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Research article

Using cost-benefit analysis to understand adoption of winter cover cropping in California's specialty crop systems

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ABSTRACT

Winter cover crops could contribute to more sustainable agricultural production and increase resiliency to climate change; however, their adoption remains low in California. This paper seeks to understand barriers to winter cover crop adoption by monetizing their long-term economic and agronomic impacts on farm profitability in two of California's specialty crop systems: processing tomatoes and almonds. Our modeling effort provides a present, discounted valuation of the long-term use of winter cover crops through a cost-benefit analysis. A net present value model estimates the cumulative economic value of this practice. We then explore how the long-term trade-offs associated with winter cover crops can affect an operation's profits under a spectrum of hypothetical changes in California's agricultural landscape. Our analysis sheds light on the barriers to adoption by reporting benefit-cost ratios that indicate profitability across several scenarios; however, benefits and costs accrue differently over time and with long planning horizons. At the same time, a small portion of gained benefits are external to the grower. Findings from this study reveal that winter cover crops in California can be profitable in the long-term, but the extent of profit depends on the cropping system, extent of irrigation savings due to improved soil function, access to financial subsidies and climate change. Winter cover crops can return positive net benefits to growers who have flexible contractual obligations, can wait for the long-term return on investment and manage cover crops as closely as cash crops. This analysis contributes to the study of conservation agriculture practices by explaining possible reasons for low adoption through an economic valuation of the implications of soil management choices and policy counterfactuals.

1. Introduction

Winter cover cropping is a promising agricultural soil management practice that may contribute to increasing food production while using natural resources more sustainably. Winter cover crops are grown on agricultural fields that would otherwise be left fallow. They mimic natural landscapes, promote soil microbial diversity, capture solar radiation, cycle nutrients, reduce erosion and mitigate climate change and climate change effects (Aguilera et al., 2013; Blanco-Canqui et al., 2015; Vukicevich et al., 2016). Widespread adoption of winter cover cropping could contribute to more sustainable agricultural production and increase the resiliency of the agriculture industry to policy and climate changes (Ewel, 1999; Kremen and Merenlender, 2018; Lu et al., 2000).

Despite their well-known soil health benefits, winter cover crop adoption varies significantly across the U.S., with very low adoption rates between the production of specialty crops in California (Soil Health Institute, 2019). Understanding trends in cover crop adoption requires knowledge of the long-term impacts on farm profitability: how do the benefits and costs of cover crops change with each operation depending on geography, cropping system, management choices and other economic factors? (Bergtold et al., 2017). This knowledge can address growers' concerns that cover crops impact cash crop performance, establishment and soil moisture for their specific cropping system (Carlisle, 2016). Understanding adoption incentives is also critical for informing agri-environmental policy and promoting sustainable agriculture in a changing climate.

Several reasons may explain low rates of winter cover crop adoption in California. First, it may be that the net present value of cover cropping in specialty crops systems is negative and observed adoption rates are a reflection of rational, profit-seeking behavior. Alternatively, it may be that the net present value is positive, but only in the long run. If it takes many years for benefits to accrue to acceptable levels, low adoption rates could then be rationalized by farmers exhibiting myopic behavior. A third explanation comes from the idea that a substantial portion of the benefits may be external to the grower who makes soil management decisions (e.g., improved water quality to a downstream user), and thus

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low adoption rates reflect the presence of these externalities. Lastly, the existence of information barriers, risk and uncertainty on behalf of farmers can hinder adoption as well (Ghadim and Pannell, 1999; Klonsky and Livingston, 1994; Prokopy et al., 2008).

This paper conducts a cost-benefit analysis of winter cover cropping for two specialty crops, processing tomatoes and almonds, which are widespread in California's Central Valley, and provides insight into possible explanations for low adoption. A review of previous studies reveals an emphasis on the benefits and costs of cover cropping in the Midwest and East Coast of the U.S. (Bergtold et al., 2017). Less well understood are the reasons for low adoption in California or how climate change may modify this ecosystem service (Bai et al., 2019). Past research on adoption of sustainable practices highlights the need for understanding long-term financial impacts (Lu et al., 2000; Prokopy et al., 2008; Wyland et al., 1996) and specific information on how practices fit into particular farming situations (Rodriguez et al., 2009).

