

Tackling Soilborne Disease and Soil Disinfestation

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Presentation outline (a focus on almond replant problems)

- Consider California's and Australia's settings for almond replant problems (RPs)
- Consider types of RPs and "management handles"
 - Physical and chemical soil challenges
 - *Phytophthora* species
 - Phytopathogenic nematodes
 - Prunus replant disease (PRD)
- More on PRD: orchard experiences & etiology
- Integrated management of RPs:
 - Preplant soil fumigation for research and mgt.
 - Rootstock interactions with RPs
 - Alternatives to soil fumigation: Ag byproduct amendments and anaerobic soil disinfestation (ASD)
 - Whole orchard recycling (WOR) and fertilization interactions
- Closing comments, ideas, general and AU-specific



Almond replant challenges in California and Australia

- Almond orchard productivity declines markedly within **20 to 25 years** after planting.
- For sustainability, Ca and AU (with ~0.6 million ~71 thousand ha of almond orchards, respectively) both have a lot of replanting to do.
- For example, in Ca, in 2025, ~9300 ha of new almonds planted, of those ~39% were to replace old almond orchards (USDA). In AU , ~40% almond trees are >20 years old
- **Young trees, low on energy reserves and building root systems, are vulnerable to replant problems**
- In California, remediation by preplant soil fumigation is used widely, but the practice is increasingly regulated, and **fumigant alternatives are needed.**



Prunus replant problems (RPs) in California (in broad sense)*

*Replant typically considered to be almond after almond, but in broad sense may be almond after some other orchard, vineyard, or even vegetable or field crop.

Abiotic:

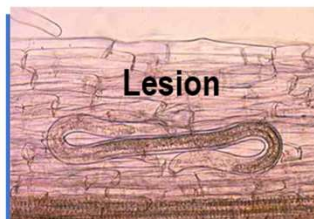
- **Physical & chemical soil challenges** related to previous production

Biotic:

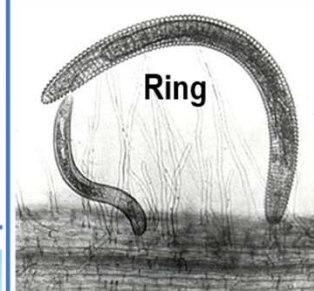
- **Aggressive pathogens and pests** (e.g., *Phytophthora* spp., *Botryosphaeriaceae*, *Armillaria*, *Verticillium*, insects, weeds, rodents, etc.)
- **Phytopathogenic (PP) nematodes** (e.g., lesion, ring, root knot species)
- **Prunus replant disease (PRD)**
Microbe-induced growth suppression; specific to *Prunus* after *Prunus*



Physical & chemical soil challenges (incl. H₂O mgt)



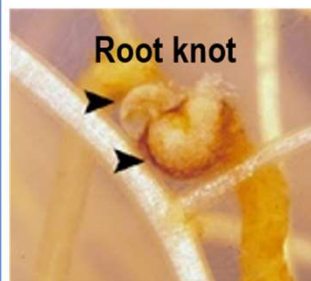
Lesion



Ring



Phytophthora crown & root rots



Root knot

Phytopathogenic nematodes



Healthy tree in fumigated soil



PRD-affected tree in non-fumigated soil

Prunus replant disease

Risk assessment for RPs, before replanting

Replant problem (RP)	Crop specificity	Predictive lab diagnostics?	Key management components
Physical and chemical soil challenges 	Low	Yes, acceptable parameters known for the soil variables, preplant testing <u>useful</u>	Preplant soil remediation, orchard design, rootstock choice, cultural practices, etc.
Phytophthora diseases 	Medium	(Yes), causal agents known, but preplant testing and history only <u>partially useful</u>	Strategic orch. design and culture; esp. w/ rootstock choice, soil H ₂ O mgt., & (potentially) fungicide use
PP nematodes 	Medium	Yes, causal agents known, preplant testing <u>useful</u>	Fallow, fumigants, anaerobic soil disinfestation (ASD), rootstock choice, postplant nematicides, etc.
Prunus replant disease (PRD) 	High (<i>Prunus</i> after <i>Prunus</i>)	No, causal agents not resolved. But, <u>local field-based fum assessments useful.</u>	Fallow, fumigants, ASD, WOR, rootstock choice, optimal N and P fertilization

More on PRD, (my) first encounters...

Browne, G.T.*, Connell, J.H., and Schneider, S.M. 2006. Plant Disease. 90:869-876.

Orchard replant failure areas were identified in four plantings near Chico and Durham, CA (northern Central Valley) in fall 2001-2003 with UC Farm Advisor Joe Connell.

Images taken in fall, a full growing season after orchard replanting. The old orchard was almond on 'Lovell'. The new orchard (pictured here) was almond on 'Marianna 2624'.



More on PRD; encounters We conducted fumigation trials in the Chico and Durham orchard replant failure areas.

- Experimental reasoning: a positive response to soil fumigation would suggest a biotic, soilborne RP...
- Trees in failed areas were removed.
- Replicated preplant soil fumigation treatments (a control and several fumigant formulations) were applied in the fall via: (i) tractor-powered shanks (**broadcast injection**) or (ii) a hand-held probe (**tree site injection**)
- New almond trees were replanted in the following spring on rootstocks of 'Marianna 2624', 'Lovell' and 'Nemaguard'.

Browne, G.T.*, Connell, J.H., and Schneider, S.M. 2006. Plant Disease. 90:869-876.



More on PRD, encounters

Aboveground responses of trees to preplant soil treatments, at Chico and Durham trials, growing season 1

At ~3 mo after planting, early spring

At ~5 mo after planting, mid summer

All trees got a good start,
regardless of preplant soil trt.

Trees in CP-fumigated soil remained
healthy

But trees in non-fumigated soil
stopped growth and suffered
defoliation

2 months later

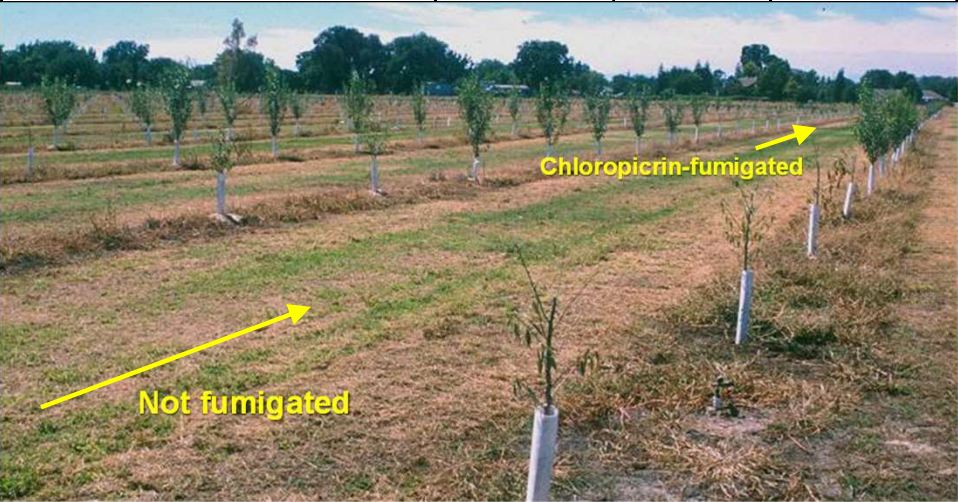
(CP, 1,3-D, MB, and IM were all
effective as spot trts. MB and 1,3-D
were less effective as “broadcasts”)

PRD encounters, cont...

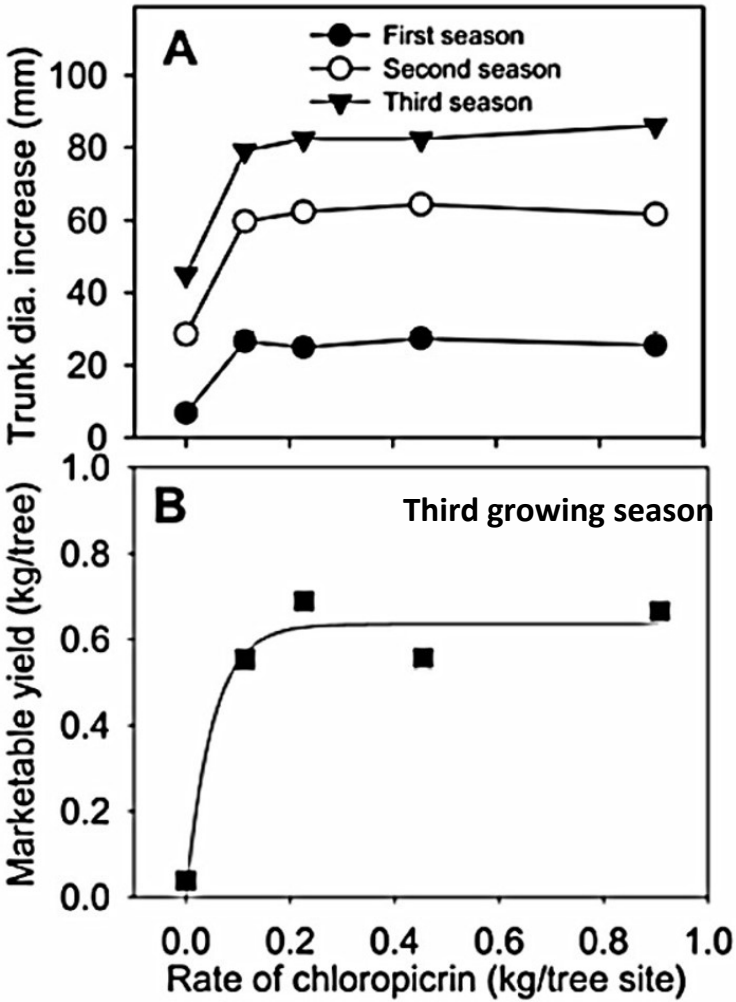
Measured aboveground tree responses, Chico and Durham trials

Broadcast shank fumigation results, Orchard 1, Chico:

Pre-plant treatment	Increase in trunk diameter (mm)	Tree height (m)	Final tree retention (%)
None (control)	1 a	1.0 a	2 a
MBr (400 kg ha ⁻¹)	4 b	1.2 a	21 a
Chloropicrin (420 kg ha ⁻¹)	10 c	1.7 b	96 b
Telone (400 kg ha ⁻¹)	2 a	1.1 a	1a



Probed tree site fumigation results, Orchard 2, Durham:



Other notes:

- All rootstocks were susceptible to PRD, but Marianna 2624 more so than 'Lovell' and 'Nemaguard'
- CP especially effective, but 1,3-D, MB, and IM all were all effective as tree site trts.
- PP nematodes were not associated with responses

PRD encounters, continued...

