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The economic viability of suppressive crop rotations for the control of verticillium wilt in organic strawberry production

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ABSTRACT

Soil-borne diseases and nitrogen availability are important limits on organic strawberry production. A trial using suppressive crop rotations to combat Verticillium wilt was conducted to see its effects on strawberry yields and net returns using a split-split-plot design. An ANOVA analysis was run to understand determinants of net returns. Results show that the suppression of wilt through the planting of non-host crops such as broccoli before the planting of strawberries can have significant effects on yield and net returns, and that suppressive crop rotations are potentially commercially viable.

KEYWORDS
Organic strawberry; crop rotation; integrated pest management; net returns; economic evaluation

Organic strawberry production in California totaled 94 million dollars in farm-level sales in 2012, around 4% of the total value of strawberry production in California (Klonsky and Healy 2013). Apart from weeding and arthropod pests, production is mainly limited by lethal and non-lethal soil-borne diseases and a lack of late-season nitrogen (N) in the soil caused by the unavailability of effective liquid organic fertilizers that can be applied via fertigation (Muramoto, Gaskell, and Shennan 2016). Verticillium wilt, caused by *Verticillium dahliae*, is a major lethal soil-borne disease for organic strawberries. Prior to the widespread use of methyl bromide for pre-plant soil fumigation beginning in the 1960s, Verticillium wilt was the major disease that affected strawberries (Wilhelm, Storkan, and Sagen 1961). Fusarium wilt (Koike, Kirkpatrick, and Gordon 2009) and charcoal rot (Koike 2008) have emerged as important lethal soil-borne diseases in recent years for organic strawberries as well (Shennan and Muramoto 2016). Although it is not lethal, black root rot caused by soil-borne pathogens such as *Pythium* spp., and *Rhizoctonia* spp. can also reduce fruit yields in organic strawberries (Subbarao, Martin, and Koike 2012). Regarding fertilizer, strawberries in the coastal California have a consistent N demand

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throughout the harvest season that typically lasts 6 months or more and it is a challenge to synchronize the N supply with the N demand in organic systems (Muramoto and Gaskell 2012).

Crop rotations are commonly used to suppress various diseases and, in the case of strawberries, rotations with *V. dahliae* non-host crops like broccoli can reduce the severity of Verticillium wilt (Muramoto et al. 2014; Subbarao et al. 2007). Unfortunately, more profitable rotation crops, like lettuce, are hosts and can increase the severity of Verticillium wilt in subsequent strawberry crops. An ongoing organic strawberry/vegetable rotation study, the "Mother Trial" is testing different crop rotations coupled with either anaerobic soil disinfestation (ASD) or mustard seed meal (MSM) as additional disease management strategies (Shennan and Muramoto 2016). ASD involves incorporation of a labile carbon source, followed by covering the soil with plastic tarp and irrigating to saturate the soil. This creates anaerobic conditions and breakdown of the carbon by various fermentation pathways that produce volatiles and other compounds that are toxic to many different pathogens (Shennan et al. 2017). After three weeks holes are punched into the plastic to allow oxygen back into the soil prior to planting strawberries. Depending on the carbon source used, significant amounts of nitrogen and other plant nutrients can be added with ASD. MSM has been shown to suppress soil-borne pathogens in other systems (Mazzola, Izzo Brown, and Cohen 2007), and contains about 5% N. Thus, it was included in this experiment for both disease suppression and as an N source to enhance soil fertility.

Each treatment is evaluated based on its capacity to suppress disease, patterns of soil N availability, crop yields, and its economic performance. The economic viability of the rotations considered in this trial is the outcome of a classic dynamic tradeoff between current and future net returns (gross revenues less costs) that occurs in many bio-economic systems: is it better to forego current net returns for better disease control, yielding higher option value for future strawberry production, or to sell something with higher potential gross revenues (price multiplied by yield), and realize higher current net returns, but lower future net returns due to inadequate disease control? This is the first study that quantifies these tradeoffs for organic rotations, using results from the first four years of the Mother Trial.

Data and methods

Experimental design

The first four years of the Mother Trial were conducted from November 2011 to November 2015. The trial is located at the organic farm in the University of California, Santa Cruz (UCSC. 36.982504, −122.056449) with Elkhorn sandy loam soil (fine-loamy, mixed, thermic pachic argixerolls) naturally infested with

V. dahliae. The experiment is a split-split plot design with four replicates. It compares two- and four-year vegetable/strawberry rotations (main plots) using two combinations of crops (sub-plots) believed to be either suppressive (broccoli-based) of Verticillium wilt, or more profitable but more conducive to disease (lettuce-based). Superimposed on the rotations are soil fertility/disease management treatments (sub-sub plots): legume/cereal winter cover crop with ASD prior to strawberries (CC), legume/cereal winter cover crop + compost + additional fertility amendments with ASD prior to strawberries (CC + C + F), cereal winter cover crop + mustard seed meal (MSM), or a bare fallow untreated control (BF) (Table 1). This results in 16 treatments replicated four times for a total of 64 plots. Each plot is 3.7 m wide and 6.9 m long consisting of 4 beds (0.93 m-wide (center-to-center) with 6.9 m-long each) for vegetables and strawberries. Middle 2 beds were used for all data collections.

Table 1. Overview of the Mother Trial treatments.

	Year 1		Year 2			Year 3		Year 4
	Fall/winter	Crop	Fall/winter	Crop 1	Crop 2	Fall/winter	Crop	Crop
Four-year rotations								
1a	CC*	Broccoli	CC	Lettuce	Cauliflower	CC	Broccoli	ASD/ Strawberry
2a	CC + C + F**	Broccoli	CC + C + F	Lettuce	Cauliflower	CC + C + F	Broccoli	ASD/ Strawberry
3a	Cereal CC + MSM***	Broccoli	Cereal CC + MSM	Lettuce	Cauliflower	Cereal CC + MSM	Broccoli	Strawberry
4a	Fallow	Broccoli	Fallow	Lettuce	Cauliflower	Fallow	Broccoli	Strawberry
5a	CC	Lettuce	CC	Lettuce	Broccoli	CC	Lettuce	ASD/ Strawberry
6a	CC + C + F	Lettuce	CC	Lettuce	Broccoli	CC	Lettuce	ASD/ Strawberry
7a	Cereal CC + MSM	Lettuce	Cereal CC + MSM	Lettuce	Broccoli	Cereal CC + MSM	Lettuce	Strawberry
8a	Fallow	Lettuce	Fallow	Lettuce	Broccoli	Fallow	Lettuce	Strawberry
Two-year rotations								
1b	CC	Broccoli	ASD**** – -Strawberry – – – – –			CC	Broccoli	ASD/ Strawberry
2b	CC + C + F	Broccoli	ASD – – – -Strawberry – – – – –			CC + C + F	Broccoli	ASD/ Strawberry
3b	Cereal CC + MSM	Broccoli	– – – – – -Strawberry – – – – –			Cereal CC + MSM	Broccoli	Strawberry
4b	Fallow	Broccoli	– – – – – -Strawberry – – – – –			Fallow	Broccoli	ASD/ Strawberry
5b	CC	Lettuce	ASD – – – -Strawberry – – – – –			CC	Lettuce	ASD/ Strawberry
6b	CC + C + F	Lettuce	ASD – – – –Strawberry – – – – –			CC + C + F	Lettuce	Strawberry
7b	Cereal CC + MSM	Lettuce	– – – – – -Strawberry – – – – –			Cereal CC + MSM	Lettuce	Strawberry
8b	Fallow	Lettuce	– – – – – -Strawberry – – – – –			Fallow	Lettuce	Strawberry