We address this knowledge gap with a model of the economic viability of growing winter cover crops in two crop systems in California's Central Valley under a spectrum of hypothetical scenarios. The model tests the hypotheses that (1) the benefits of winter cover crops are not captured in an annual analysis, but rather accrue over time to a point of financial return, and (2) the economic profitability of growing winter cover crops will switch in response to changes in climate, water and policy. Further, our model improves on previous methodologies by validating literature estimates through grower interviews and field data collection. We contribute to the literature on conservation and sustainability by exploring policy counterfactuals, monetizing impacts of soil management choices and shedding light on diffusion of environmental innovation (Aldieri et al., 2019). Results from this research can inform on-farm and policy decisions as producers and regulators strive to maintain sustainable agricultural production under a changing climate.

2. Material and methods

Our goal was to comprehensively quantify the costs and benefits associated with winter cover cropping in monetary terms for two of California's specialty crop systems. The valuation exercise had two purposes. First, it explained how the long-term trade-offs associated with this soil management practice affect an operation's profits. Second, it tested the economic viability of cover cropping under a spectrum of hypothetical changes in California's agricultural production and policy conditions. This research was focused on two specialty crop systems of interest: processing tomato (referred to as tomato) (Turini et al., 2018) and almond (Duncan et al., 2016). The tomato system was analyzed as part of a typical crop rotation consisting of onions, winter grains, cotton and garlic. Tomatoes and almonds were chosen so that the analysis represented one annual and one perennial system, both of which are leading commodities in California (California Department of Food and Agriculture, 2018). We collected data to model these systems with interdisciplinary methods by supplementing a traditional literature review with on-the-ground field research conducted in agricultural production areas of the Central Valley.

2.1. Data collection

Our study used data from three main sources: estimates from previous literature, semi-structured grower interviews and a field-based experiment. We used these data to estimate the main costs and benefits associated with winter cover crops. Costs included expenses associated with cover crop seeds, planting, termination, financial losses due to the harvest complications with cash crops, depreciation of machinery and the opportunity cost of time spent learning to grow winter cover crops. Benefits included increased income from greater yields; reductions in expenses associated with soil erosion control, nutrient cycling, weed control and mycorrhizal fungi colonization; reduced tillage operations and lower beehive prices for tomatoes and almonds, respectively; and ecosystem services such as increased soil organic matter, reduced surface water runoff and soil-carbon storage. The benefit of improved soil function and subsequent impacts to water management were not included in the model for baseline conditions but were addressed in model simulations.

Agricultural prices and management costs associated with winter cover crops serve as the primary data to estimate the economic viability of cover cropping. First, data on prices and costs were collected from the Cost and Return Studies compiled by the University of California Cooperative Extension (Duncan et al., 2016; Turini et al., 2018) as well as a collection of scientific publications on cover crop adoption across the U.S. (Auffhammer, 2018; Creamer et al., 1996; Gravuer, 2016; Malik et al., 2000; Nearing et al., 2017; Pratt et al., 2014; Rahmani et al., 2004; Robinson et al., 2014; Sarrantonio and Gallandt, 2003; Swan et al. n. d.).

Second, semi-structured grower interviews were conducted (Table 1) to ground-truth results from the literature and establish a timeline for the costs and benefits associated with winter cover crop adoption. Researchers received IRB exemption 1007081–1 to conduct the interviews, which took place from 2017 to 2018. The sample included growers participating in a study supported by a California Department of Food and Agriculture Specialty Crop Block Grant (grant agreement #15037). The growers recommended additional growers to participate in the interview process, and the final sample of twelve growers reflected the diversity of operations throughout the region (i.e. a range of climates, crop types, management strategies and sizes of farming operations). The sample of growers included six winter cover crop adopters, two non-adopters and four growers who were undecided.

Growers received a list of questions and conversation topics before the interviews were conducted. The process changed iteratively and subsequent interviews were informed by the successes and challenges of previous ones (Watt, 2007). The interview process slowly adapted from a strict survey to a fluid conversation, allowing time for trust to build between the interviewer and interviewees. Descriptive data such as physical characteristics of the farm, anecdotal experiences and real or perceived monetary costs and benefits were compiled in a database to describe thematic trends in the interviews. These trends provided data for analysis and informed subsequent design of our research methodology based on the grounded theory approach (Bitsch, 2005).