Belowground responses to preplant soil treatments, **Chico and Durham trials**, growing season 1

CP-
fumigated
soil (A-C)
➡



Non-
fumigated
soil (D-E)
➡



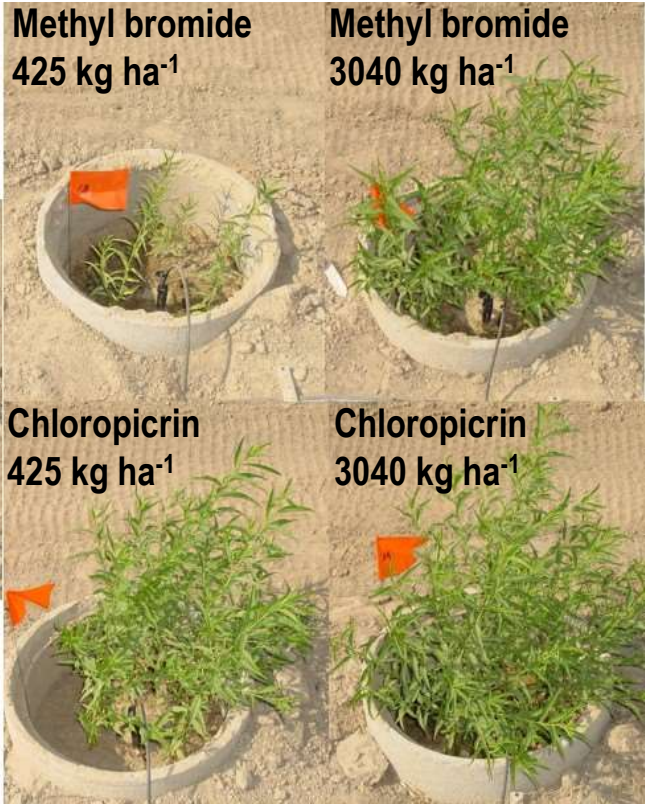
1 month after planting

2 months after planting

4 months
after planting

PRD
encounters,
continued...

Responses to preplant soil fumigation of peach replant soil near Parlier, San Joaquin Valley (microplots, Nemaguard rootstock)



Fumigant	Fumigant dose (kg ha ⁻¹)	Root wt. (g)	Root rot (%)
None (ctl)	-	2.7 a	46 a
Methyl bromide	425	5.0 ab	42 ab
	3040	13.3 b	13 ab
Chloropicrin	425	13.8 b	18 ab
	3040	13.1 ab	11 b

Notes:

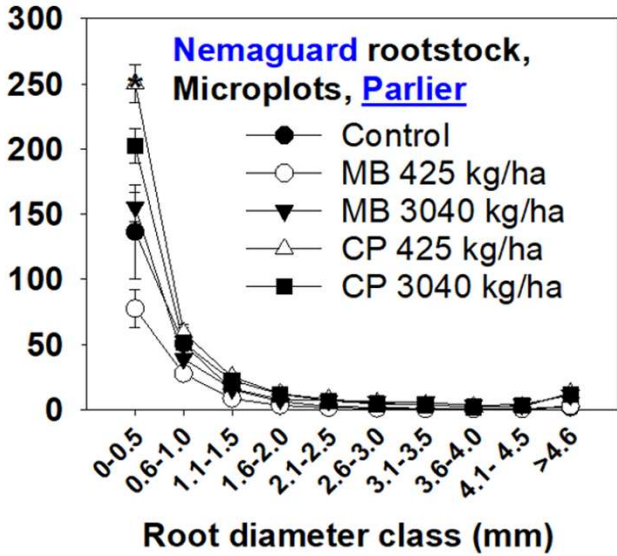
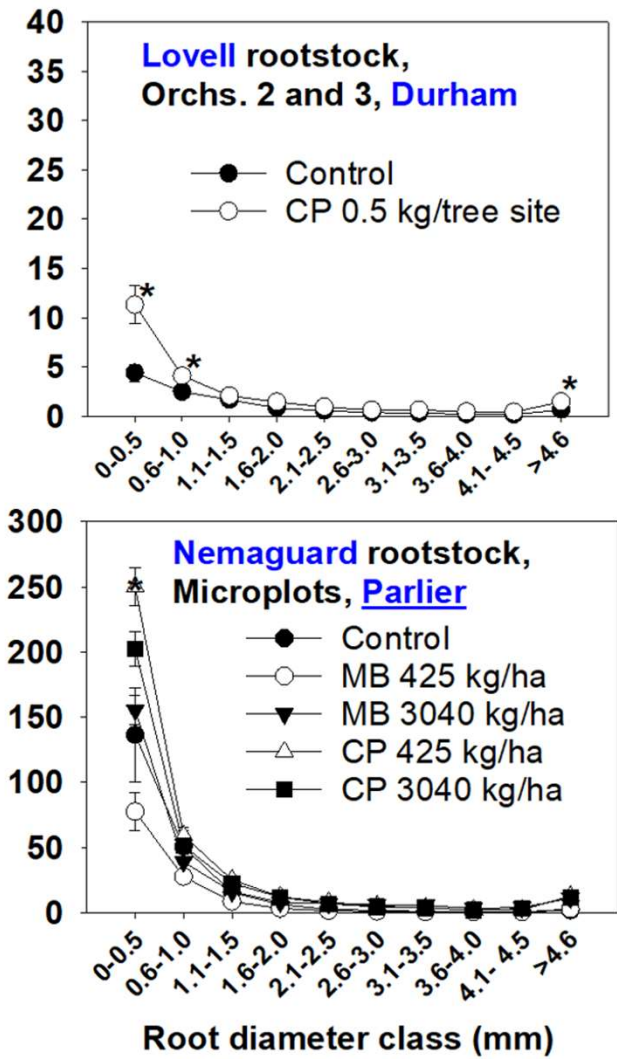
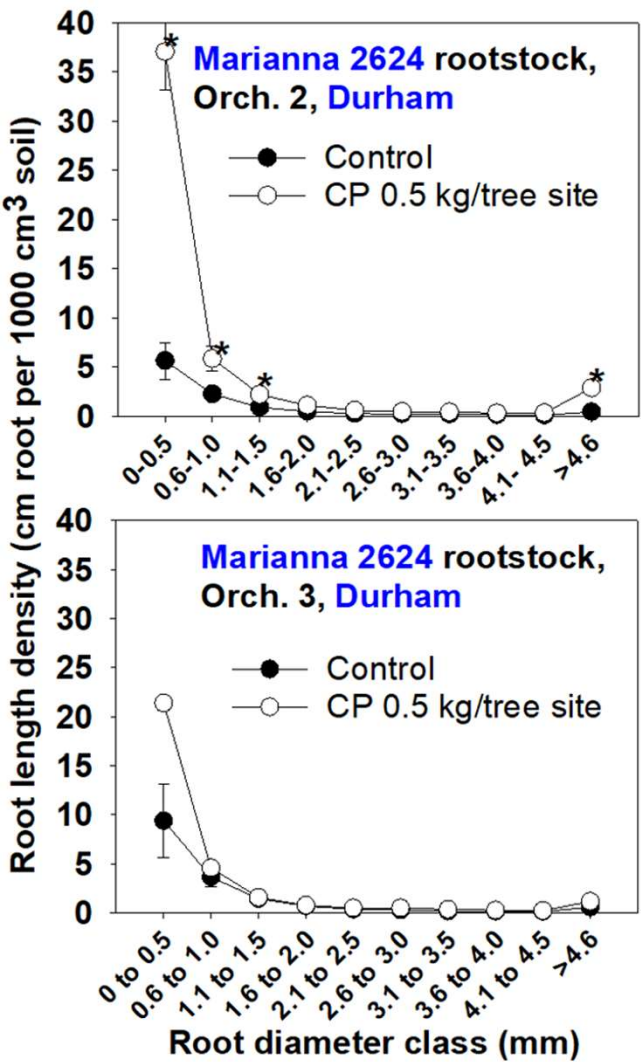
- Both CP and MB prevented growth suppression (PRD); but CP more potent than MB.
- Root and growth impacts similar to those in N. CA orchards

PRD encounters,
contd.

Root length density (RLD) responses, Durham and Parlier trials?

Notes:

- Based on WinRhizo system scans
- All locations and rootstocks: RLD of roots ≤ 1 mm diameter significantly reduced in control, compared to chloropicrin (CP) trts.
- CP increased RLD more than methyl bromide (MB) did.
- All trial locations: PP nematode counts were negligible and not associated with the PRD, based on repeated soil and root sampling, sugar floatation, and mist chamber extractions.
- Conclusions: Feeder root health and dynamics may be a key to PRD, PP nematodes were not the cause of growth suppression in these trials.



PRD etiology studies

Root isolations and pathogenicity testing suggested occasional contributions of soil *Cylindrocarpon*, *Pythium*, and *Phytophthora* spp. To PRD on Nemaguard seedling rootstock

Root isolations were from fine roots of healthy and PRD-affected plants; pathogenicity testing done in greenhouse