Source: Mother Trial Study
*: Cereal/legume cover crop
**: Cereal/legume cover crop plus compost and supplemental organic fertilizer based on soil tests prior to vegetable crops
***: Mustard Seed Meal
****: Anaerobic soil disinfestation prior to planting strawberry

Winter cover crops in the CC and CC + C + F treatments were a mixture of bell bean (*Vicia faba* L.) 45%, purple vetch (*Vicia benghalensis* L) 45%, and cereal rye (*Secale cereale* L) 10% and were drill seeded at a rate of 367 kg ha^{-1} in November each fall and incorporated with a spader in April to May. In CC + C + F treatments, compost (6.2 t ha^{-1} for vegetables and 22 t ha^{-1} for strawberries) and organic fertilizer (feather meal-based. 112 kg-TN ha^{-1} only for vegetables) were added pre-plant for each crop. The cover crop was cereal rye for MSM treatments and mustard seed meal (a mixture of *Sinapis alba* and *Brassica juncea*. Farm Fuel Inc, Watsonville, CA) was added at a rate of 2.1 t ha^{-1} for vegetables and 3.4 t ha^{-1} for strawberries >2 weeks prior to planting of each crop. Treatments BF are untreated controls and did not receive any amendments. Treatments CC + C + F received supplemental fertilizer prior to broccoli or lettuce crops if the pre-side dress nitrate test showed levels below 25 mg kg^{-1}, Strawberries grown in all treatments received supplemental fertigation from liquid organic fertilizer (7 kg-N ha^{-1} $week^{-1}$) from May to September of the harvest period.

Broccoli (*Brassica oleracea* L. (Italica group) 'Marathon') and Romaine lettuce (*Lactuca sativa* L. var. *longifolia* 'Salvius') were transplanted on June 27, 2012 in year 1. Romaine lettuce was transplanted on April 30, 2013 and broccoli and cauliflower (*Brassica oleracea* L. (Botytis group) 'Apex') was transplanted on July 25, 2013 in year 2. Broccoli and Romaine lettuce were transplanted on May 21, 2014 in year 3. Broccoli was transplanted by 2 rows per bed with 28 cm spacing between plants (78,288 plants ha^{-1}). Romaine lettuce was transplanted by 2 rows per bed with 30 cm spacing between plants (71,764 plants ha^{-1}). Cauliflower was transplanted by 1 row per bed with 30 cm spacing between plants (35,882 plants ha^{-1}). Each vegetable crop was sprinkler irrigated for the first two weeks then drip irrigated with a high flow tape (1 tape per bed) until harvest.

Strawberries (*Fragaria ananassa* Duch 'Albion') were transplanted with 1 row per bed and 25 cm spacing between plants (43,058 plants ha^{-1}) in the 2yr rotation on November 16, 2012, and on November 18, 2014 in all treatments in year 4. Prior to strawberry planting in CC and CC + C + F treatments, ASD was carried out as follows: year 2—using rice bran (10 t ha^{-1}) and molasses (12 t ha^{-1}) as the carbon source: year 4—using rice bran (13 t ha^{-1}) and molasses (9.6 t ha^{-1}). In years 2 and 4, rice bran was incorporated to a depth of 15 cm using a rolling cultivator to bed tops and beds then reshaped, and molasses (diluted with water 1:2) added through the drip line. In year 2 the ASD treatment lasted 29 days and was terminated on November 9, 2012, in year 4 treatment lasted 31 days ending November 17, 2014. Water was applied through drip lines to create anaerobic conditions, 10.6 ha mm (+30 mm precipitation) in year 2; and 17.7 ha mm in year 4. Strawberry plants were drip irrigated throughout the growth period.

Vegetable crop yield was evaluated by harvesting 3.0 linear-m of each of the middle two beds per plot. When the harvest continued for more than one day, it was done by block(s) for each date. Romaine lettuce was harvested on August 15 and 16, 2012 and broccoli on September 4 and 11, 2012 in year

1. Romaine lettuce was harvested on June 17, 20, 24, and 27, 2013, broccoli on October 4 and 7, 2013, and cauliflower on October 7 and 11, 2013 in year 2. Romaine lettuce was harvest on July 9, 14, and 16, 2014, and broccoli on July 29 and 30, 2014 in year 3.

Strawberries were harvested from 20 marked plants bi-weekly from April 2 to September 2, 2013, and from March 12 to September 24 in 2015. Wilt scores were assessed from 20 plants in the middle 2 beds for each plot using a 1 to 5 scale with 1 = healthy plant, 2 = <25% dead leaves, 3 = 26–50% dead leave, 4 = 51–75%, 5 = 76–100% dead leaves. A wilt index was then calculated as index = ∑ (number of plants*score)/total number of plants.

Yield and wilt data were analyzed as a mixed-effects linear model with interactions between all treatments, random effects from blocks, and nested error from the split-split-plot spatial design. Mean separation was conducted at each treatment level (main, split-plot, split-split-plot, no comparisons between split-split-plot clusters) using Dunnett's Multiple Comparisons at the $p = 0.05$ critical level. Analysis was performed using the *lme* and *emmeans* packages in R (R Development Core Team; Lenth 2018).

Economic analysis

Economic viability is assessed using a partial budget analysis, which evaluates costs and gross revenues that vary across treatments in order to identify any differences in net returns. Most cost data, including seed costs, listing and shaping beds, transplanting, laying and removing drip tapes were collected during the trial and calculated on a per-plot basis. Weeding times were averaged across plots for each treatment. Water and harvest labor cost estimates required adjustments because the trial was conducted at a university farm under conditions that do not approximate commercial operations. Because water costs were prohibitively expensive at the UCSC farm for commercial agricultural production ($174 per acre-inch), we used the price of water from a University of California for strawberry production on the Central Coast (Bolda et al. 2014) of $22.50 per acre-inch. Harvest was conducted by student researchers, so for the purposes of the economic analysis we used harvest rates from various cost studies for organic lettuce, broccoli, cauliflower, and strawberries (Bolda et al. 2014, Smith, Klonsky, and De Moura 2001, Tourte et al. 2004, 2009). Following Bolda et al. (2014), fully loaded wages (including benefits) were assumed to be $25 per hour for machine operation and $12.50 per hour for other field work. Plastic tarp costs were obtained from Bolda et al. (2014).