Third, data from the aforementioned field experiment was used to inform the development of model simulations (DeVincentis et al., In

Table 1
Details from cover crop informational interviews with growers throughout California's Central Valley.

A sample of interview questions:
How did you decide to start farming?
Can you tell me a brief history of your operation?
What type of crops do you grow? How many acres? For how many years?
What factors do you consider when deciding how many acres to grow?
Rank importance of these inputs in determining the success of your operation:
Money, land, water, labor, pesticides, weather
Do you use any monitoring equipment?
What type of cover crops do you grow? How many acres? For how many years?
Why did you decide to use cover crops?
Can you quantify your costs and benefits of cover cropping?
What costs have you incurred from cover cropping? Seeds, labor, risks?
What benefits have you incurred from cover cropping? Soil health or reduced inputs?
Have you seen your water use change since you adopted cover crops?
Do you encourage other growers to cover crop? What are your reasons?
Notable interview excerpts:
"It's a fine line of when am I going to save water [with cover crops]. Most times it is negligent."
"I do think over time cover crops will make an operation more profitable. You'll incur less costs and water. Better fertility, yield, and disease resistance."
"From what it used to be we now use at least 30% less water. I think it's due to a combination of the organic matter increasing and field capacity increased so the water that we put in the soil stays longer."
"There's a tradeoff between efficiency and flexibility - we are too big to be inefficient and you need to be flexible to cover crop."

prep). The field experiment included eleven agricultural fields of specialty crops that are either active farms or research sites. During the experiment, the University of California team collected a variety of soil and agronomic data to describe water movement in the soil of fields with winter cover crops versus those of fields without cover crops. These data and the time spent working in the agricultural community informed the adjustment of model parameters used to simulate possible changes to climate, water availability and policy that may affect agricultural production in the Central Valley.

2.2. Model construction and evaluation

We built a net present value model to estimate the cumulative economic value of winter cover cropping. All inputs in the model were costs or benefits related to winter cover crop adoption that would cause a change to baseline profits (Bergtold et al., 2017). Our data set includes values for fifteen variables (Table 2) that we calculated based on underlying raw data from various sources, as detailed in the appendix. These fifteen inputs were labeled as either direct or indirect costs and benefits and assigned two monetary values to capture a range of possible prices, reported in 2018 US dollars per acre. The greatest challenge was to assign monetary value to perceived costs and benefits that vary greatly across operations, but we were able to do so by computing average values from grower interviews. Winter cover crops were assumed to be seeded on 100% of acreage for tomato fields and to cover 75% of acreage in almond orchards based on common planting practices.

The monetary values for each input were incorporated into the model at specific years when that cost or benefit was experienced. Years were chosen based on considerations from the grower interviews and expert opinions of agricultural professionals. These values were discounted to the present using a discount rate of 2.6% to incorporate the future value of money (USDA, 2019). An advantage of this approach is that it provides both a visual representation of the long-term accumulation of costs and benefits and the present discounted value of the long-term use of a management practice, which may drive grower decision-making.

Separate models were built for each system to address crop-specific management strategies. The time horizons for tomato and almond operations were 10 and 30 years, respectively, to reflect typical crop rotation patterns. Winter cover crop type remained constant every year in the tomato model, while an alternative structure was developed to mimic a more realistic adoption of winter cover cropping in almond orchards. It was assumed that the first three years of an almond orchard were used to add biomass to the soil without complicating harvest. For these years we modeled the use of a green manure where a winter cover crop seed was planted and terminated similarly to the row crop fields, with residue being incorporated into the soil. In subsequent years (4–30), we assumed almond growers would experience reduced benefits from planting an annual reseeding variety once to mimic native vegetation and minimize management.

