in the N or P contents (data not shown), but K and manganese (Mn) levels were significantly affected by the fertilizer treatment, and Ca levels were marginally affected by the fertilizer treatment (Table 4). Greater leaf K and Ca levels were measured in control and "+NPK+micros" treatments than in the "+NPK" and "+N" treatments (Table 4). Also in July, the leaf Mn content was higher in the "+NPK+micros" treatment compared with all other treatments except for the "+NPK" treatment. By September of year 1, Mn was the only measured leaf nutrient variable significantly affected by fertilizer treatment, and the leaf Mn content was greater in the "+NPK+micros" treatment compared with all other treatments (Table 4).

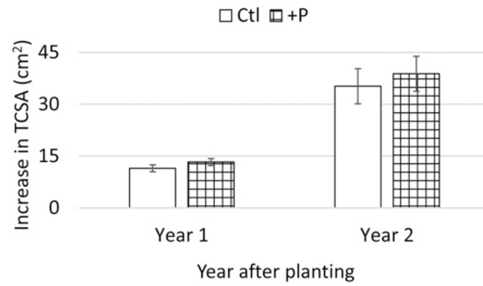

Fig. 2. 'Monterey' almond trunk cross-sectional area (TCSA) gain in years 1 and 2 after planting as a function of postplant phosphorus (P) fertilization treatment (Expt. 2). The control (Ctl) and the P treatment [2.6 oz/tree P (+P)] were applied during March of the first growing season after planting, and measurements of the trunk diameter and circumference were used to calculate increases in TCSA in years 1 and 2 after planting. The experimental treatments were applied in addition to grower applications of composted chicken manure and calcium ammonium nitrate fertilizer that included totals of 85 lb/acre nitrogen, 30 lb/acre P, and 70 lb/acre potassium. Error bars are 95% confidence intervals. 1 oz = 28.3495 g; 1 lb/acre = 1.1209 kg·ha^{-1}; 1 cm^2 = 0.1550 inch^2.

Expt. 2. The P fertilization treatment significantly increased TCSA growth of 'Monterey' trees through both years 1 and 2 compared with the control ($P = 0.02$ for both years) (Fig. 2). However, the experimental treatment did not significantly affect the growth of 'Nonpareil' during year 1 ($P = 0.74$) or year 2 ($P = 0.12$) (data not shown).

Expt. 3. The preplant soil fumigation treatment significantly increased TCSA growth for both cultivars over both years (Fig. 3A, B, Table 5). TCSA growth was approximately doubled in fumigated treatments during both years and for both cultivars compared with the nonfumigated treatment (Fig. 3A, B). There was no significant interaction between the fumigation and

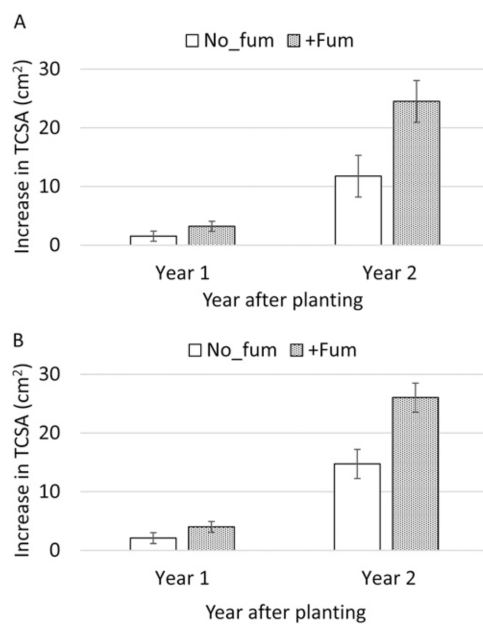

Fig. 3. Trunk cross-sectional area (TCSA) gain in years 1 and 2 after planting for (A) 'Monterey' and (B) 'Nonpareil' almond as a function of preplant soil fumigation treatment (Expt. 3). Successive measurements of the trunk diameter and circumference were used to calculate increases in TCSA in years 1 and 2 after planting. Data from different fertilization treatments were pooled within the nonfumigated (No_Fum) and fumigated (+Fum) treatments. Fumigation was performed with 1, 3-dichloropropene (332 lb/acre treated) plus chloropicrin (200 lb/acre treated); shank injection was performed at a depth of 18 inches in soil. Error bars are 95% confidence intervals. 1 lb/acre = 1.1209 kg·ha^{-1}; 1 cm^2 = 0.1550 inch^2.