Because many operations, such as transplanting and irrigation, were performed for many plots at once, the cost per plot was calculated by dividing the total cost of the operation by the total acreage involved. These costs did not vary across plots for each rotation in a given year, but did vary across rotations with different crops in a given year. Yields were yearly per plot yields in the case of all crops except strawberries, which had weekly per plot yields. Strawberry yields were recorded every week from the months of April to September in years 2 and 4. Price data were from the USDA Agricultural Marketing Services (AMS 2018) for the Salinas/Watsonville shipping point for romaine lettuce, cauliflower, broccoli and organic strawberries. Weekly prices during the harvest season were used for organic strawberries. The average daily price in the month of harvest was used for broccoli, cauliflower, and lettuce. Price data were not available for organic broccoli, lettuce or cauliflower during the trial period; AMS only began reporting those data in 2016. Instead of using conventional prices, the average 2016 daily organic-conventional price ratio was calculated for the harvest month. This multiple was then multiplied by the conventional price to obtain the price used to calculate net returns. As a point of comparison, for strawberries the average organic-conventional price multiple for the years 2009–2015 was around 1.6, which is similar to the average daily price ratio for 2016 used for lettuce (1.8), broccoli (1.5) and cauliflower (1.3).

Strawberry prices were weekly prices for 8–1 lb containers from April to September 2013 and from April to September 2015. Broccoli prices per carton were for August 2012, October 2013, and July 2014. Lettuce prices per 12 packages of 3 heads of lettuce were for August 2012, June 2013, and July 2014. Cauliflower prices per film-wrapped carton were for October 2013. Table 2 reports prices for each crop for each year it was produced including the average weekly price for strawberries.

Gross revenues were calculated by multiplying price by yield. In the case of strawberries, gross revenues were calculated on a weekly basis and summed. For broccoli, lettuce and cauliflower, 100% of reported yield was assumed to be marketable. Gross revenues are

$$R_{tr} = p_t \phi Y_{tr}$$

where p_t is the conventional price at harvest month in year t, ϕ is the organic-conventional multiple described above, and Y_{tr} is the yield in year t of rotation r.

Because the treatments were done over the course of several years, we discount the stream of net returns. This is necessary because we must take

Table 2. Organic prices per pound by year*.

Year	Broccoli	Lettuce	Cauliflower	Strawberry
2011	0.53	0.38	-	-
2012	0.76	0.58	1.60	1.71
2013	0.39	0.78	-	-
2014	-	-	-	1.83

Source: Agricultural Marketing Service.
https://www.ams.usda.gov/
*Converted from conventional prices using factors in Table 1.

into account the fact that future net returns are less valuable today than current net returns are today. Following Bolda et al. (2014), we use a return on capital of 0.0575, yielding a discount factor of $\delta = 0.946$. This discount factor captures the extent to which net returns obtained one period in the future are valued less than the same dollar value of net returns obtained one period in the future. The net present value of the stream of net returns is determined by this discount factor and the stream of net returns over time. It reflects the tradeoff between making money selling a cash crop today, versus investing in higher yields (and net returns) tomorrow. The net present value of net returns for rotation r is

$$\pi_r = \sum_{t=0}^{4} \delta^t (R_{tr} - C_{tr})$$

where C_{tr} is the cost for year $t + 1$, respectively.[1] The corresponding net present value of gross revenues is $R_r = \sum_{t=0}^{4} \delta^t R_{tr}$.

We used Tukey tests to identify statistically significant separations of means for yields, gross revenues, and net returns. We used split-split plot ANOVAs to evaluate the determinants of gross revenues and net returns. The split-split plot approach enables us to restrict randomization so that it is consistent with the design of the trial.

Results

Vegetable yields

No significant effects of rotation length or crop sequence were evident in vegetable yields over the first three years of the study, except for higher lettuce yields following broccoli than following cauliflower in year 2 (Table 3). Differences between crops in year 1 were almost significant for both lettuce and broccoli which reflect some variation in initial soil conditions at the start of the rotation experiment, however these differences diminished over time. There were few consistent effects of soil management other than broccoli yields tending to be highest in the cc + c + f treatment in year 3 (2014) probably due to greater nitrogen availability at head formation since supplemental nitrogen was added as a sidedress if indicated by soil tests. Other work has shown that cover crops alone do not support as high broccoli yields as cover crops with sidedress N additions do (Muramoto et al. 2011).

Strawberry disease and yields

In year 2 strawberry yields were generally low due to poor bed construction, but were highly correlated with disease severity as measured by wilt score (Shennan

Table 3. Vegetable and strawberry crop yields (marketable pounds per acre).

	2012		2013				2014		2015
Treatment	Broccoli	Lettuce	Broccoli	Cauliflower	Lettuce	Strawberries	Broccoli	Lettuce	Strawberries
1a	24216**ab**			6103**a**	30926a		15642a		31413a
2a	30632**a**			13949**b**	29629a		19498a		31158a
3a	18269**b**			15851**b**	35168a		15243a		34091a
4a	25839a**b**			7483**ab**	35606a		15161a		27927a
5a		32136**a**	29691a		33284a			34769**a**	22772a
6a		30762**ab**	32674a		36627a			45213**bc**	32015a
7a		34479**ab**	35034a		39273a			50421**c**	28861a
8a		27518**b**	34678a		38874a			39985**ab**	27998a
1b	20973**ab**					14979**a**	18687**ab**		[35030a
2b	23223a**b**					15394**a**	25465**a**		34326a
3b	17740**a**					11103**b**	15778**bc**		33514a
4b	22192**b**					11153**ab**	13828**c**		31303a
5b		42766a				14954a		54041a	28256**ab**
6b		36755a				12828a		50219a	28852**a**
7b		31685a				9726a		42635a	20003**b**
8b		33123a				11607a		49014a	17509**b**
Main (2yr vs 4yr)	**0.0844**	**0.095**	NA	NA	NA	NA	0.109	0.177	0.473
Split Lettuce vs Broccoli (2 year main)	NA	NA	NA	NA	NA	0.390	NA	NA	**<0.001**
Split Lettuce vs Broccoli (4 year main)	NA	NA	NA	NA	**0.041**	NA	NA	NA	0.137

et al. 2015). In year 4 wilt scores were significantly lower in the broccoli rotations compared to the lettuce rotations, and lower overall in the four-year versus the two-year rotation. The lowest levels of wilt in the two-year rotations were observed in the ASD treatments, whereas in the four-year broccoli rotation there was no effect of soil treatment and all had low wilt incidence; and in the year 4 lettuce, the ASD cc treatment had high wilt scores and the ASD cc + c + f had the lowest wilt scores (Table 4). Recall, however, that strawberry yields were not significantly higher in the four- than two-year rotation overall, as reported in Table 3, in part because the yields in the broccoli rotations were similar irrespective of rotation length reflecting the benefits of growing broccoli prior to planting strawberries as observed in other studies (Subbarao et al. 2007). The lowest strawberry yields were observed in the treatments with the highest wilt scores, notably the two-year lettuce bf and msm treatments, and the four-year lettuce ASD cc. Other work has demonstrated the ability of ASD to successfully control *Verticillium dahliae*—the dominant pathogen present at this site (Shennan et al. 2017). In this study ASD reduced wilt and increased yields in the two-year rotation as expected, but only the ASD cc + c + f was effective in the four-year lettuce rotation. The reason for the failure of ASD cc to control wilt in the four-year lettuce rotation is unclear, and it will be interesting to see if this pattern is repeated over the next rotation cycle.