To demonstrate how each budget component was valued on a per acre basis, we detail how the cost of winter cover crop seeds was quantified. The direct cost of seeds was determined to be in the range of \$24–90 in years 1–10 for tomatoes and \$15–65 for years 1–4 for almonds. These values are based on conversations with farmers, extension specialists and advisors, and seed company representatives. The range in price describes the variety of potential seed mixes that are commonly used for winter cover cropping in California's Central Valley for annual and perennial systems. The mixture considered for tomato operations was assumed to be a small grain forage mix (e.g. bell beans, winter peas, common vetch) purchased for \$0.40–0.75 per lb. and planted at a rate of 60–120 lbs. per acre. The mixture considered for almonds was assumed to be a more expensive clover mix purchased for \$1–2.15 per lb. Planted at a lower rate of 20–40 lbs. per acre. Detailed explanations of the calculations for the remaining inputs can be found in the appendix.

Table 2
Summary of monetized costs and benefits associated with winter cover cropping in two specialty crop systems in California's Central Valley. Values are calculated by the authors based on raw data from various sources (detailed in the appendix) and are reported in 2018 US \$ per acre. These values were used to construct baseline scenarios of winter cover crop adoption.

Budget components	Monetary value		Years of occurrence
	Low	High	
Tomatoes			
Direct costs			
Seed	\$24.00	\$90.00	1–10
Planting (labor)	\$9.61	\$19.21	1–10
Termination (labor)	\$19.21	\$38.42	1–10
Indirect costs			
Harvest complications with cash crops	\$119.33	\$1872.45	5, 10
Depreciation of machinery	\$3.75	\$22.50	1–10
Opportunity cost of time spent learning to grow cover crops	\$192.10	\$384.20	1–5
Direct benefits			
Increased yield	\$119.33	\$312.08	5–10
Soil erosion control	\$7.63	\$15.26	5–10
Nutrient cycling	\$19.80	\$118.80	5–10
Weed control	\$1.00	\$6.00	5–10
Mycorrhizal fungi colonization	\$29.16	\$583.29	5, 10
Reduced tillage operations	\$15.00	\$25.00	5–10
Indirect benefits			
Increased soil organic matter	\$21.72	\$46.54	5–10
Reduced surface water runoff	\$0.87	\$4.76	1–10
Soil-carbon storage	\$4.36	\$22.53	1–10
Almonds			
Direct costs			
Seed	\$15.00	\$64.50	1–4
Planting (labor)	\$7.69	\$15.38	1–4
Termination (labor)	\$15.38	\$30.76	1–3
	\$22.50	\$75.00	4–30
Indirect costs			
Harvest complications with cash crops	\$47.56	\$970.15	5
	\$65.39	\$1333.96	10, 15, 20, 25, 30
Depreciation of machinery	\$1.80	\$10.79	1–30
Opportunity cost of time spent learning to grow cover crops	\$205.06	\$410.13	1–5
Direct benefits			
Increased yield	\$11.89	\$40.42	3
	\$23.78	\$80.85	4
	\$47.56	\$161.69	5
	\$65.39	\$222.33	6–30
Soil erosion control	\$5.72	\$11.44	5–30
Nutrient cycling	\$11.41	\$68.46	5
	\$14.51	\$87.04	6–30
Weed control	\$3.03	\$18.17	5–30
Mycorrhizal fungi colonization	\$21.87	\$437.47	5, 10, 15, 20, 25, 30
Discounted beehives	\$4.71	\$28.25	3
	\$9.42	\$56.50	4
	\$18.83	\$112.99	5
	\$23.54	\$141.24	6–30
Indirect benefits			
Increased soil organic matter	\$16.29	\$34.90	5–30
Reduced surface water runoff	\$0.65	\$3.57	1–30
Soil-carbon storage	\$3.27	\$16.90	1–3
	\$1.64	\$8.45	4–30

2.3. Baseline impact of winter cover crops

To test our first hypothesis that the benefits of winter cover cropping accrue over time, we used the net present value models to calculate how the baseline economic performance of tomato and almond operations would change with the addition of winter cover cropping. We used these numbers to calculate benefit-cost ratios with Equation 1: $\textit{Benefit cost ratio} = \frac{\sum_{t=0}^{t=T} \frac{Benefits_t}{(1+r)^t}}{\sum_{t=0}^{t=T} \frac{Costs_t}{(1+r)^t}}$ where t denotes the time period when the value is incurred, $T \in \{10, 30\}$ is the time horizon considered, and r is the discount rate. A benefit-cost ratio greater than 1 is equivalent to a positive net present value, i.e. total discounted benefits exceed total discounted costs over the time period considered. We report benefit-cost ratios and temporal points of financial return to determine the economic profitability of incorporating winter cover crops into both specialty crop operations.