Table 5. Results of analyses of variance of treatment effects on increases in 'Monterey' and 'Nonpareil' almond tree trunk cross-sectional area growth in Expts. 3 and 4.[i]

		'Monterey'				'Nonpareil'			
		Yr 1		Yr 2		Yr 1		Yr 2	
Expt. no.	Effect	*F*	*P*	*F*	*P*	*F*	*P*	*F*	*P*
3	Fumigation	17.07	0.03	38.43	<0.001	14.43	0.03	62.51	<0.001
	Fertilization	2.27	0.15	1.62	0.24	3.37	0.07	12.31	0.001
	Fumigation × fertilization	0.30	0.75	0.40	0.68	2.27	0.15	1.75	0.22
4	Fumigation	209.69	<0.001	584.24	<0.001	79.02	<0.001	293.92	<0.001
	Whole orchard recycling (WOR)	0.30	0.59	0.07	0.80	0.00	0.98	7.41	0.008
	Fumigation × WOR	9.21	0.003	11.28	0.001	0.69	0.41	1.70	0.20
	Fertilization	8.74	0.004	1.95	0.15	3.66	0.03	1.83	0.17
	Fumigation × fertilization	3.96	0.02	0.29	0.75	0.55	0.58	0.36	0.70
	WOR × fertilization	0.41	0.67	0.66	0.52	0.92	0.40	0.17	0.84
	Fumigation × WOR × fertilization	0.41	0.66	0.29	0.75	0.70	0.50	0.36	0.70

[i] Increases in the trunk cross-sectional area were measured from the time of planting until the end of the growing years specified.

fertilization treatments for either cultivar in either year (Table 5). Postplant fertilization treatments did not significantly impact TCSA increases in 'Monterey' for either year, but they did impact TCSA increases in 'Nonpareil' by year 2. By year 2, regardless of the preplant soil fumigation treatment, 'Nonpareil' trees that received P fertilization grew more than those that did not (Fig. 4). There was no growth benefit to adding an additional 2 oz/tree N during the first growing season for either 'Monterey' (data not shown) or 'Nonpareil' (Fig. 4).

Expt. 4. As in Expt. 3, preplant soil fumigation in Expt. 4 approximately doubled the TCSA increase for 'Nonpareil' by year 1 (2.6 cm^2 in the control vs. 5.3 cm^2 in the fumigation treatment) and year 2 (14.1 in control vs. 29.7 cm^2 in the fumigation treatment); the increases were statistically significant in both years (Table 5). TCSA growth of 'Monterey' was also approximately doubled by preplant fumigation, but there was a significant interaction between fumigation and WOR treatments (Table 5, Fig. 5). For 'Monterey', without preplant soil fumigation, WOR chips increased TCSA growth by ~17% and 25% in years 1 and 2, respectively, compared with the control without WOR; however, with preplant soil fumigation, WOR chips decreased TCSA growth by ~11% and 7% by years 1 and 2, respectively (Fig. 5). 'Nonpareil' did not exhibit a significant fumigation × WOR interaction in either year; however, by year 2, it had accumulated a statistically significant 10% increase in TCSA growth in plots with WOR chips compared with plots without the chips (Table 5, data not shown). There was no significant effect of WOR chips on 'Nonpareil' growth in year 1.

'Monterey' and 'Nonpareil' had different responses to fertilizer treatments. 'Monterey' TCSA increases were affected significantly by the fumigation × fertilizer interaction in year 1, but not in year 2 (Table 5, Fig. 6). With 'Monterey' in nonfumigated soil, P fertilization increased the TCSA growth by approximately 19% in year 1, whereas the high N treatment supported equivalent growth in comparison with the standard N-only treatment (Fig. 6). With 'Monterey' in fumigated soil, however, year 1 TCSA increases were approximately 16% greater with P added and approximately 11% less in the high N treatment compared with the standard N treatment with no P (Fig. 6). 'Nonpareil' growth was only affected by the main effects of fertilizer treatments, and only in year 1 (Table 5, Fig. 7). P fertilization modestly boosted 'Nonpareil' growth (by ~11%) in year 1 across fumigated and nonfumigated treatments, compared with standard N fertilization, whereas the higher rate of N did not improve growth (Fig. 7).