Gross revenues

We examine the net present value of gross revenues by treatment, $R_{tr} = \sum \delta^t R_{it}$. The largest source of gross revenues was strawberry production in year 4 for both two-year and four-year rotations. The second largest source of gross revenue was year 2 gross revenues. In two-year rotations these gross revenues were from strawberry production. In four-year rotations these gross revenues were from lettuce and cauliflower or broccoli production. Year 2 gross revenues were higher for strawberries in the two-year rotations than gross revenues from other crops were in the four-year rotations. The net present value of average gross revenues by treatment are reported in Figure 1.[2] Based on the mean separation results of a Tukey test, there is a statistically significant difference in gross revenues between using a host crop versus a non-host crop in the two-year rotations (p-value of less than .001) for year 4 strawberry revenues (Table 5). This is also the case in the four-year rotations with a higher p-value of 0.028). This suggests that that using non-host crops is influential in increasing future strawberry revenues for growers.

Net returns

A similar pattern appears for net returns, although the addition of costs dampens some of the benefits. Although there is once again a statistically significant effect between using non-host crops vs. host crops for two-year

Table 4. Wilt scores across the strawberry production season 2015.

Main	Split	Split split	4/22/15	5/27/15	6/27/15	7/15/15	7/29/15	8/12/15	8/26/15	9/8/15	9/23/15	Split split*	Split†	Main‡
4 Year	Broccoli	ASD cc	1.09	1.04	1.3	1.18	1.25	1.25	1.27	1.92	1.85	a		
4 Year	Broccoli	ASD cc + c + f	1.16	1.01	1.24	1.2	1.11	1.14	1.11	2.19	1.6	a	1.36	
4 Year	Broccoli	msm	1.06	1.04	1.38	1.32	1.32	1.29	1.29	1.84	1.68	a		
4 Year	Broccoli	bf	1.06	1.05	1.3	1.36	1.27	1.45	1.5	2.1	1.85	a	$p < 0.0001$	1.58
4 Year	Lettuce	ASD cc	1.11	1.23	1.9	2.15	2.21	2.41	2.61	3.41	3.44	c		
4 Year	Lettuce	ASD cc + c + f	1.14	1.1	1.35	1.32	1.36	1.4	1.34	2.37	1.85	a	1.79	
4 Year	Lettuce	msm	1.04	1.15	1.64	1.7	1.66	1.79	1.79	2.54	2.42	b		$p = 0.0012$
4 Year	Lettuce	bf	1.01	1.16	1.54	1.56	1.57	1.71	1.74	2.61	2.4	ab		
2 Year	Broccoli	ASD cc	1.05	1.06	1.43	1.3	1.35	1.38	1.41	2	1.75	a		
2 Year	Broccoli	ASD cc + c + f	1.2	1.07	1.3	1.14	1.19	1.3	1.4	2.26	1.9	a	1.47	
2 Year	Broccoli	msm	1.08	1.06	1.4	1.19	1.2	1.33	1.4	2.2	1.85	a		
2 Year	Broccoli	bf	1.05	1.06	1.54	1.36	1.4	1.71	1.81	2.46	2.41	b	$p < 0.0001$	1.69
2 Year	Lettuce	ASD cc	1.14	1.16	1.49	1.25	1.36	1.46	1.54	2.2	2.26	a		
2 Year	Lettuce	ASD cc + c + f	1.06	1.09	1.5	1.48	1.71	1.96	2.19	2.83	2.59	b		
2 Year	Lettuce	msm	1.06	1.21	1.86	1.71	1.8	2.41	2.52	3.2	3.24	c	1.89	
2 Year	Lettuce	bf	1.04	1.15	1.89	1.88	1.96	2.36	2.62	2.96	3.19	c		

* letters indicate differences in average wilt score across the season at $p < 0.05$ for different soil management treatments (split-split) within a given crop/rotation treatment.
† numbers refer to average wilt scores across the season for each crop/rotation length treatment (split) and the significance level of the comparison across crops within a given rotation length

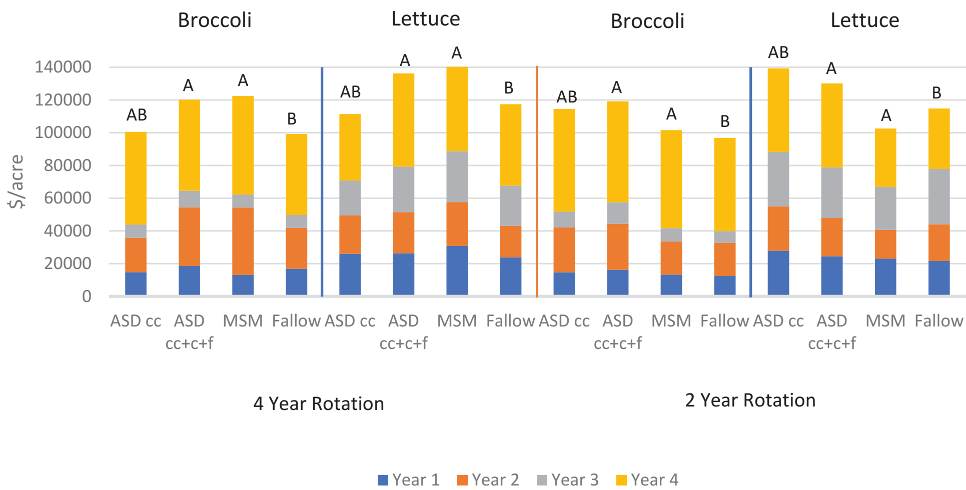

Figure 1. Net present value of gross revenues by year.

rotations, this is no longer the case for four-year rotations, based on the mean separation result of a Tukey test (Table 6). This is most likely due to the fact that once costs are factored in, non-host crops tend not to be profitable leading to a reduction in the benefits that broccoli has on strawberry yields (and subsequently revenues).

Within the set of four-year rotations, among the soil treatments the MSM and N + ASD treatments produced the highest net present value net return. Comparing the rotation crops within the set of four-year rotations, the broccoli rotations generated higher net revenues than the lettuce rotations for all soil treatments except the untreated control (fallow). Among the two-year rotations, year 2 strawberry net returns were very low compared to year 4 strawberry net returns, and the lettuce rotations had higher net returns than the broccoli rotations (Figure 2).

Certain questions of note can be seen from this figure: (1) for rotations with the same first-year plantings, why do two rounds of the two-year rotation consistently result in lower net returns than the four-year rotation (2) for rotations with different first-year plantings, can broccoli in the first or second year be part of a net return-maximizing rotation despite generating lower net returns than either lettuce or cauliflower?