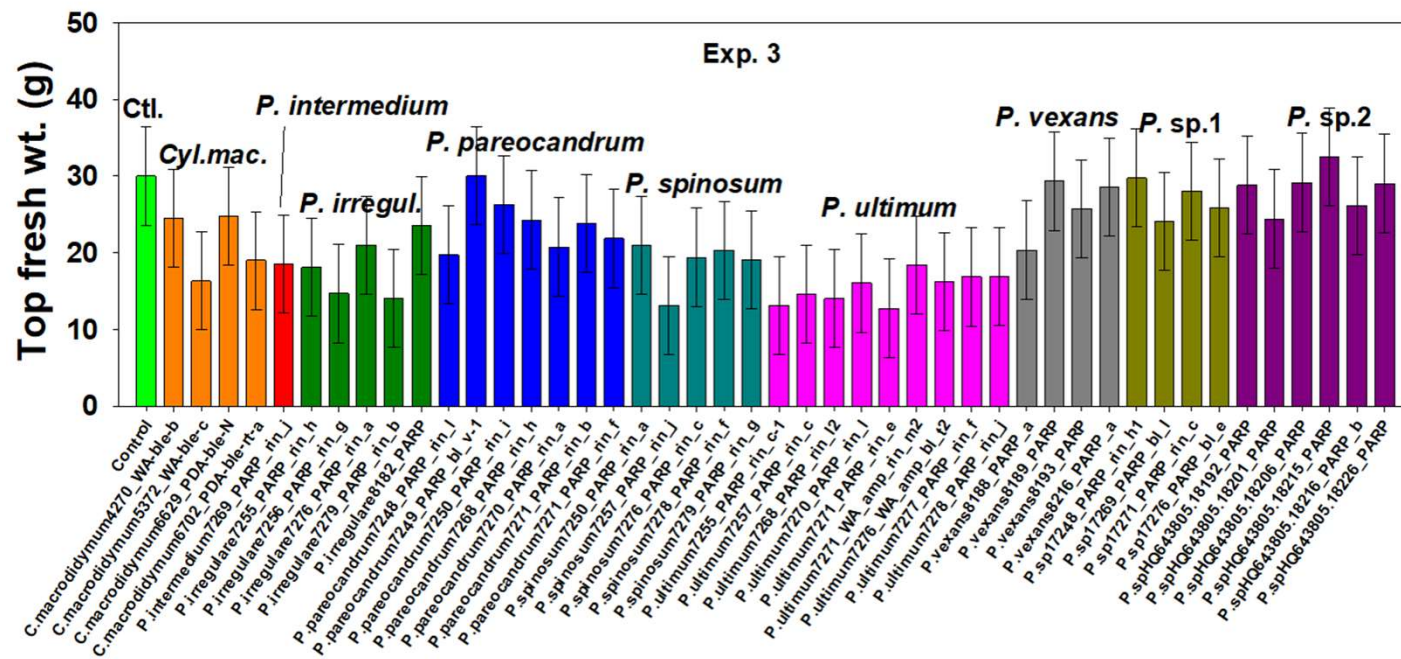
Control

Cyl. macrodidymum



Control

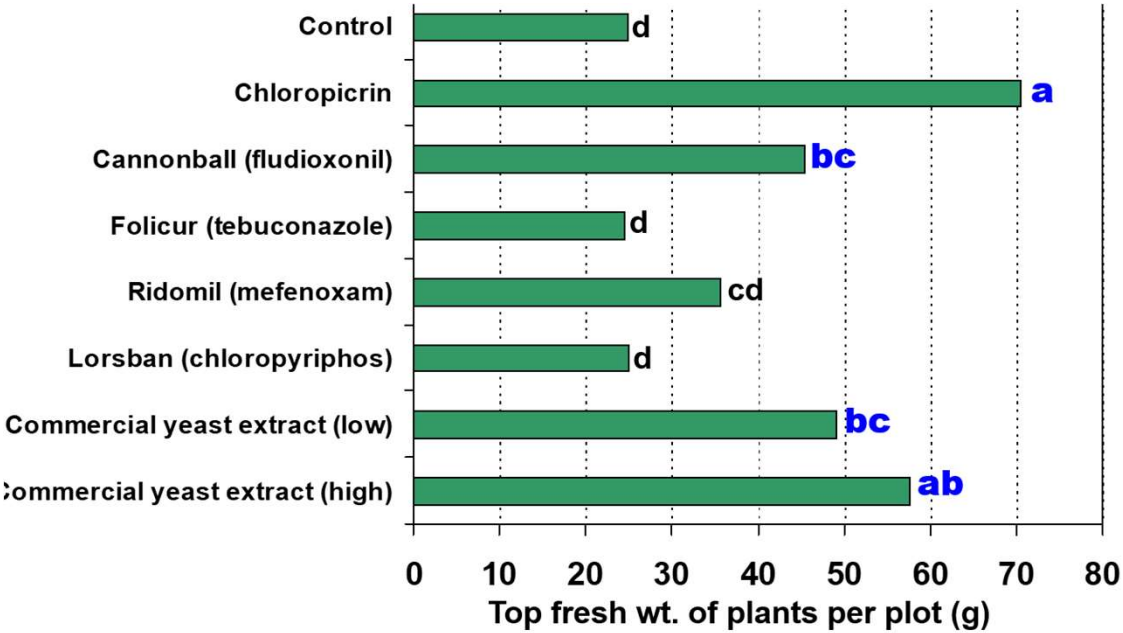
Pythium ultimum



Microplot trialing of semi-selective soil treatments for PRD



- Positive standard of chloropicrin highly effective as measured by seedling growth
- Fludioxonil fungicide partially effective, fungal PRD mechanism?
- Yeast extract partially effective, nutritional/biological PRD mechanism?
- Conclusion: best to think of PRD as a complex



Systemiatic approach to soils, roots, and their microbial communities associated with PRD

Used conventional physicochemical soil analyses, high-throughput sequencing of rRNA gene amplicons from bacterial, fungal, and oomycete communities in soil and roots, and a greenhouse-based PRD assay.

Collected 25 diverse Central Valley soil sets representing:

- 20 Prunus replant soils
- 3 Field-fumigated or ASD-treated Prunus replant soils
- 2 Grape replant soils

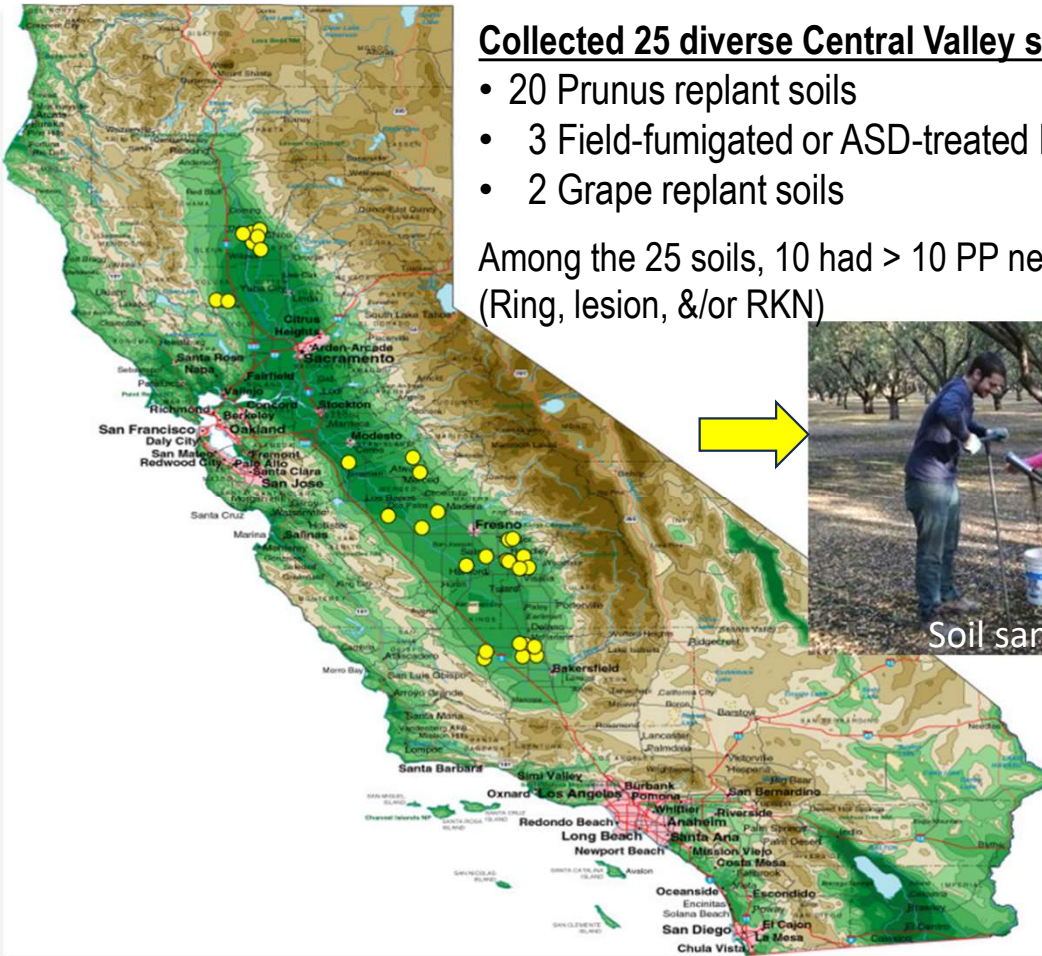
Among the 25 soils, 10 had > 10 PP nematodes /250 cc soil (Ring, lesion, &/or RKN)

Khan AR, Wicaksono WA, Ott NJ, Poret-Peterson AT, Browne GT (2021) Characterization of soils conducive and non-conductive to Prunus replant disease. PLOS ONE 16(12)

Khan AR, Wicaksono WA, Ott NJ, Poret-Peterson AT, Browne GT (2022) Random forest analysis reveals taxa predictive of Prunus replant disease in peach root microbiomes. PLOS ONE 17(10)

Soil used for:

1. Total DNA extr., rRNA gene amplicons fr. bac, fungi, oomycetes
2. physical, chemical, & PP nematode pop. determinations
3. Greenhouse bioassay for PRD potential



Soil sampling



Mixing w/ sterile sand



Soil pasteurization, Fum, & control trts.

Soil potted for bioassay

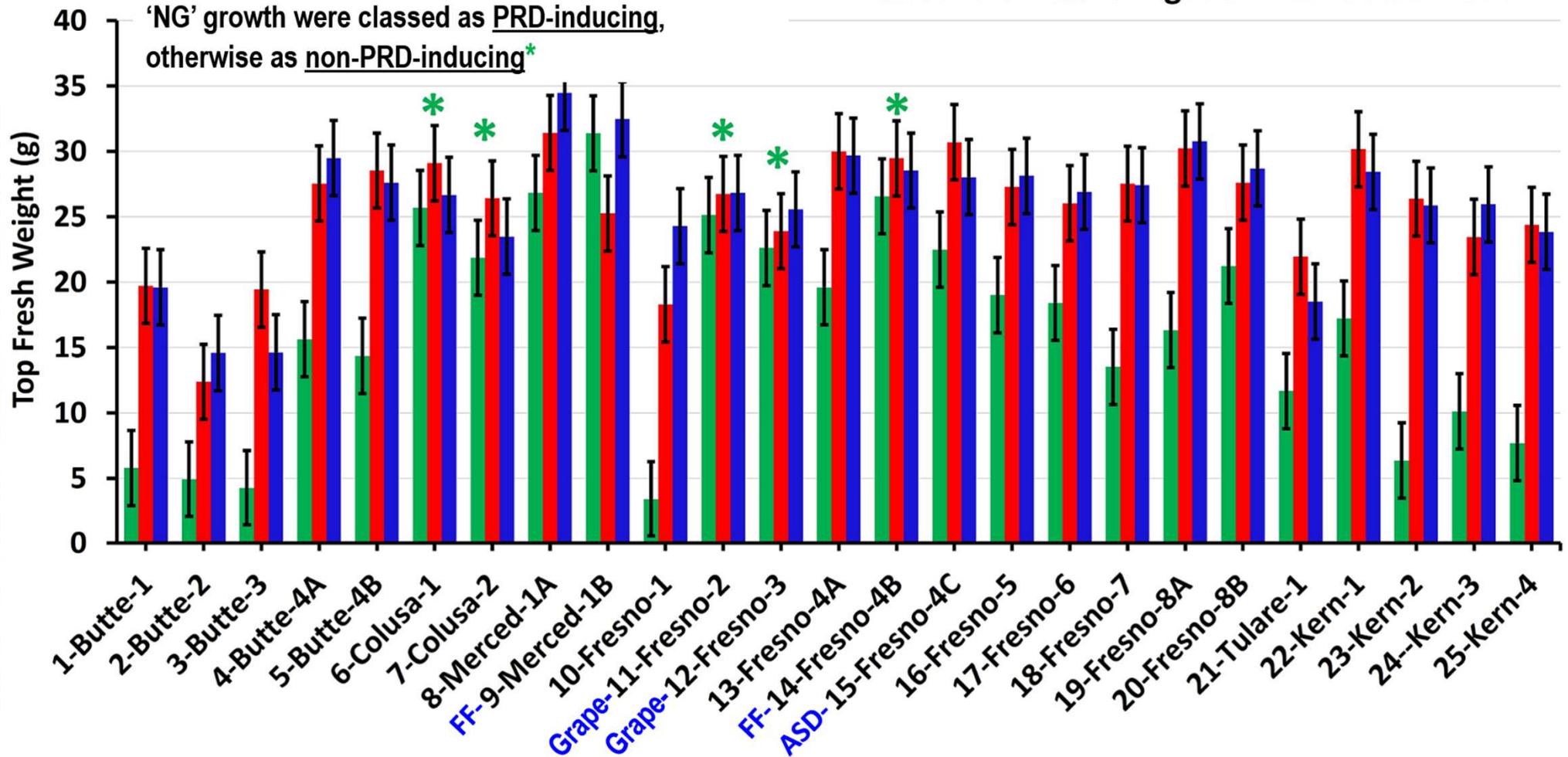
PRD etiology,
continued

Greenhouse bioassay, spring-summer 2015



Soils in which CP fum. and pasteurization improved
'NG' growth were classed as PRD-inducing,
otherwise as non-PRD-inducing*

■ Control ■ Fumigation ■ Pasteurization



PRD etiology, continued

Key results, systematic approach to soils and roots and their microbial communities associated with PRD induction.