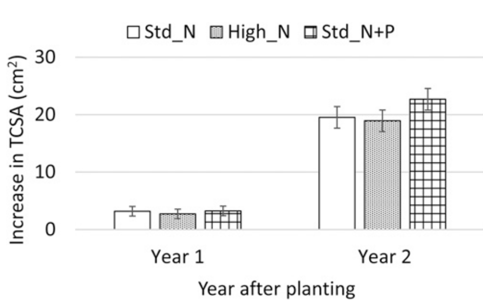

Fig. 4. 'Nonpareil' almond trunk cross-sectional area (TCSA) gain in years 1 and 2 after planting as a function of nitrogen (N) and phosphorus (P) fertilizer treatments in year 1 (Expt. 3). Successive measurements of the trunk diameter and circumference were used to calculate increases in TCSA in years 1 and 2 after planting. Effects of fertilizer treatments, which included 3.5 oz/tree N (Std_N), 5.5 oz/tree N (High_N), and 3.5 oz/tree N plus 2.6 oz/tree P (Std_N+P), were not significant in year 1 but significant in year 2 (Table 5). Main effects of fertilization treatments are shown pooled over nonfumigated and shank-fumigated treatments. Error bars are 95% confidence intervals. 1 oz = 28.3495 g; 1 cm^2 = 0.1550 $inch^2$.

Discussion

The central hypothesis of this work was that P fertilization can increase the growth rates of young almond trees in replant settings of the San Joaquin Valley. We tested the hypothesis during four replicated trials representing three distinct locations, soils, and site management circumstances using triple super phosphate formulation placed in soil adjacent to trees in their first growing season. In all experiments, significant gains in TCSA resulted from P fertilization in at least one of the almond cultivars within the first 2 years after planting,

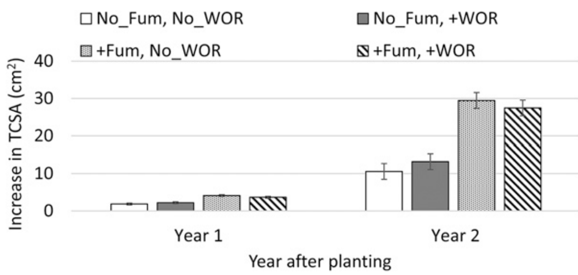

Fig. 5. 'Monterey' almond trunk cross-sectional area (TCSA) gain in years 1 and 2 after planting as an interactive function of preplant soil fumigation and whole orchard recycling (WOR) treatments (Expt. 4). The treatment combinations included the following: no fumigation; no WOR (No_Fum, No_WOR); no fumigation and with WOR (No_Fum, +WOR); with fumigation and no WOR (+Fum, No_WOR); and with fumigation and with WOR (+Fum, +WOR). Fumigation was performed with 1,3-dichloropropene (332 lb/acre treated) plus chloropicrin (200 lb/acre treated); shank injection was performed at a depth of 18 inches (45.7 cm) in soil. The WOR was simulated by incorporating almond orchard chips at 61 tons/acre (136.7 t·ha^{-1}) in the soil to a depth of 4 inches (10.2 cm). Successive measurements of the trunk diameter and circumference were used to calculate increases in TCSA in years 1 and 2 after planting. The interactive means were pooled over fertilization treatments. Error bars are 95% confidence intervals. 1 lb/acre = 1.1209 kg·ha^{-1}; 1 cm^2 = 0.1550 inch^2.

supporting our hypothesis that P fertilization can benefit the growth of replanted almond orchards. In Expt. 1, the growth of 'Padre' trees was also improved by fertilizers that supplied other nutrients along with P. All test locations represented settings where almond trees were being replanted within ~1 year of removing an old almond or peach orchard, which is a circumstance that commonly leads to ARD. In Expts. 3 and 4, the fact that preplant soil fumigation strongly improved tree growth indicated that trees in these experiments were indeed impacted by the ARD complex. Trees affected by ARD exhibit growth suppression, decreased root length density, and consequential yield suppression, and preplant soil fumigation or anaerobic soil disinfestation can be used to prevent the condition (Browne et al. 2006, 2013, 2018a, 2018b).