Two- vs. four-year rotations: second year strawberry net returns

One reason to consider a two-year rotation rather than a four-year rotation is that it yields two years of strawberry production during a four-year period. However, in the trial, year 2 strawberry gross revenues were far outweighed by costs; all two-year rotations had negative net returns that year, regardless of the first-year treatment. This was due to significantly lower strawberry yields in the

Table 5. Gross revenues by year (in dollars per acre).

	2012		2013				2014		2015
Treatment	Broccoli	Lettuce	Broccoli	Cauliflower	Lettuce	Strawberries	Broccoli	Lettuce	Strawberries
1a	14836**a**			14364**b**	15890**a**		9102**a**		66936**a**
2a	18570**a**			17299**bc**	15224**a**		11346**a**		65876**a**
3a	13138**a**			16103**c**	18295**a**		8869**a**		71285**a**
4a	16844**a**			8116**a**	18070**a**		8822**a**		58497**a**
5a		11773**a**	12522**a**		17102**a**			30259**a**	48018**a**
6a		11950**a**	28618**b**		18820**ab**			39349**b**	67366**a**
7a		13957**a**	32520**b**		20179**ab**			43881**b**	61024**a**
8a		10833**a**	15352**ab**		19974**b**			34799a**b**	58830**a**
1b	14760**a**					28905**a**	10874**ab**		74124**a**
2b	16168**a**					29721**a**	14818**b**		72908**a**
3b	13305**a**					21310**a**	9181**a**		70882**a**
4b	15704**a**					21369**a**	8046**a**		67376**a**
5b		15359**a**				28597**a**		47032**a**	60398**bc**
6b		13479**a**				24719**a**		43706**a**	60732**c**
7b		12699**a**				18538**a**		37105**a**	42207**a**
8b		11870**a**				22495**a**		42656**a**	36961**ab**
Main (2yr vs 4yr)	**0.4414**	**0.3103**	NA	NA	NA	NA	0.109	0.177	0.670
Split Lettuce vs Broccoli (2 year main)	NA	NA	NA	NA	NA	0.654	NA	NA	**<0.001**
Split Lettuce vs Broccoli (4 year main)	NA	NA	NA	NA	**0.028**	NA	NA	NA	0.134

Table 6. Net returns by year (in dollars per acre).

	2012		2013				2014		2015
Treatment	Broccoli	Lettuce	Broccoli	Cauliflower	Lettuce	Strawberries	Broccoli	Lettuce	Strawberries
1a	5677**ab**			8534**a**	5248**a**		−771**b**		24617**a**
2a	7297**b**			21619**b**	5332**a**		−375**b**		23198**a**
3a	3066**a**			25846**b**	4789**a**		−2339**a**		26344**a**
4a	7303**b**			11639**ab**	6551**a**		−486**b**		20568**a**
5a		371**b**	7080**b**		5917**a**			16818**a**	12040**a**
6a		−266**ab**	9011**b**		6013**ab**			22812**a**	24219**a**
7a		−486**a**	7508**b**		5953**ab**			25381**a**	20160**a**
8a		451**ab**	3013**a**		7503**b**			20577**a**	21050**a**
1b	5630**ab**					−747**a**	88**b**		20201**a**
2b	5809**b**					−972**a**	1307**b**		28008**a**
3b	3170**a**					−5623**a**	−2187**a**		26337a
4b	6598**ab**					−2757**a**	−861**b**		27186**a**
5b		1523**a**				−1038**a**		29155**a**	20467**bc**
6b		225**a**				−4147**a**		26017**a**	19842**c**
7b		−889**a**				−7415**a**		20397**a**	7800**a**
8b		784**a**				−1954**a**		26356**a**	6710**ab**
Main (2yr vs 4yr)	**0.442**	**0.3103**	NA	NA	NA	NA	0.109	0.178	0.295
Split Lettuce vs Broccoli (2 year main)	NA	NA	NA	NA	NA	0.650	NA	NA	**<0.001**
Split Lettuce vs Broccoli (4 year main)	NA	NA	NA	NA	**0.105**	NA	NA	NA	0.147

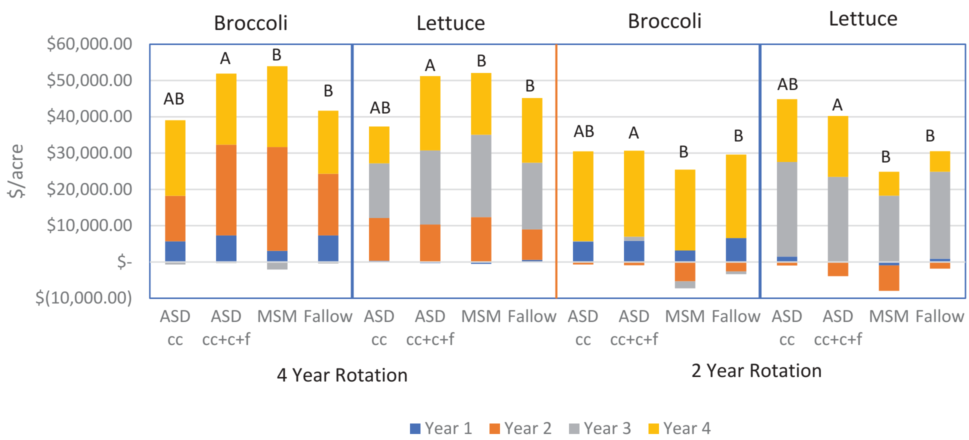

Figure 2. Net present value of net returns by year.

two-year rotations than in the fourth year of the four-year rotation for each pair with the same crops in years 1 and 3. The low strawberry yields in year 2 were in part due to an exacerbation of Verticillium wilt disease caused by poor drainage and lower than normal bed heights (Shennan and Muramoto 2016). For all soil treatments paired with broccoli and for three of the four soil treatments paired with lettuce (Low N + ASD, MSM, BF), four-year treatments significantly outperformed two-year treatments.

Effect of broccoli on strawberry net returns

The choice of commercial crop in year 1 affected the magnitude of year 2 net losses. Six of the eight pairs of two-year and four-year rotations with broccoli grown in year 1 had higher strawberry net returns in year 4 and year 2 than rotations in which lettuce was grown instead (Figure 2). The difference was due to greater Verticillium wilt damage in lettuce plots. The remaining two treatments were ones in which the plot was fallowed rather than receiving any soil fertility/disease management treatment.

Low net returns in years two and three

The second question regards the determinants of the low net returns across both two-year four-year rotations in the second and third years, both within rotation lengths, and across rotation length. Prices of the crops in the rotations played an important role.

Effect of cauliflower price on net returns

Four-year rotations that followed lettuce with cauliflower in year 2 had higher net returns than ones that followed lettuce with broccoli, due to the high price of cauliflower in the harvest month of year 2. The October 2013 price of cauliflower was over twice as high as the October average for the four-year period of the trial. Figure 3 plots the price series. The orange square point indicates the October 13 price.[3] In order to ascertain the extent to which net returns were driven by this unusually high price, net returns for the four rotations in question were recomputed using the average October cauliflower price for the 2008–2015 period. Using the historical average price, cauliflower is no longer a large contributor to net returns; its impact was driven by a higher than average price for that year. Figure 4 shows the reduction in net returns due to the difference in the cauliflower price.