Soil-focused paper, 2021, PLOS ONE:

Characterization of soils conducive and non-conducive to Prunus replant disease

Abdur R. Khan¹, Wisnu A. Wicaksono^{1a}, Natalia J. Ott², Amisha T. Poret-Peterson², Greg T. Browne^{2*}

From the soil-focused paper:

- PRD induced in 18 of 25 soils
- PRD severity correlated positively w/ exch K, pH
- PRD induction capacity coincided w/ shifts in bacterial, fungal oomycete communities among replant soils
- No PRD relation to nematode counts
- **From soil, no specific “easy targets” for PRD diagnostics, but distinction between PRD-inducing and non-inducing was possible (with collected sets).**

Root-focused paper, 2022, PLOS ONE:

Random forest analysis reveals taxa predictive of Prunus replant disease in peach root microbiomes

Abdur R. Khan^{1a}, Wisnu A. Wicaksono^{1ab}, Natalia J. Ott², Amisha T. Poret-Peterson², Greg T. Browne^{2*}

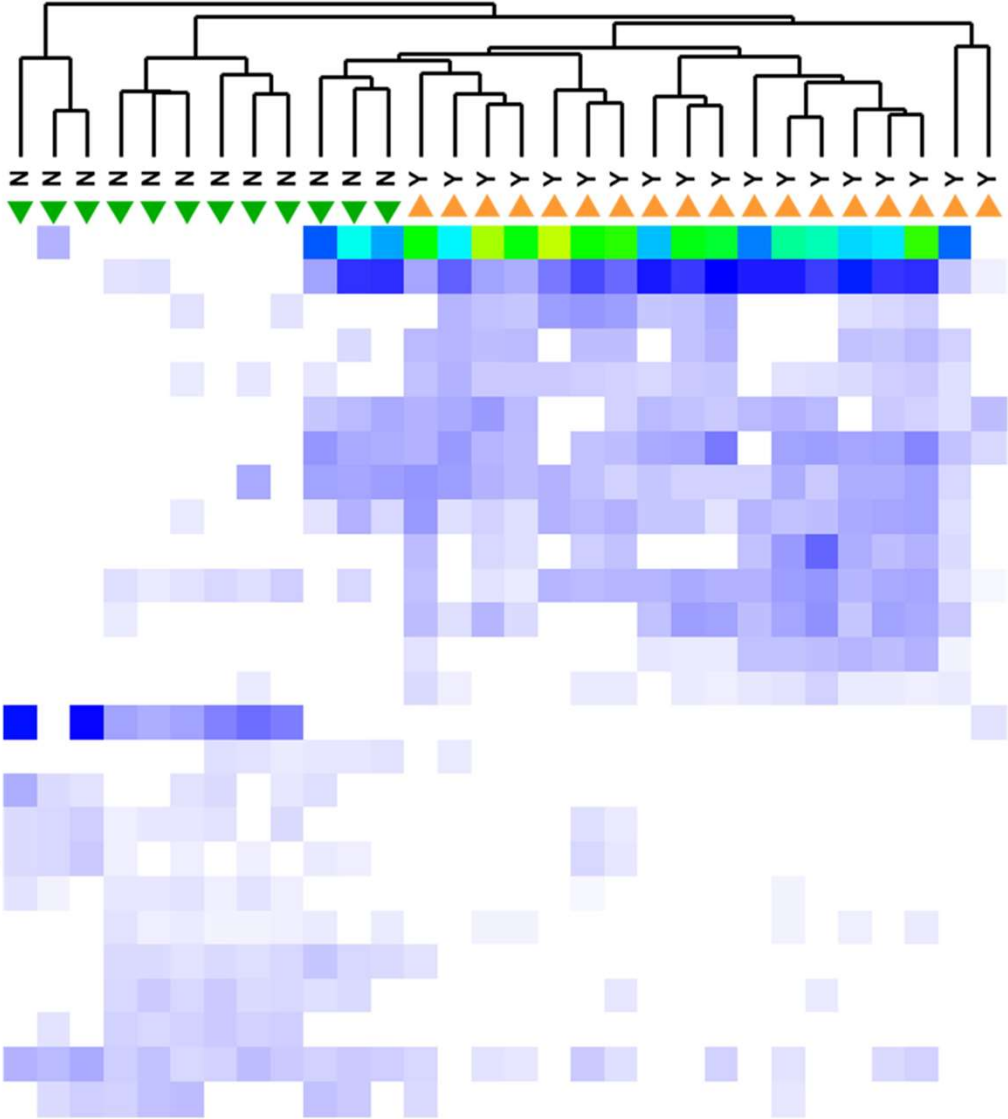
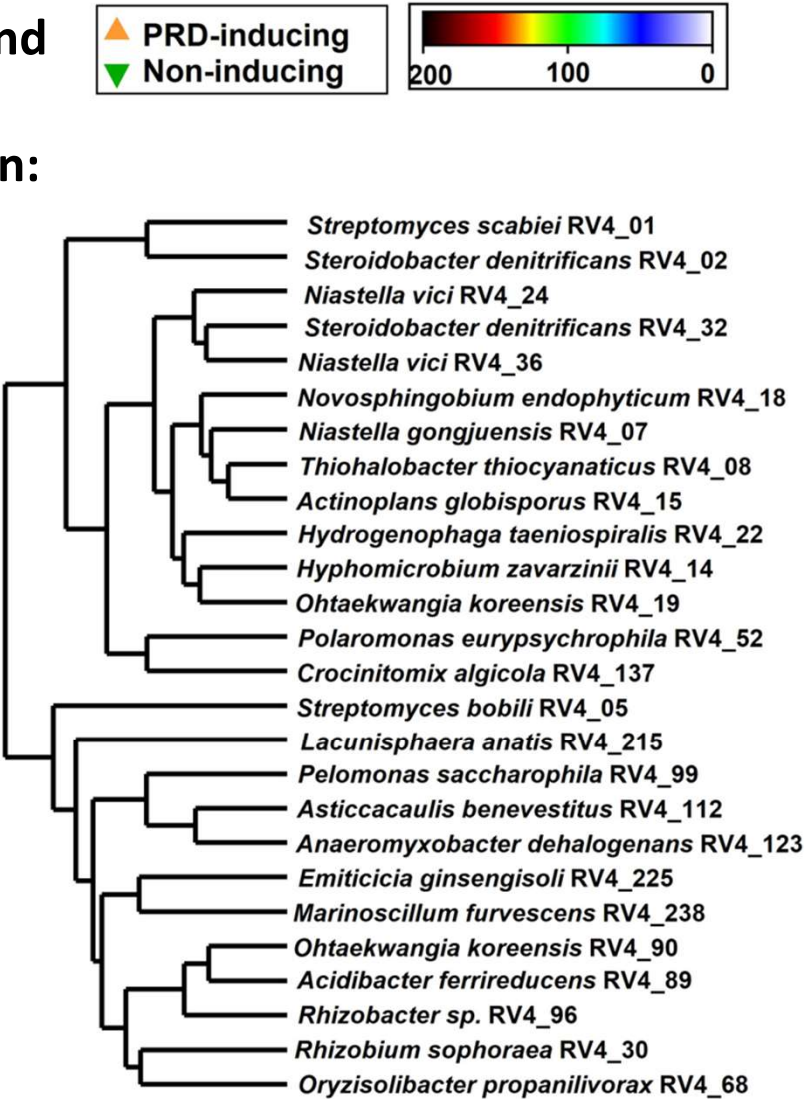
From the root-focused paper:

- Bacterial, fungal, and oomycete root communities characterized from 6 PRD-inducing & 4 non-inducing soils
- Bacterial taxa were prominent as PRD predictors
- Among the most abundant root bacteria, **abundances of *Streptomyces scabiei* and *Steroidobacter denitrificans* were positively correlated with PRD incidence.**
- *Streptomyces bolbili* and *Pythium mamillatum* abundances were negatively correlated with PRD incidence
- **From roots, worthy candidate targets identified for further study in PRD etiology**

PRD etiology, contd.

Heatmap and clustering visualization:

Top-26 root-associated bacteria associated with PRD incidence



Shifting to Mgt: RP mgt. considerations before replanting

Replant problem (RP)	Crop specificity	Predictive lab diagnostics?	Key management components
Physical and chemical soil challenges 	Low	Yes, acceptable soil parameters known, preplant testing <u>useful</u>	Preplant soil remediation, orchard design, rootstock choice, cultural practices, etc.
Phytophthora diseases 	Medium	(Yes), causal agents known, preplant testing and history <u>partially useful</u>	<u>Strategic orch. design and culture</u> ; esp. w/ rootstock choice, soil H ₂ O mgt., & (potentially) fungicide use
PP nematodes 	Medium	Yes, causal agents known, preplant testing <u>useful</u>	<u>Fallow, fumigants, anaerobic soil disinfestation (ASD)</u> , rootstock choice, postplant nematicides, etc.
Prunus replant disease (PRD) 	High (<i>Prunus</i> after <i>Prunus</i>)	No, causal agents not resolved. But, <u>local field-fum-trial-based orch. assessments are useful.</u>	<u>Fallow, fumigants, ASD, WOR, rootstock choice</u> , optimal N and P fertilization

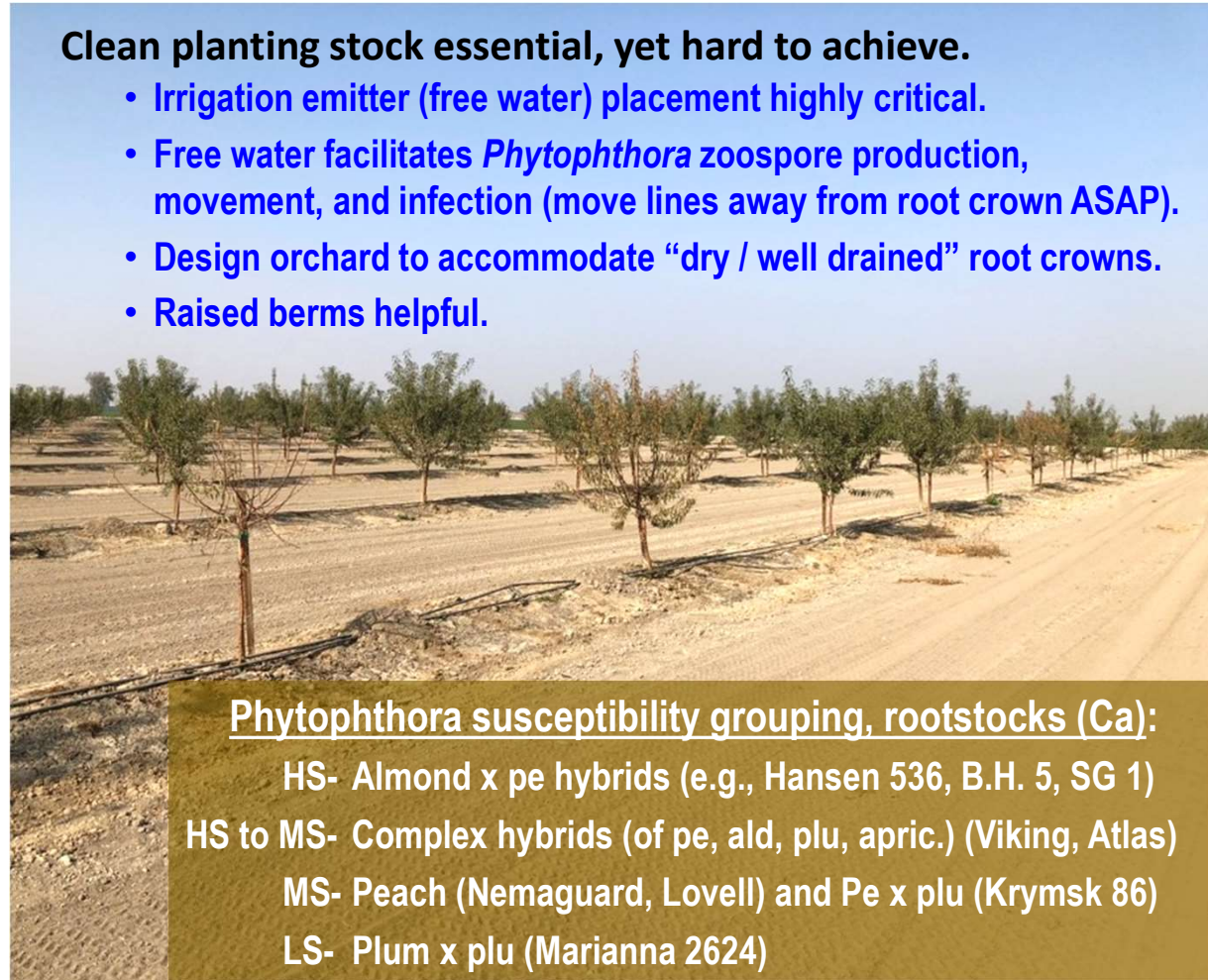
Mgt. of RPs,
contd.