The generally positive responses to P across trial locations, variables, and conditions suggested that such responses may be expected among many almond replant soils in California and are not limited to settings with or without preplant soil fumigation or with or without WOR. The positive responses to P with and without fumigation indicated that the benefit of P fertilization is independent of ARD and its effects on trees. Our soil test results did not suggest that any of the soils used for our trials were particularly P-deficient (i.e., with Olsen *P* values less than 10 ppm) (Fulton 2010); therefore, soil testing may not be useful for predicting P fertilization benefits such as those we measured, at least not in many soils of the San Joaquin Valley. Similarly, several previous studies found that tree responses to P fertilization were not well-predicted by soil P test levels (Ferreira et al. 2018; Neilsen and Yorston 1991; Taylor 1975).

Despite the generally positive impact of P fertilization in all experiments, the results were nuanced by cultivar, time of assessment after planting, and perhaps other variables that were not controlled or tested, such as the irrigation system, timing of replanting, and general growing practices. It must be considered that cultivar effects were confounded in known and potential ways with other factors. For example, different cultivars may be grown in different nursery tree blocks with somewhat different soils, fertilization practices, or other management practices, and it is conceivable that environmental conditions at the nursery could influence responses to P after orchard planting. Additionally, rootstock, and factors confounded with rootstock may have impacted cultivar responses; for example, although 'Monterey' and 'Nonpareil' were used in Expt. 2 (Chowchilla), Expt. 3 (Parlier), and Expt. 4 (Parlier), the rootstock of Expt. 2 was 'Viking', whereas that of Expts. 3 and 4 was 'Nemaguard'. Additionally, in Expt. 2, 'Nonpareil' was planted 3 months after 'Monterey'; therefore, the cultivars could not be compared.

In Expt. 1, we compared responses to P as triple super phosphate (0N–19.6P–0K) with responses to other formulations containing P (i.e., 15N–6.5P–12.4K and 15N–3.9P–10K + micronutrients) and formulations containing only N (46N–0P–0K) or micronutrients ("+Micros" formulation). The responses of trees to 0N–19.6P–0K, 46N–0P–0K and 15N–6.5P–12.4K formulations suggested the need for careful consideration; each of these formulations was applied on the same schedule, and each supplied the N, P, or N and P components in total amounts of 5 or 6 oz/tree N and/or 1.6 or 2.2 oz/tree P. If N and P were both limiting without fertilization, as suggested by growth responses to 46N–0P–0K and 0N–19.6P–0K formulations, then it would seem logical to expect a better response

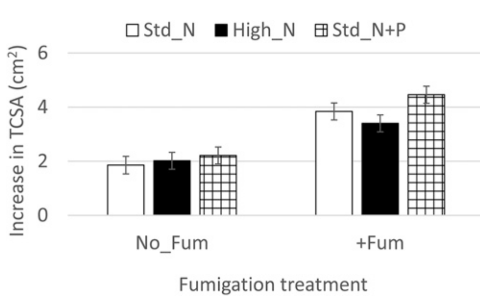

Fig. 6. 'Monterey' almond trunk cross-sectional area (TCSA) gain in year 1 after planting as an interactive function of preplant soil fumigation (Expt. 4) no fumigation (No_Fum) vs. preplant shank fumigation [1,3-dichloropropene + chloropicrin, 332 + 200 lb/acre treated (+Fum), respectively] and postplant fertilizer treatment [totals of 3.5 oz/tree N (Std_N), 5.5 oz/tree N (High_N), or 3.5 oz/tree N plus 2.6 oz/tree P (Std_N+P)] in year 1 after planting. Successive measurements of the trunk diameter and circumference were used to calculate increases in TCSA in years 1 and 2 after planting. The means were pooled over whole orchard recycling treatments. Error bars are 95% confidence intervals. 1 lb/acre = 1.1209 kg·ha^{-1}; 1 oz = 28.3495 g, 1 cm^2 = 0.1550 inch^2.