Effects of broccoli and lettuce prices on net returns

For four-year rotations the net returns were driven in part by differences in relative prices. In other words, lettuce and broccoli net returns were not driven by differences in yields or costs across treatments. The rotations were fixed in the experiment. Consequently, in some treatments one crop was grown when the other would have realized higher net returns given the realized yields and costs. Accordingly, we examine the influence of realized prices on the relative net returns across rotations. Lettuce had a relatively high harvest price in year 3, causing positive net returns for the third year of the trial in all four-year rotations that included lettuce in year 3. Figure 5 illustrates this difference in the organic lettuce price. The 2013 price (the orange square point) is relatively high compared to other prices in the 2011–2015 period. In comparison, organic broccoli generated low or negative

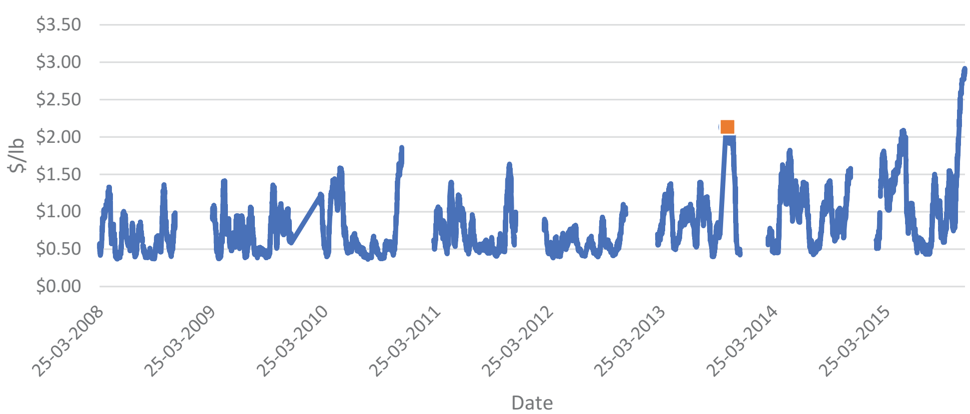

Figure 3. Organic cauliflower price per pound: 2008–2015.

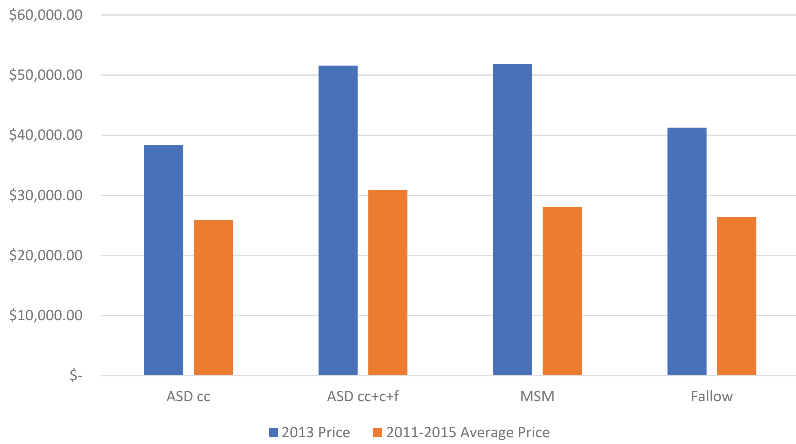

Figure 4. Effect of changing 2013 cauliflower price to 2011–2015 average price on net present value of net returns.

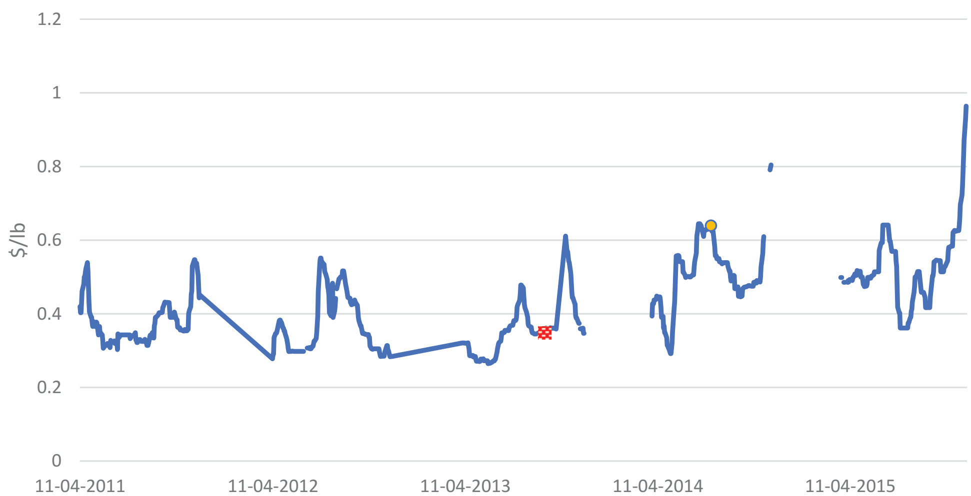

Figure 5. Organic lettuce price per pound: 2011–2015.

net returns in year 3 of the trial due in large part to its relatively low price in that year (the orange square point) compared to the prices in other years during the trial period (Figure 6).

In practice, growers have the flexibility to adjust rotations based on market conditions; however, the decision to adjust will be based not only on the anticipated prices for the rotational crops but also the impact of the crop grown prior to strawberries in terms of increased disease pressure, which may outweigh the value of growing a higher value rotational crop. Examining the price series for lettuce and broccoli suggests that a rotation which provided more flexibility for growers to respond to relative prices and the associated net returns would be economically viable under a broader set of

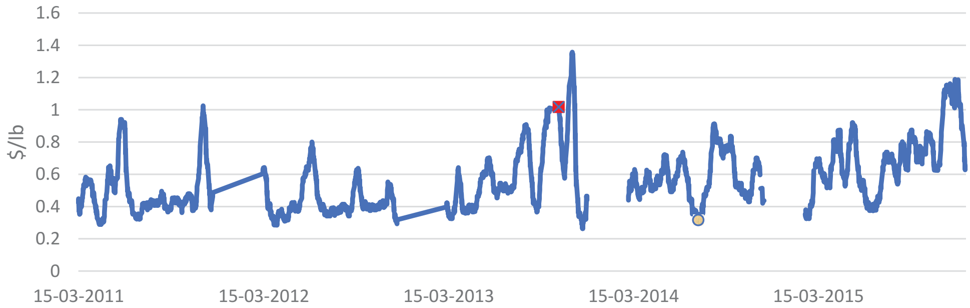

Figure 6. Organic broccoli price per pound: 2011–2015.

market conditions. However, technical efficacy may limit growers' crop choice flexibility due to the different crops' differing degrees of susceptibility to Verticillium wilt, and the efficacy of ASD for controlling wilt in strawberries grown following lettuce. In this trial, the higher net returns from lettuce in year 3 almost compensated for lower net returns from strawberries in year 4 (as seen earlier in Figure 2). More research is required to determine how much flexibility is feasible or attractive to growers. Specifically, it would be important to analyze the extent to which growers who produce both vegetables and strawberries value such flexibility and to what extent the prices of lettuce, broccoli, and strawberries correlate. If crop choice is sufficiently constrained by the need to suppress wilt, growers might wish to stagger the implementation of a rotation across time.