Strategic orchard design & culture for *Phytophthora* crown and root rots, a common but not universal RP in Ca



Clean planting stock essential, yet hard to achieve.

- Irrigation emitter (free water) placement highly critical.
- Free water facilitates *Phytophthora* zoospore production, movement, and infection (move lines away from root crown ASAP).
- Design orchard to accommodate “dry / well drained” root crowns.
- Raised berms helpful.



Phytophthora susceptibility grouping, rootstocks (Ca):

- HS- Almond x pe hybrids (e.g., Hansen 536, B.H. 5, SG 1)
- HS to MS- Complex hybrids (of pe, ald, plu, apric.) (Viking, Atlas)
- MS- Peach (Nemaguard, Lovell) and Pe x plu (Krymsk 86)
- LS- Plum x plu (Marianna 2624)

Mgt. of RPs,
contd...

Fumigant formulations of choice for PPN & PRD

(based on data from many almond and other stone fruit replant trials)

1,3 dichloropropene (1,3-D) (Telone II)

- Good for PPN, weak on PRD

Chloropicrin (CP)

- Good for PRD, weak on PPN

1,3-D + CP (mixtures & co-applications)

- Good for both PRD and PPN

Browne et al. 2013. California Agriculture 67:128-138.
<http://californiaagriculture.ucanr.edu>



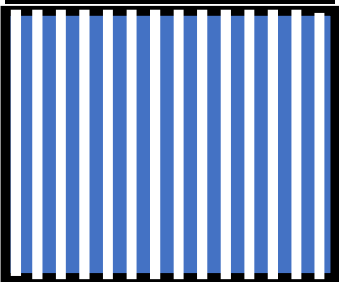
Mgt. of RPs, continued...

Fumigant placement options in Ca and AU, GPS-based control and recording

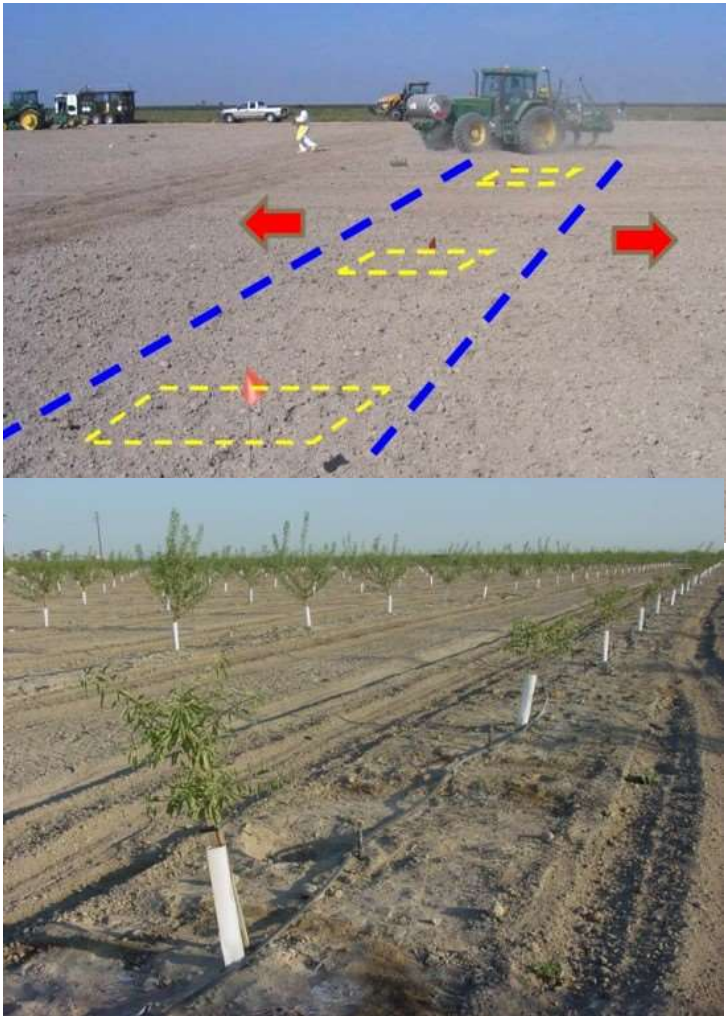
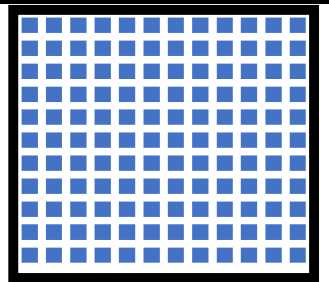
Broadcast
100% coverage



Strip
~50% coverage



GPS-Spot
<20% coverage



Mgt. of RPs,
contd.

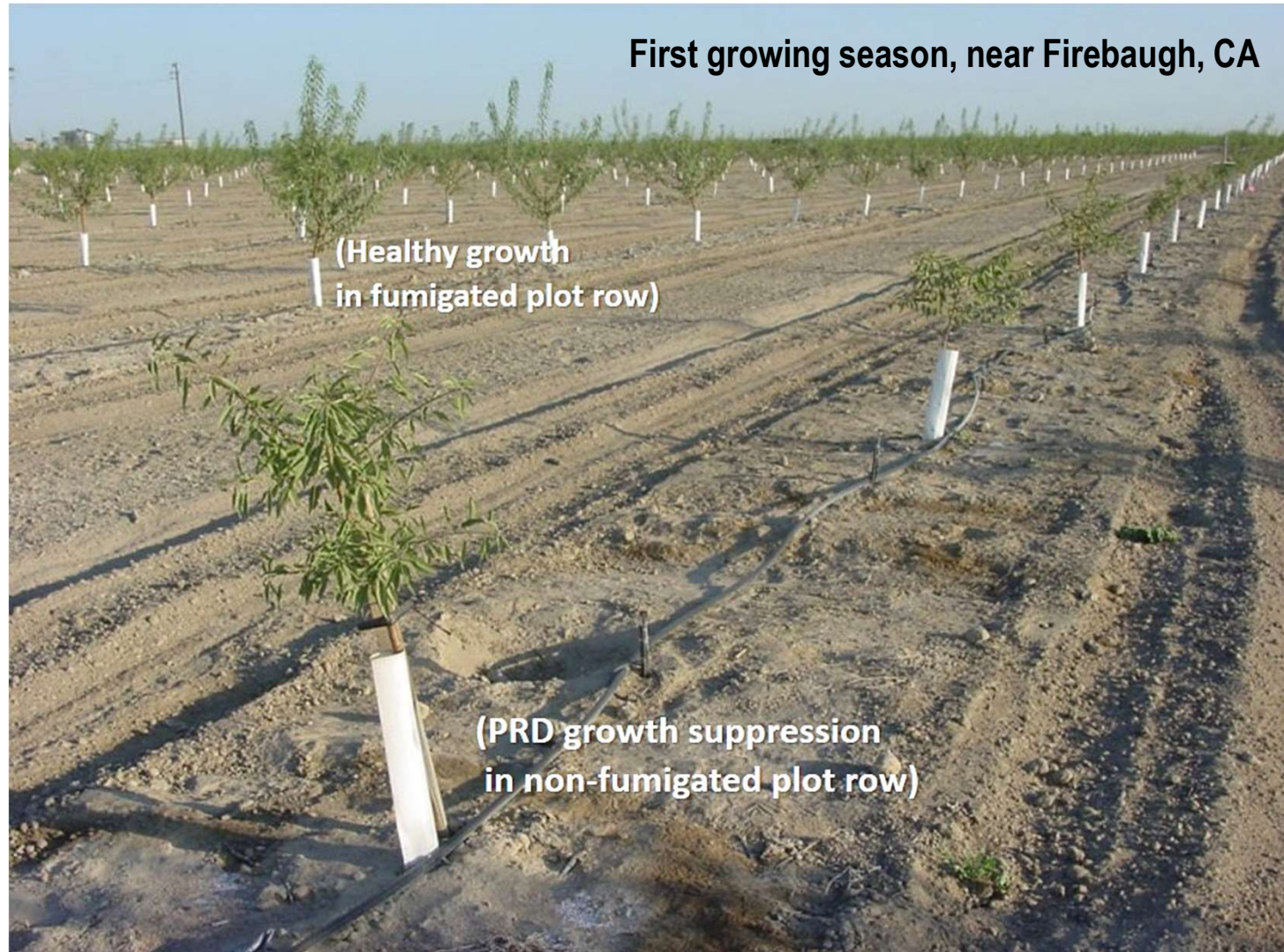
Use of preplant soil fumigation as a predictive tool for PRD

Right foreground: PRD-affected trees, control plot

Left background: Healthy trees growing in soil fumigated w/ chloropicrin plus 1,3-dichloropropene

(No significant populations of phytopathogenic nematodes or acute pathogens were present; well-prepared soil)

Results of small replicated fumigation trials in trial replant blocks can be invaluable for evaluating PRD risk & whether or not to fumigate larger adjacent land areas, especially when PPN not present.