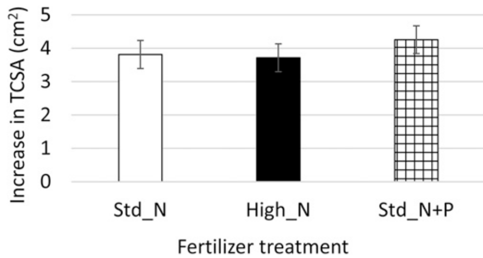

Fig. 7. 'Nonpareil' almond trunk cross-sectional area (TCSA) gain in year 1 after planting as a function of postplant fertilizer treatment (Expt. 4): 3.5 oz/tree N (Std_N), 5.5 oz/tree N (High_N), or 3.5 oz/tree N and 2.6 oz/tree P (Std_N+P). Successive measurements of the trunk diameter and circumference were used to calculate increases in TCSA. The means were pooled over whole orchard recycling and fumigation treatments. Error bars are 95% confidence intervals. 1 oz =28.3495 g; 1 cm^2 = 0.1550 $inch^2$.

to 15N–19.6P–12.4K than with either 46N–0P–0K or 0N–19.6P–0K alone. For unknown reasons, the formulation combining N, P, and K was not more effective than the N-only or P-only formulations. A conceivable explanation is that the chemistries of the formulations somehow contributed to the results, or, perhaps more likely, that some other stressing nutritional or biotic factor prevented the potential of the N+P fertilization benefit from manifesting fully in tree growth. For example, by the end of year 1, the trees in Expt. 1 were infested with web-spinning spider mites (*Tetranychus* sp.), which are known to stress young almond trees. Although the trees were not defoliated, their leaves were severely stippled by the end of the season, and this may have limited the tree growth potential, regardless of fertilization treatment. Our results suggested no significant benefit of the application of micronutrients in this orchard.

Results from Expts. 3 and 4 indicate that P application alone is not an adequate substitute for preplant soil fumigation for overcoming ARD. Although there is no commercial assay for ARD, its impact is best assessed under field conditions during the first year after replanting according to growth improvement in fumigated soil over that in nonfumigated soil, with all other factors being equal. In year 1 of Expt. 3, for example, compared with the nonfumigated control, preplant fumigation increased TCSA growth of 'Monterey' and 'Nonpareil' by averages of 109% and 91%, respectively, whereas P application did not significantly increase the growth of 'Monterey' and increased growth of 'Nonpareil' by 2% (14% by year 2) compared with the standard treatment without P. Similarly, in year 1 of Expt. 4, preplant fumigation increased Monterey and Nonpareil TCSA growth by 92% and 106%, respectively, compared with the control, whereas the addition of P fertilizer increased Monterey and Nonpareil TCSA growth by 17% and 12%, respectively, compared with the standard treatment without P.

The results of Expts. 3 and 4, both with and without the use of preplant soil fumigation and with and without the presence of WOR chips, were consistent with the current first-year recommendations of N rates of 3 to 4 oz/tree for nonbearing almonds (Jarvis-Shean et al. 2018). In fact, in Expt. 4, the high N treatment, which applied 5.5 oz/tree N over the season, was slightly detrimental to the growth of 'Monterey' trees in fumigated soil. One caveat that may be important to seasonal N rates is the planting time. Trees in Expts. 3 and 4 were planted at the beginning of summer rather than in the spring or fall, which are more favorable planting times, and it is possible that fall-planted or spring-planted trees, which would have a longer growing season and would be more established before the summer heat, may respond better to higher N fertilizer rates than the trees in Expts. 3 and 4.

Our results justify further work involving P fertilization for replanted California almonds. It is uncertain whether the responses to P fertilization in this study will translate to significant or economical kernel yield responses, and we intend to examine this during the coming years. Practical experimentation that optimizes P application procedures in young orchards, perhaps in combination with other nutrients, could be beneficial.

Conclusions

Almond orchards replanted in California's San Joaquin Valley are likely to exhibit early growth responses to P fertilizer placed in the root zone. Although different almond cultivars and rootstocks responded differently to applied P in different experiments outlined in this report, the results were sufficiently consistent for us to suggest that 2.2 oz/tree P should be applied at or close to planting to benefit replanted almond orchard growth. Our results contrast with the previous guidelines published by University of California Cooperative Extension, which stated that P was not needed for almond trees except when leaf tissue samples indicate a deficiency is present. It is important to determine whether the growth responses to applied P translate to yield responses; therefore, this topic is being investigated. Finally, our results at Kearney Agricultural Research and Extension Center confirmed that 3 to 4 oz/tree N during the first year after planting can be optimal for replanted almond orchard growth with or without WOR and with or without preplant soil fumigation.

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