Land rents

One cost that isn't included in the partial budget analysis is land rent. For renters, this is a direct cost. For owners, land rent is the opportunity cost of using their land in production rather than renting to another grower. Bolda et al. (2014) assumed land rent for organic land to be $3,000 per acre per year. Applying their figure to this study, the net present value of land rent would be $11,056 for the four-year period. This cost would offset much of the realized net returns, but would not lead to negative net returns.

As a back of the envelope calculation, we assume that land rents would have stayed constant over the course of the trial and calculate breakeven land rents for the worst and best performing replicates of the trial. If land rents were about $4600 per acre per year, then even the worst performing rotation would break even (rotation 7b), which was a two-year rotation with lettuce and a cereal cover crop with MSM soil fertility/disease management treatment. At the other end of the spectrum, if land rents were about $15,000 per acre per year then only the highest performing rotation would be able to break even (rotation 6a), which was a four-year rotation with lettuce and high N cover crop plus ASD treatment.

ANOVA analysis

The effects of rotation length, choice of year 1 crop and other factors that contribute to net returns were examined using ANOVAs. Because the trial used a split-split-plot design, a split-split-plot ANOVA test was run to evaluate the effect of each factor.

Split-split-plot ANOVA

Leveraging the split-split-plot design of the trial, we ran ANOVAs on gross revenues and net returns. Only two factors were statistically significant for gross revenues, both at the 1% level: the soil fertility/disease management treatment (p = ~0.005) and the interaction of rotation length and soil fertility/disease management treatment (p = ~0.0005) (Table 7).

For net returns, two factors were significant at the 10% level: rotation length (p = ~0.02), soil fertility/disease management treatment (p = ~0.08) (Table 8). The interaction of rotation length and soil fertility/disease management treatment was significant at the 1% level (p = ~0.003).

The importance of rotation length is likely due to the very low gross revenues from second year strawberry production. The significance of the interaction variable is driven in part by high net returns from the MSM treatments in the

Table 7. Split-split-plot ANOVA: Gross revenues.

Source	Degrees of Freedom	Sum of Squares	Mean Square	F-Statistic	*p*-value
Block (A)	3	12,360,000,000	4,121,000,000		
Four-year vs. Two-year (B)	1	1,315,000,000	1,315,000,000	2.07	0.25
Error A*B	3	1,905,000,000	635,100,000		
Cash Crop vs. Non-host Crop (C)	1	1,102,000,000	1,102,000,000	2.09	0.20
B*C	1	16,750,000	16,750,000	0.03	0.86
Error A*B*C	6	3,171,000,000	528,500,000		
Soil Fertility/Disease Management (D)	3	3,511,000,000	1,170,000,000	5.13	0.005
B*D	3	5,218,000,000	1,739,000,000	7.62	0.0005
C*D	3	154,700,000	51,550,000	0.23	0.88
B*C*D	3	586,000,000	195,300,000	0.86	0.47
Error A*B*C*D	36	8,218,000,000	228,300,000		
Total	63	37,560,000,000			
Grand Mean	117,009				
CV(block*fouryear)	21.54				
CV(block*fouryear*lettuce)	19.65				
CV(block*fouryear*lettuce*fertility)	12.91				

Table 8. Split-split-plot ANOVA: Net returns.

Source	Degrees of Freedom	Sum of Squares	Mean Square	F-Statistic	*p*-value
Block (A)	3	5,222,000,000	1,741,000,000		
Four-year vs. Two-year (B)	1	5,951,000,000	5,951,000,000	22.41	0.02
Error A*B	3	796,700,000	265,600,000		
Cash Crop vs. Non-host Crop (C)	1	321,700,000	321,700,000	1.30	0.30
B*C	1	126,300,000	126,300,000	0.51	0.50
Error A*B*C	6	1,481,000,000	246,800,000		
Soil Fertility/Disease Management (D)	3	750,500,000	250,200,000	2.46	0.08
B*D	3	1,737,000,000	579,100,000	5.70	0.003
C*D	3	254,400,000	84,800,000	0.84	0.49
B*C*D	3	418,900,000	139,600,000	1.37	0.27
Error A*B*C*D	36	3,650,000,000	101,500,000		
Total	63	20,720,000,000			
Grand Mean	37,340				
CV(block*fouryear)	43.64				
CV(block*fouryear*lettuce)	42.07				
CV(block*fouryear*lettuce*fertility)	26.99				

4 year rotation, similar to the high fertility cover crop and ASD treatments, whereas for 2 year rotation the MSM net returns were much lower.

The consistency between the determinants of gross revenues and net returns implies that some combination of adequate N availability and use of ASD is vital for the long-term success of a suppressive crop rotation and its commercial viability. It is important not only that a non-host crop be given enough time to suppress Verticillium wilt, but that it be coupled with enough N so that the broccoli and strawberry crop yields are sufficiently high to contribute positively to net returns.

The choice of gross revenue-generating cash crop vs. non-host suppressive cash crop have a significant effect on year 4 strawberry yields as discussed previously. Suppressive crop rotations were effective at increasing strawberry yields, the main driver of commercial viability, however, while the high lettuce price in year 3 largely compensated for lower strawberry yields in year 4 such that net returns and gross revenues did not show a cash crop versus non-host suppressive cash crop effect. Nonetheless the strong negative effect on Verticillium wilt incidence and strawberry yields cautions against growing lettuce prior to strawberry.

Robustness of net returns

In order to evaluate the extent to which crop prices affected the relative magnitudes of net returns across treatments, we recalculated net returns in three ways using different measures of price at the Salinas/Watsonville shipping point: the average low price in the harvest month, the average high price in the harvest month, and the historical average price for the harvest month from

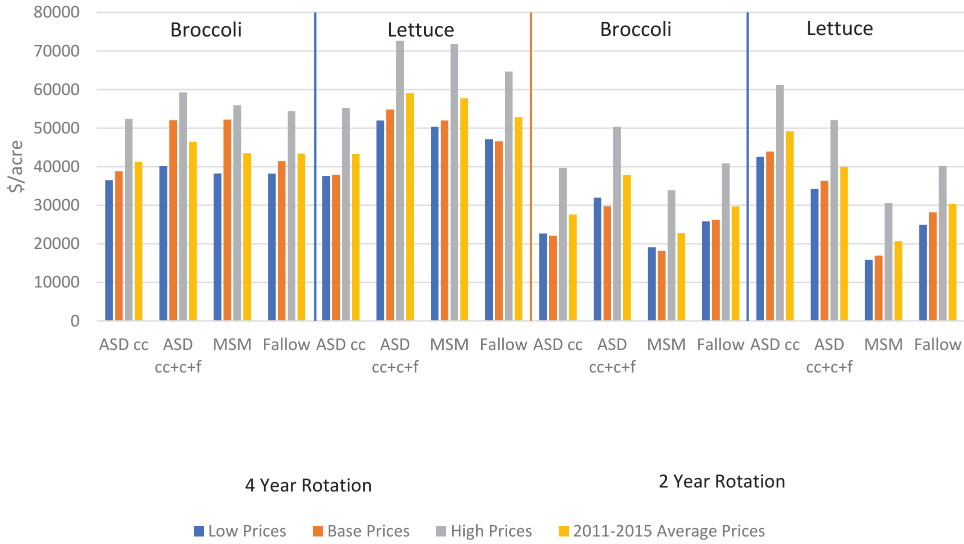

Figure 7. Net revenues by type of price used.