2.4. Model sensitivity

A sensitivity analysis was performed to test the robustness of the baseline modeling results and identify which inputs were most influential on the model results. An average value for each input was used in the models and the influence of each input was tested by replacing the average value with its low and high ranges, culminating in 30 model runs to test the significance of the 15 variables in each cropping system model. This method of sensitivity analysis accounted for both the range of input prices between low and high values and the proportion of each input to the overall budget.

2.5. Counterfactual scenario construction

To explore the second hypothesis that the economic profitability of winter cover crops may switch in response to changes in California's agricultural production context, we simulated six scenarios that describe social and biophysical changes to agricultural operations (Table 3). Scenarios were chosen based on analysis from the farmer interviews and results from the sensitivity analysis that revealed which variables had the most leverage. For each of the six scenarios, the baseline model was constructed using average input values and one or more variables were either changed, removed or added to simulate the circumstances.

Climate change will alter agricultural production in California and the potential economic consequences of these impacts warrant consideration (Pathak et al., 2018). Scenario 1 addresses this by calculating how climate change will impact the baseline profit of an average operation growing winter cover crops. This scenario models the potential impact of four simultaneous climate changes, which include warmer temperatures and more frequent extreme weather events (e.g. heat waves, floods, and droughts). We assumed that the prices of irrigation water would increase due to warmer temperatures that alter the timing of spring runoff, which is a critical component in the network of surface water storage facilities that moves California's water from the northern part of the state to the southern part (Hanak et al., 2011). The price of water was added to the model, estimated at a 10–25% increase to the average per acre irrigation costs, which are \$635.32 for tomatoes and range from \$229.13 in the first year to \$874.86 past the fourth year for almonds (Duncan et al., 2016; Turini et al., 2018). This scenario also addresses changes in yield due to more heat waves, which are predicted under climate change (Pathak et al., 2018). Tomatoes and almonds were treated differently because more heat waves may result in greater yields for tomatoes, but lower yields for almonds. Yield benefits increase or decrease 5% for tomatoes and almonds, respectively. Lastly, Scenario 1 includes the impact of more frequent floods and droughts. This scenario incorporates a 10% increase in benefits from soil erosion control due to cover crops in response to more frequent floods, and a 3-inch increase in irrigation requirements in response to more frequent droughts and subsequent depletion of soil moisture.

Three water scenarios explore how water-related parameters impact the profitability of winter cover cropping. These are important to consider under the lens of compliance with new resource management policies in California and a changing hydrologic landscape. Sustainable agriculture will require field conditions to improve so applied water (e.g. precipitation and irrigation) is used more efficiently as water becomes more scarce, expensive and polluted (Jury and Vaux, 2005). Scenario 2 addresses this by simulating better field conditions when cover crops improve infiltration, retention and re-distribution of soil water. These conditions could improve water management conditions on agricultural fields and potentially reduce irrigation costs. This scenario simulated an ideal situation where winter cover crops increase soil water availability for summer cash crops and reduce irrigation requirements by 30%. Water costs per acre are \$635.32 for tomatoes and range from \$229.13 in the first year to \$874.86 after the fourth year for almonds (Duncan et al., 2016; Turini et al., 2018). Scenarios 3 and 4 compare the profitability of winter cover cropping in the northern and southern regions of the Central Valley, which face different hydrologic constraints, including annual precipitation and the cost of surface water deliveries. These simulations increase and decrease the frequency of harvest complications with cash crops, which increases to every 3 years and decreases to none in the northern and southern parts of the Central Valley, respectively.

Two policy scenarios explore the impacts of growing winter cover crops under a new regulatory landscape in California. Scenario 5 simulates the economic profitability of growing winter cover crops while receiving subsidies for their ecosystem services. A range of values was used to identify the price necessary to break even, starting at \$55 per acre based on average prices of government subsidies for cover cropping throughout the U.S. Scenario 6 simulates an increase in the value of carbon that cover crops store in the soil through agricultural mitigation.

Table 3
Description of scenarios used to simulate future changes in climate, water and policy in California. Values are reported at the end of the systems' life cycles – 10 and 30 years for tomato and almond, respectively.