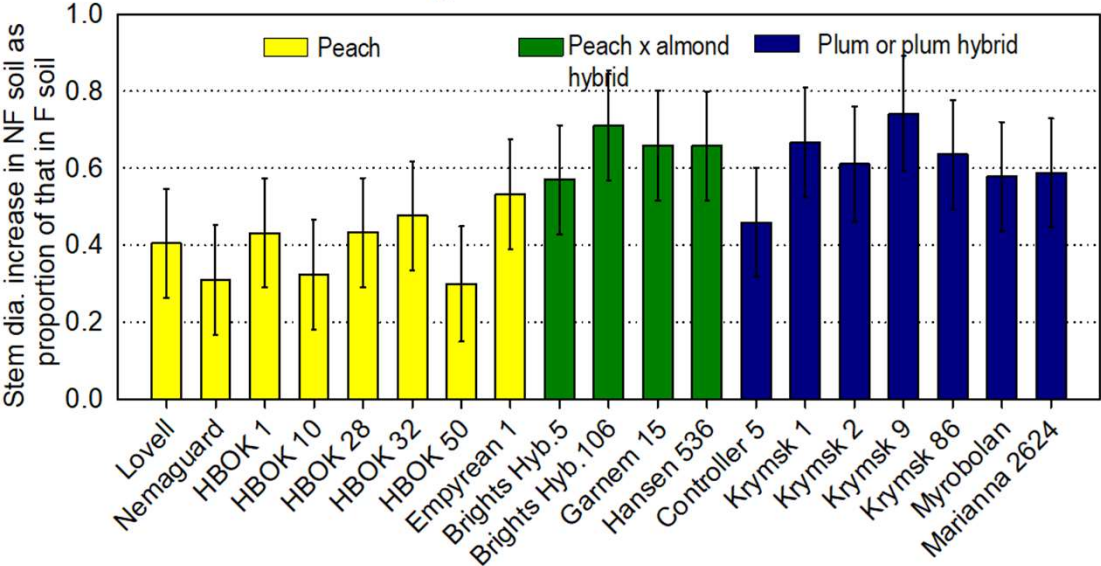
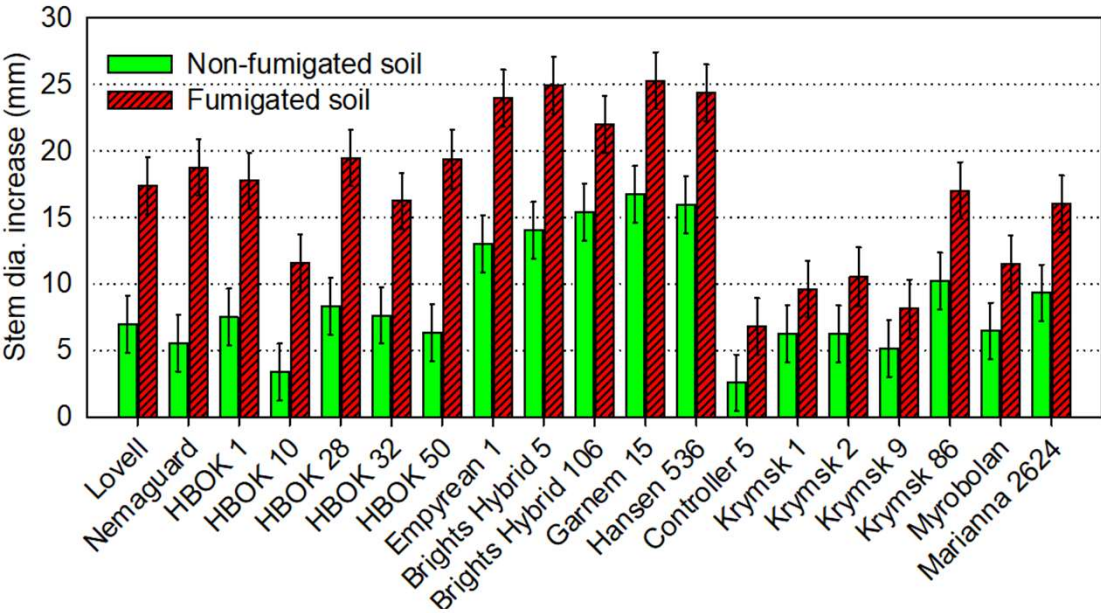


The impact of rootstock (x fumigation) for PRD



2011-13 rootstock x fumigation trial, Parlier

Browne et al. 2013. California Agriculture 67:128-138.
<http://californiaagriculture.ucanr.edu>



Mgt. of RPs, continued...

Agricultural byproducts as fumigant alternatives?



Rice bran (Rb), byproduct of milling process

- $\sim 190 \times 10^3$ metric tons / year in CA
- ~ 220 \$ / metric ton
- C:N = 19
- % N-P-K = 2.4-1.8-1.4



Ground almond hull and shell (Ahs)

- $\sim 3.4 \times 10^6$ metric tons/ year in CA
- ~ 121 \$ / metric ton
- C:N = 41
- % N-P-K = 0.9-0.1-2.1

Mgt. of RPs, continued...

Components of anaerobic soil disinfestation (ASD)



Typical responses to ASD in soil

During ASD process:



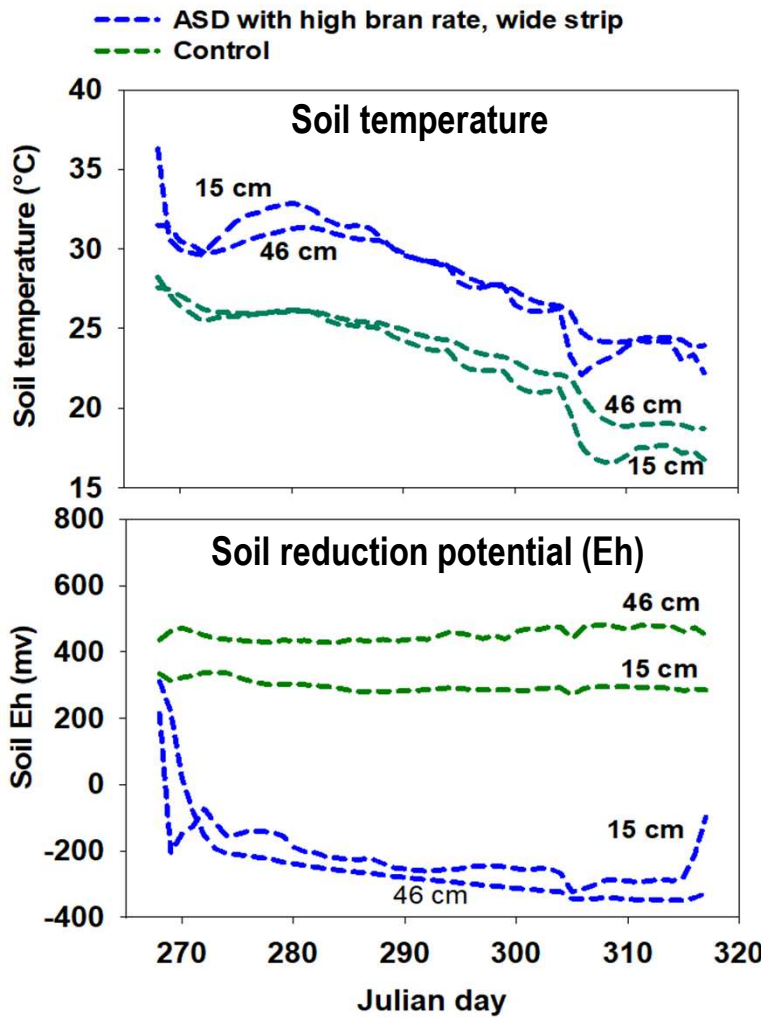
- Increase in temperature
- Decrease in redox potential
- Microbial community proliferation & shifts
- Gen. of organic acids, volatiles
- Reduction in soil pH
- Reduced soil pest populations

After ASD process:



- Microbial community shifts
- Reduced soil pest populations
- Reduction in soil pH
- Increased levels of some nutrients (e.g., NPK)

During ASD process:



Mgt. of RPs,
continued...

Trialing ASD and soil amendment treatments, KARE, Parlier, 2020-2026

Seven preplant soil treatments, each applied to four 150 ft x 19 ft plots in RCBD



Amendment treatments (Ahs, Rb) at 9 t/ac and control (& Ctl)



Full ASD treatments (Ahs+WT, Rb+WT) (9t/ac) and (&Ctl+WT)



The standard: shanked 1,3-dichloropropene + chloropicrin (Fum)



Assessment: Planted 'Monterey' and 'Nonpareil' on NG, May 2021

Mgt. of RPs,
continued...

Treatment assessments for ‘Monterey’ and ‘Nonpareil’ in KARE trial

- Increases in trunk cross sectional area from date of planting (TCSA, cm²)
- Nut (kernel) yields (kg ha⁻¹)



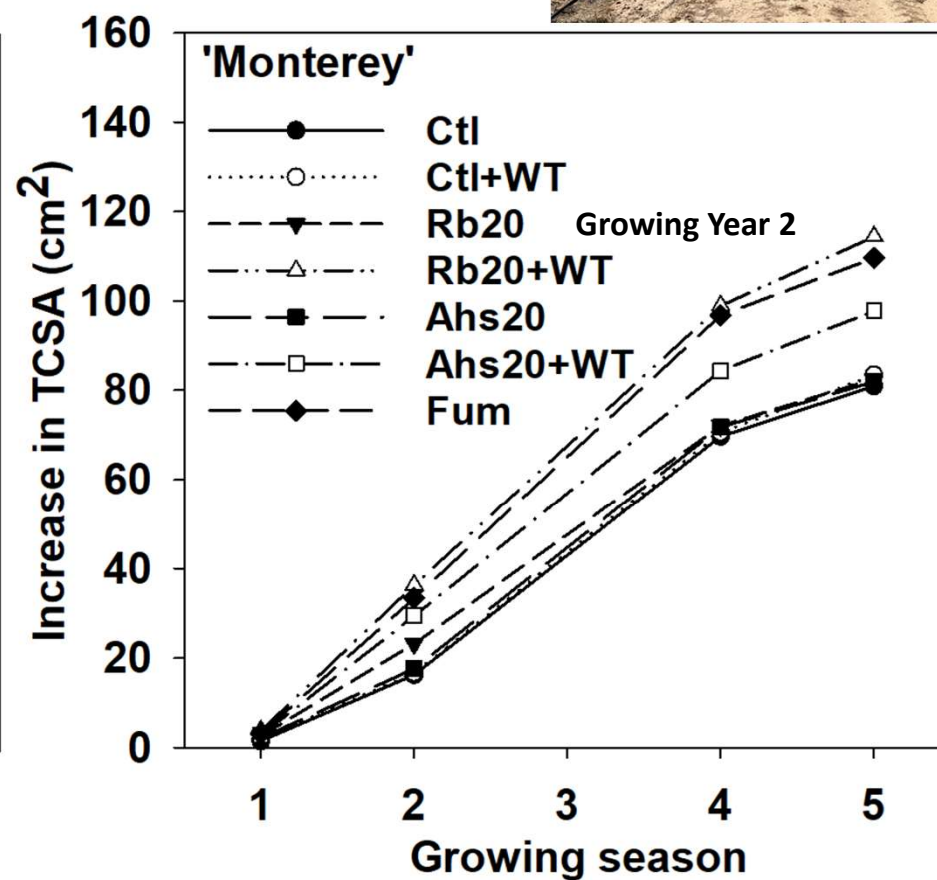
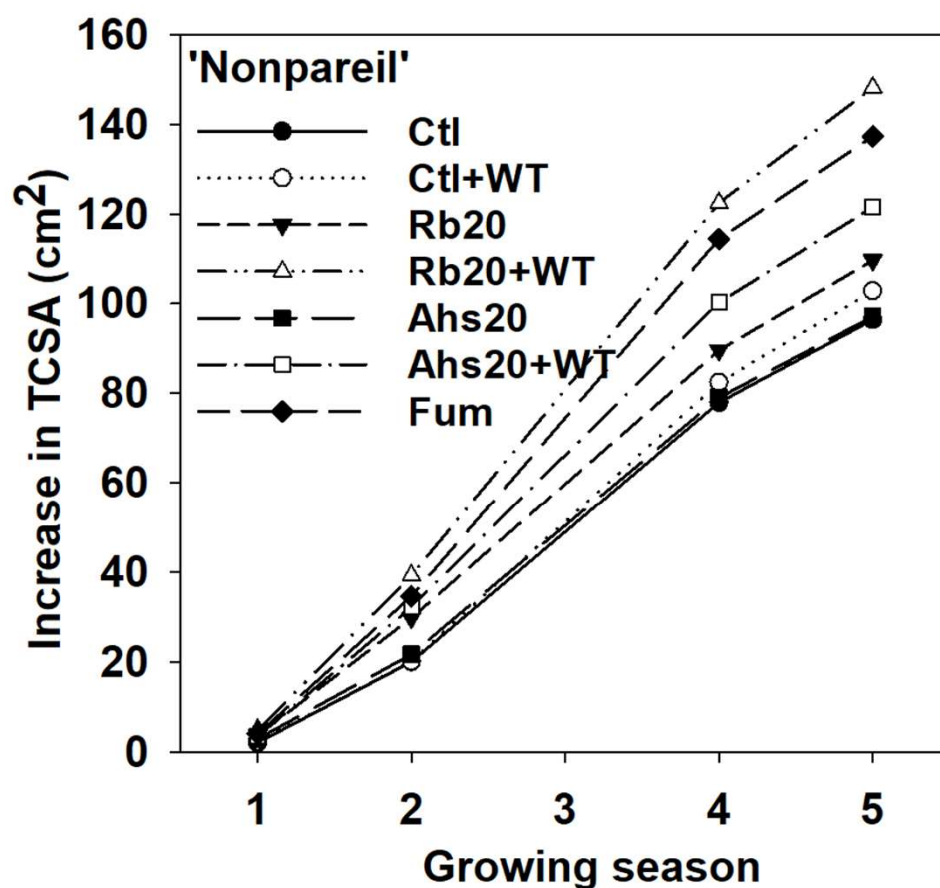
Seven preplant treatments applied to four 12-tree row-strip plots in RCBD:

Treatments:

- | | | | |
|-----------|------------|-------------|--------------------------|
| 1. Ctl | 3. Rb20 | 5. Ahs20 | 7. Fum 1,3-D +Pic, shank |
| 2. Ctl+WT | 4. Rb20+WT | 6. Ahs20+WT | |

Increases in trunk cross sectional area

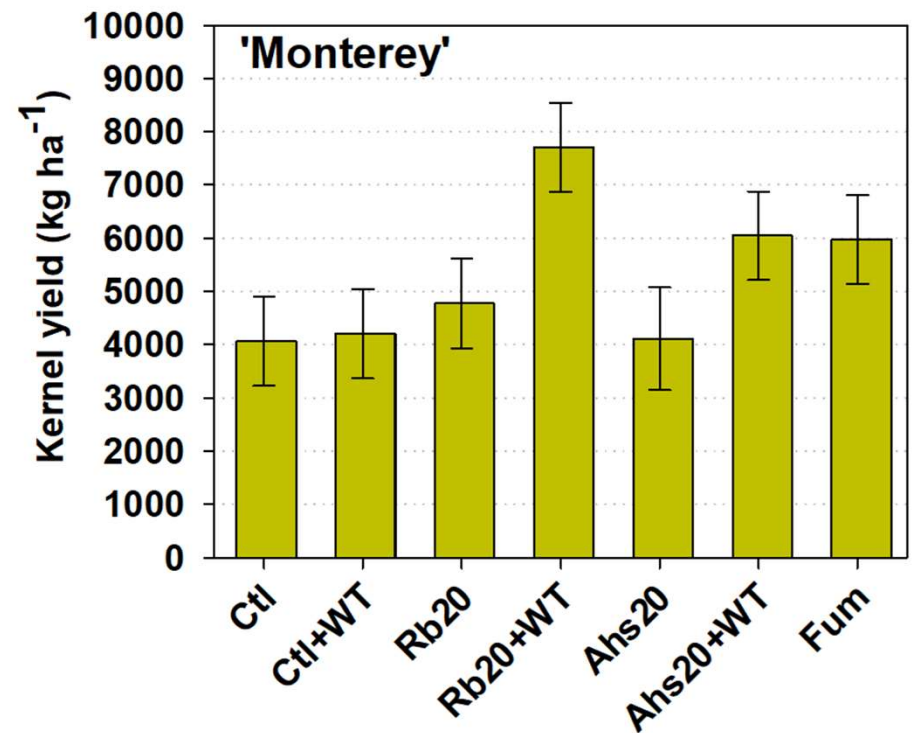
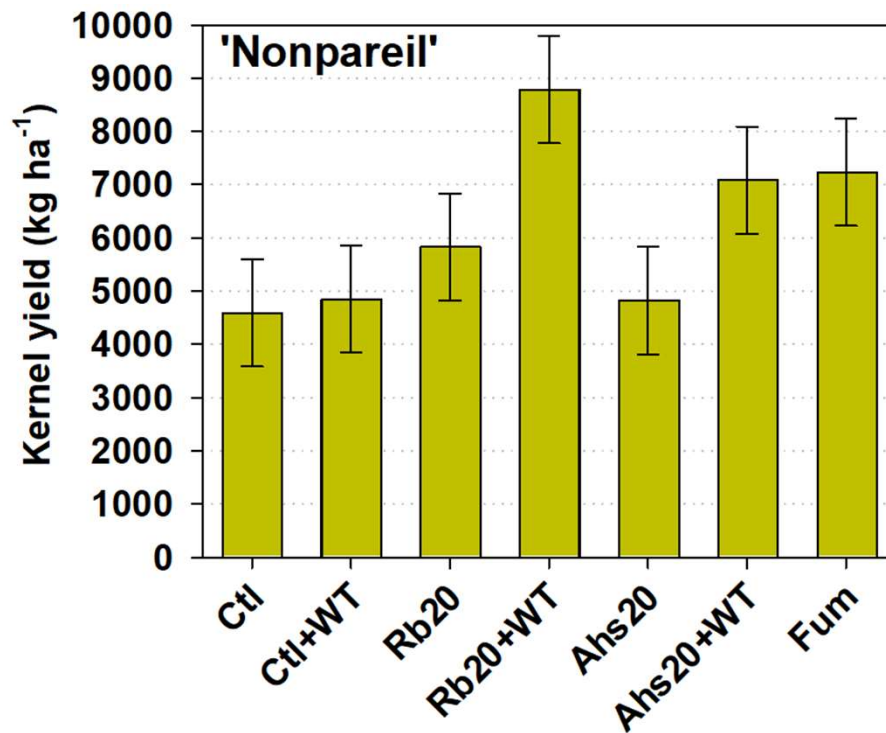
Growing seasons 1-5 after planting (2021-2025)



Mgt. of RPs, KARE 2021-2026 trial continued...

Nut kernel yields (cumulative)

Growing seasons 3-6 after planting (2023-2026)



Mgt. of RPs, continued...

Economic estimates of preplant treatment values, based on 4-yr cumulative yields, KARE replant trial 2021-2026.

Notes:

- About 1/3 of ASD costs (for Rb20+WT, Ahs20+WT) are for tarping and tarp disposal.
- Limited data indicate tarping may not be needed for PRD management.
- Fumigation costs here did not include tarp, which may be required in future.



For 'Nonpareil', based on \$5.26/kg

Preplant treatment	Preplant trt. cost (\$/ha)	Cum. yield (kg/ha)	Cum. yield value (\$/ha)	Cum. yield value minus trt. cost (\$/ha)
Ctl	0	4,588	24,133	24,133
Rb20	3,139	5,829	30,661	27,521
Rb20+WT	5,412	8,783	46,199	40,787
Ahs20	2,339	4,821	25,359	23,020
Ahs20+WT	4,611	7,086	37,274	32,662
Fum	3,540	7,230	38,027	34,488

For 'Monterey', based on \$4.74/kg

Preplant treatment	Preplant trt. cost (\$/ha)	Cum. yield (kg/ha)	Cum. yield value (\$/ha)	Cum. yield value minus trt. cost (\$/ha)
Ctl	0	4,065	19,268	19,268
Rb20	3,139	4,774	22,629	19,489
Rb20+WT	5,412	7,704	36,517	31,106
Ahs20	2,339	4,113	19,495	17,156
Ahs20+WT	4,611	6,046	28,657	24,045
Fum	3,540	5,973	28,312	24,773