2011–2015. Strawberries used weekly rather than monthly prices to compute each measure of average price for the season, consistent with the base analysis. Overall, net returns varied in predictable ways; higher prices increased net returns and lower ones reduced them. The sizes of the differences varied depending on the crops in each rotation and, as discussed earlier, how the prices for those crops in the base analysis compare to the alternative pricing measures (Figure 7). We then performed an ANOVA on net returns to see whether the results were significantly different from the primary analysis.

Results show that using the historical average prices results in higher net returns, but the increase is not statistically significant (Table 9). Using average low crop prices reduces net returns, but the decrease is not statistically significant (Table 10). In contrast, using average high prices results in a significant increase in net returns (p = ~0.002) (Table 11).

Conclusion

The primary economic question examined in the trial is the dynamic tradeoff between increasing current net returns with gross revenue-generating crops or increasing future net returns through the current planting of non-host crops in exchange for higher strawberry yields (and gross revenues) later. Strawberry yields in year 4 of the four-year rotations generate positive net returns and are the biggest driver of net returns. Relative to four-year rotations, the two-year rotations do not perform as well economically because of the larger incidence of Verticillium wilt disease in the two-year rotations.

Table 9. ANOVA for difference in net returns using historical prices for crops.

SUMMARY						
Groups	Count	Sum	Average	Variance		
Historic Price Net Returns	16	645,676.2509	40,354.76568	135,341,305.5		
Base Net Returns	16	597,444.4657	37,340.27911	159,336,499.5		
ANOVA						
Source of Variation	**Sum of Squares**	**Degrees of Freedom**	**Mean Square**	**F**	***p*-value**	**F criterion**
Between Groups	72,697,034.3	1	72,697,034.3	0.493400134	0.487829358	4.170876786
Within Groups	4,420,167,075	30	147,338,902.5			
Total	4,492,864,109	31				

Table 10. ANOVA for difference in net returns using average low prices for crops.

SUMMARY						
Groups	Count	Sum	Average	Variance		
Low Price Net Returns	16	557,355.2968	34,834.70605	116,714,239.3		
Base Net Returns	16	597,444.4657	37,340.27911	159,336,499.5		
ANOVA						
Source of Variation	**Sum of Squares**	**Degrees of Freedom**	**Mean Square**	**F**	***p*-value**	**F criterion**
Between Groups	50,223,170.78	1	50,223,170.78	0.363869128	0.550898928	4.170876786
Within Groups	4,140,761,082	30	138,025,369.4			
Total	4,190,984,253	31				

Table 11. ANOVA for difference in net returns using average high prices for crops.

SUMMARY						
Groups	Count	Sum	Average	Variance		
High Price Net Returns	16	835194.8	52199.67	1.57E + 08		
Base Net Returns in Paper	16	597444.5	37340.28	1.59E + 08		
ANOVA						
Source of Variation	**Sum of Squares**	**Degrees of Freedom**	**Mean Square**	**F**	***p*-value**	**F criterion**
Between Groups	1,770,000,000	1	1,770,000,000	11.18044	0.00223	4.170877
Within Groups	4,740,000,000	30	158,000,000			
Total	6,510,000,000	31				

When comparing rotations of a given length, it is difficult to reach firm conclusions regarding the relative commercial performance of different crop combinations. While broccoli tended to increase future strawberry yields, current gross revenues from lettuce were higher. Net returns were driven not just by yields or costs, but by prices. Specifically, given the prices that were available at each harvest *during the trial period* broccoli prices were low in year 3 and lettuce prices were high in year 2. If crop choice had been made independently of the choice of rotation for disease suppression and yields and costs were unchanged, net returns would have been higher with a different ordering of crops planted. Of course, it is likely that yields would be affected; no trial data are available to evaluate the joint effect on net returns.

The ANOVA analysis shows that the choice of rotation, coupled with soil fertility/disease management treatment choices are important factors in net returns. The choice of planting lettuce or broccoli was an important determinant of year 4 strawberry yields, showing that suppressive crop rotations were effective, but did not have a discernible effect on the net present value of net returns. This shows that the suppressive crop rotation is effective in managing disease but, due to the prices realized during the trial, it was not possible to identify a consistent effect. The experiment, however, is continuing and we will be able to reassess over an eight-year cycle.

There are several caveats regarding this analysis. In addition to standard caveats and cautions regarding partial budget analysis and using field trial results to project commercial scale net returns, there are some issues related to this study specifically. First, some treatment costs were obtained from sources outside the trial. Water and harvest labor costs were computed based on information in cost of production studies because the UCSC experimental farm's operating costs for labor and water do not reflect the costs that would be incurred in commercial production. Furthermore, the cost studies that were utilized were not from the trial years. As such, they may not adequately reflect actual costs. Another significant caveat is that organic prices were not available for the years that the trial was performed. This lack of contemporary price data could potentially introduce bias if the ratio of organic to conventional prices during the trial period was significantly different from the observed 2016 values for one or more crops. According to Shennan and Muramoto (2016), during the second year of the trial, poor drainage and lower than normal bed heights exacerbated the Verticillium wilt in the soil, which led to low second year strawberry yields, and likely biased the net returns downward for the two-year rotations. A new bed shaper was added to create better conditions in the fourth year and higher strawberry yields were realized in the two-year rotations.

There are several exciting new directions for future research. One is the evaluation of the Mother Trial as more years of the rotations become available. This will provide the ability to calculate a more precise evaluation of these suppressive crop rotations' commercial viability. Another topic to explore is incorporating the trial's findings into a grower decision-making model that enables the identification of the key grower characteristics that would influence the adoption of such rotations.

Notes

1. The expression is defined in terms of year $t + 1$ to take into account that mathematically time starts at year 0, prior to incurring expenses and earning gross revenues, not year 1.
2. For the rest of the document, when we refer to gross revenues and net returns, we will mean the net present value of each of gross revenues and net returns.
3. In Figure 3, gaps in the time series are periods during which the USDA did not report prices. The orange circle indicates the October 2013 harvest price.

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