Scenario	Variable type	Scenario description	Benefit-cost ratio		Percent change from baseline	
			Tomato	Almond	Tomato	Almond
Scenario 1 explores potential impacts of climate change by combining the following variables						
1	Cost	Warmer temperatures change spring runoff timing, thereby decreasing the reliability of surface water deliveries and increasing water prices	0.45	0.68	−26%	−45%
	Benefit & cost	More frequent heat waves affect agronomic performance of tomato plants and almond trees, increasing or decreasing yields respectively				
	Benefit	Cover crops reduce erosion losses during more frequent floods				
	Cost	More frequent droughts increase irrigation requirements of cash crops				
Scenarios 2 – 4 explore potential hydrologic changes						
2	Benefit	Winter cover crops increase soil-water in the winter, thereby decreasing summer irrigation requirements by 30%	1.02	2.21	69%	77%
3	Cost	There is a greater risk of harvest complications with cash crops, which is likely to be experienced in the Northern part of the Central Valley due to the unpredictability of spring precipitation	0.49	0.91	−19%	−27%
4	Benefit	There is no risk of harvest complications with cash crops, which is likely to be experienced in the Southern part of the Central Valley due to the predictability of spring precipitation	1.02	2.45	69%	96%
Scenarios 5 & 6 explore potential policy changes						
5	Benefit	State policies incentivize cover cropping through a subsidy for the ecosystem and societal services that winter cover crops provide	0.72	1.46	20%	17%
6	Benefit	State subsidizes carbon storage through agricultural mitigation practices such as winter cover crops	0.66	1.31	10%	5%

The soil-carbon sequestration variable was altered by doubling the price of carbon (Frances et al., 2017; Nordhaus, 2017). These numbers reflect an increased societal valuation of carbon sequestration that could be feasible if law makers and society focus on the implementation of climate change mitigation policies.

3. Results

The following results are based on the output of the models that calculate the net present value of costs and benefits from growing winter cover crops in California. We estimate the profitability of this practice by calculating baseline benefit-cost ratios for winter cover cropping in operations that produce tomatoes and almonds over 10- and 30- year horizons, respectively. After testing the baseline models with a sensitivity analysis, we conduct a scenario analysis that shows how the incentives for adoption vary as climate, water availability and environmental regulations change. Winter cover cropping in California may be profitable in the long-term, but this depends on the crop system, extent of irrigation savings due to improved soil function, access to financial subsidies and climate change impacts.

3.1. Baseline impact of winter cover crops

Winter cover cropping is an investment in the long-term viability of agricultural operations. The value of this conservation practice is evident when using a planning horizon beyond the next planting season. The annual breakdown of the cumulative modeling results reveals that benefits and costs accrue differently over time, supporting our first hypothesis that the value of winter cover crops is not captured in an annual analysis (Fig. 1). The costs vary significantly from year-to-year depending on the occurrence of harvest complications with cash crops. Additionally, only a small portion of cumulative benefits are indirect, which suggests that the existence of social benefits (i.e. benefits accruing to those external to the decision-maker) are not a driver of low adoption rates. Modeling results also reveal different experiences for tomato and almond growers, which experience cumulative benefit-cost ratios of 0.6 and 1.2, respectively.

Results from the sensitivity analysis validate the performance of the models and identify which inputs had the most leverage. The two crop models change distinctly due to changes in variable parameter values (Fig. 2). The almond model is more sensitive and displays a wider range of possible benefit-cost ratios. The variables that affected the benefit-cost ratios most were harvest complications with cash crops (i.e. reduced revenue), yield increases (i.e. increased revenue) and mycorrhizal fungi colonization (i.e. foregone cost of soil amendments).

Through 30 baseline model runs, the benefit-cost ratio is never above 1 for tomatoes but is closest to breaking even when the cost of harvest complications with cash crops is minimized. This variable is estimated to be less significant in almond production, which contributes to the almond system having a benefit-cost ratio more consistently over 1. The harvest complication variable represents the potential for winter cover crops to complicate the harvest of summer cash crops, a risk that was revealed from grower interviews. These complications look slightly different for the two cropping systems of interest. For tomato growers, late winter rain could delay termination of a winter cover crop due to wet field conditions. This could in turn delay their tomato transplanting schedule, which is designed to provide weekly harvests to meet contracts with tomato canneries throughout the summer. For almond growers, winter cover cropping could complicate summer harvests that require sweeping up almond hulls off the orchard floor. The industry standard is to have a 'clean floor' by August, however a cover crop could persist between rows and potentially interfere with harvest equipment.