Impacts of whole orchard recycling (WOR) on PRD Mgt



Brent Holtz



Brent Holtz

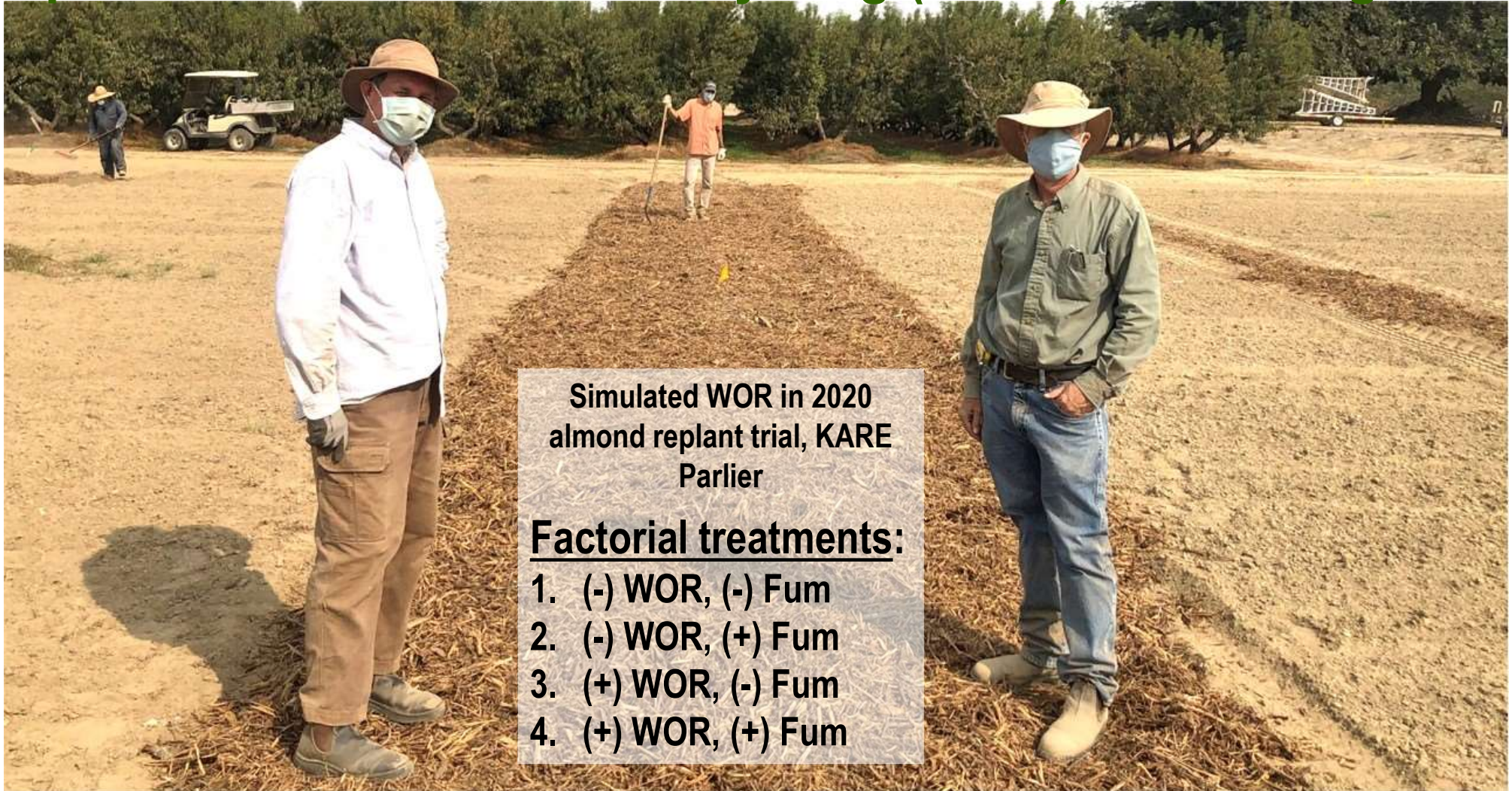


Brent Holtz



Brent Holtz

Impacts of whole orchard recycling (WOR) on PRD Mgt



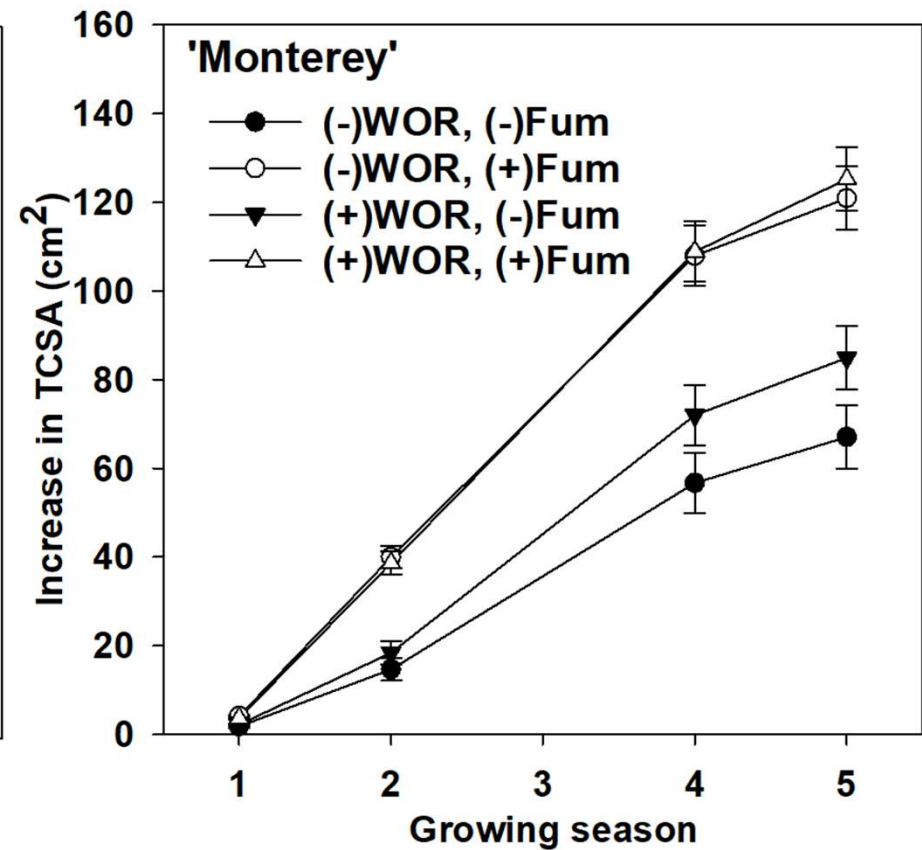
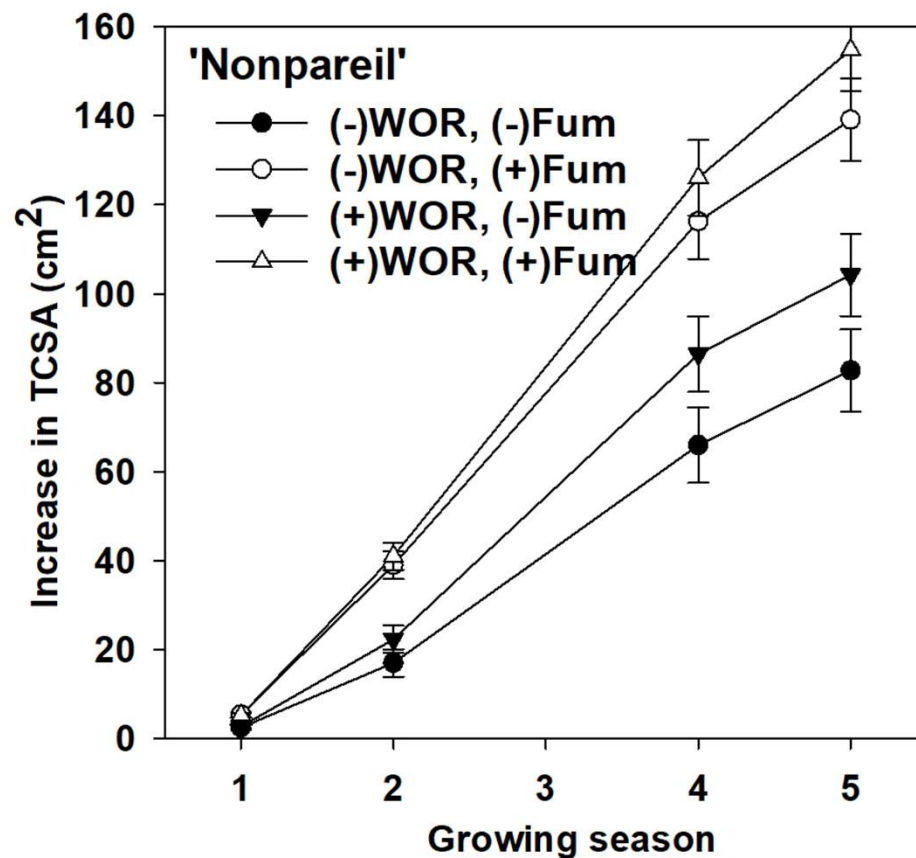
**Simulated WOR in 2020
almond replant trial, KARE
Parlier**

Factorial treatments:

- 1. (-) WOR, (-) Fum**
- 2. (-) WOR, (+) Fum**
- 3. (+) WOR, (-) Fum**
- 4. (+) WOR, (+) Fum**

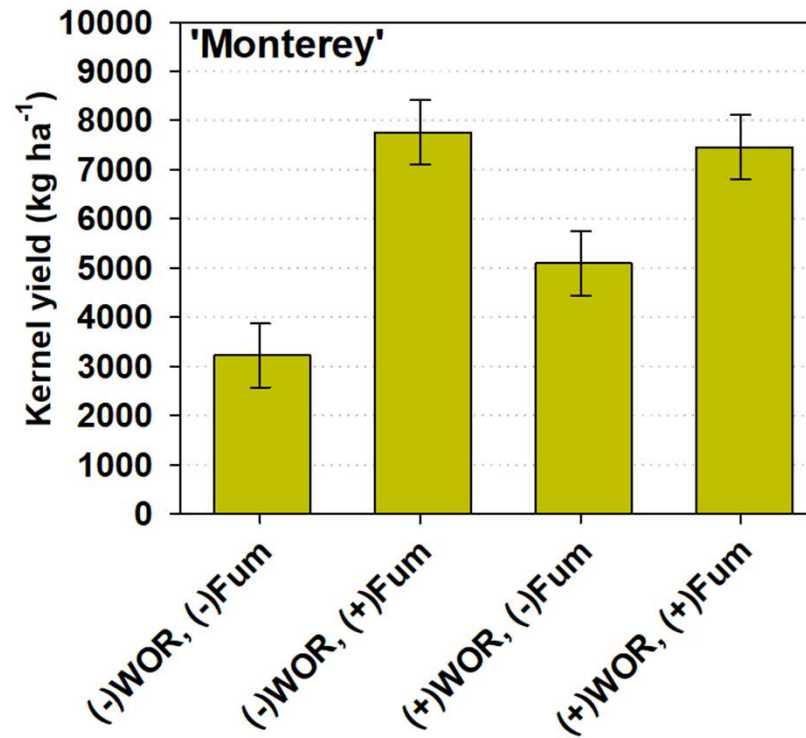
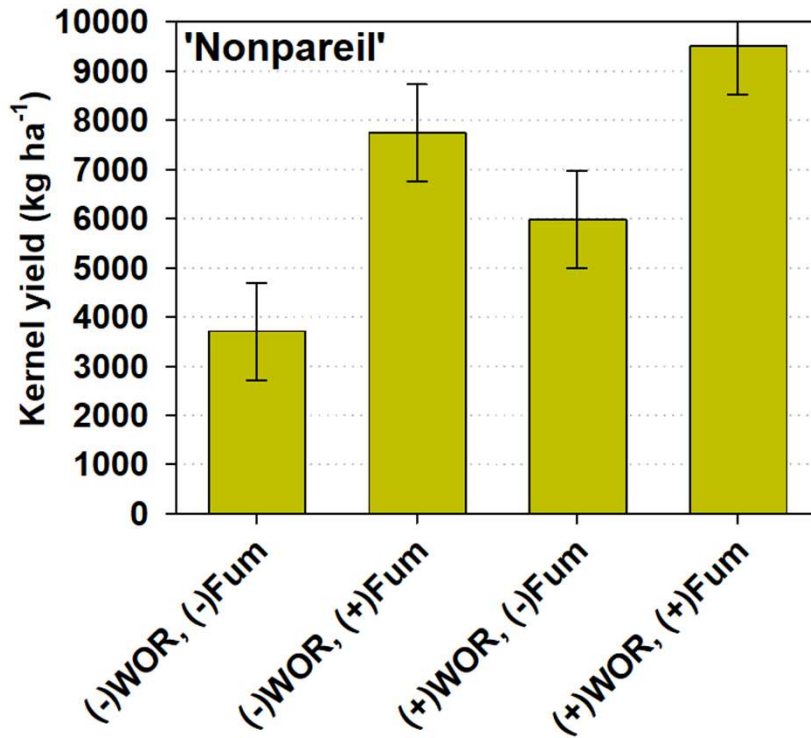
WOR x Fum trial results, tree TCSA growth

Growing seasons 1-5 after planting (2021-2025)



WOR x Fum trial results, nut kernel yields

Growing seasons 3-6 after planting (2023-2026)



Notes:

- Based on replicated trials, WOR is compatible with ASD.
- WOR chips alone are not a good carbon source for ASD, but ASD based on Ahs carbon source worked effectively in the presence of WOR chips.

Closing comments, ideas

1. Promising research and management directions for RPs, based on results to date:

- **Lab diagnostics for PRD.**
- **Locally optimized ASD** (i.e., targeting: local economical C-sources, water use optimization, non-tarped methods, integration of WOR and fallowing).
- **Ag byproducts utilization for general soil improvement** (incl. WOR, hulls, shells, etc).
- **Soil fertility-RP interactions** (e.g., robust almond tree growth responses to **phosphate fertilization** at planting were documented repeatedly in replant trials (not discussed).

2. Promising AU-specific RP research and management directions:

- **Regional replant trials** (adaptive, interdisciplinary, farm-based, industry-allied).
- **AU-specific lab diagnostics for PRD** (systematic, field-trial-integrated, including use of AI modeling to predict PRD, other RPs) (**SARDI diagnostic strengths**).
- **Regional abiotic and biotic RP database** developed, shared.
- **Regional trialing of rootstocks for RP performance** (with rootstock priorities based on local needs & experience).
- **Regional trialing of fallowing vs. fumigation vs. ASD**, using chosen rootstocks. (Every year of fallow said to decrease PRD severity by ~50%).



Many Thanks!

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Closing comments, ideas

3. Orchard design considerations, especially for *Phytophthora*:

- **Design orchards to leave sufficient room between rows for drip line placements that will not wet trunk or root crown as orchard matures.** (Design to irrigate the roots, not the root crown; move lines out ASAP). This is good practice for avoiding fungal wood rot pathogens too (e.g., *Ganoderma*).
- **Choose rootstock(s) carefully**, with awareness of soil adaptation and *Phytophthora* susceptibility.
- **Consider planting trees on raised berms** to shed water, unless soil water drainage and infiltration are very good.
- **Design irrigation system not to exceed soil water infiltration rate.**
- **Train trees to spread scaffold branches vertically** along trunk and avoid the following: narrow branching angles, “water pockets”, compression cracks and limb breakage, all of which can favor aboveground infection by *Phytophthora* species.
- **If needed, consider use of phosphite** treatments after shoot elongation and before leaf senescence (foliar sprays optimal, chemigation ok during high ET).



Many Thanks!

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