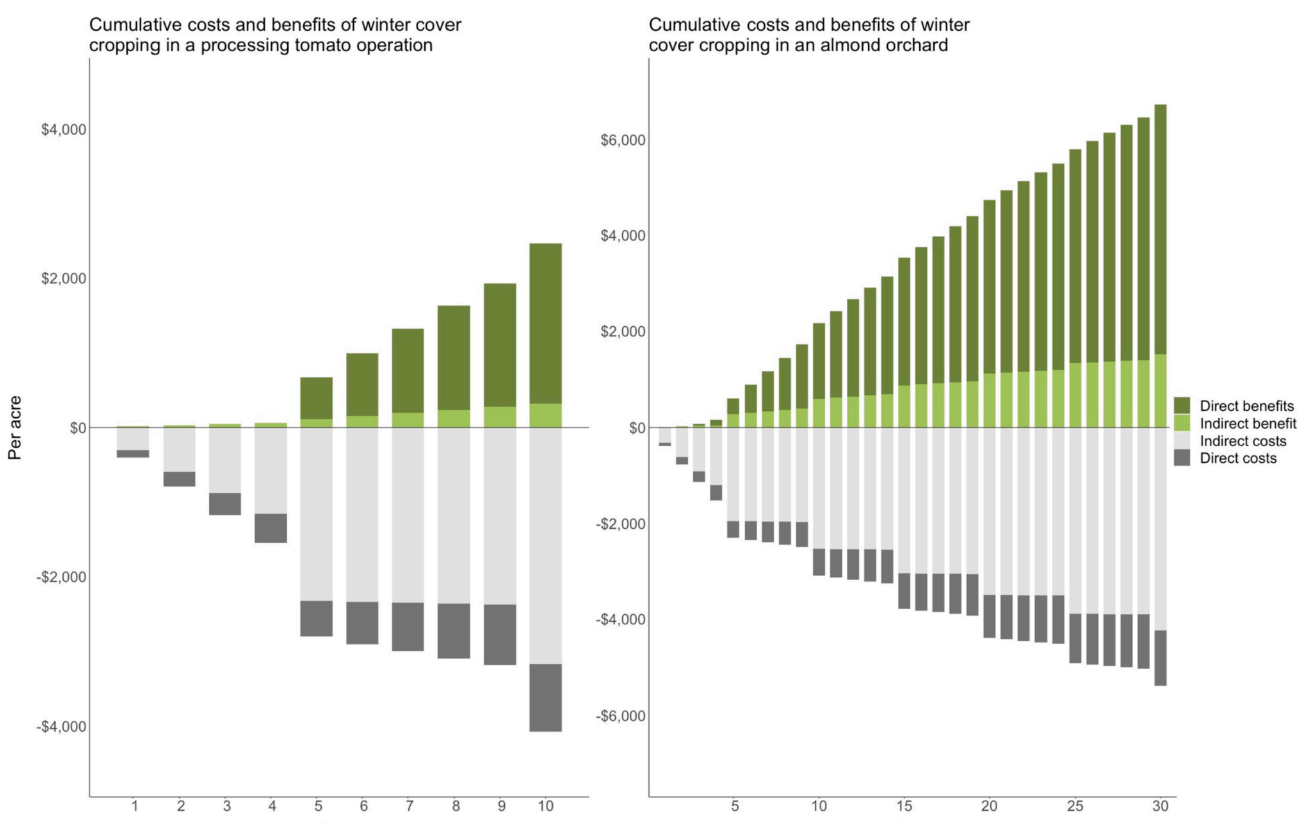

Fig. 1. Breakdown of cumulative costs and benefits due to winter cover cropping in processing tomato and almond operations. Values are reported in 2018 US dollars per acre and discounted annually. Benefits and costs are separated based on their designation as "indirect" or "direct" costs or benefits. These values reflect model results under baseline conditions.

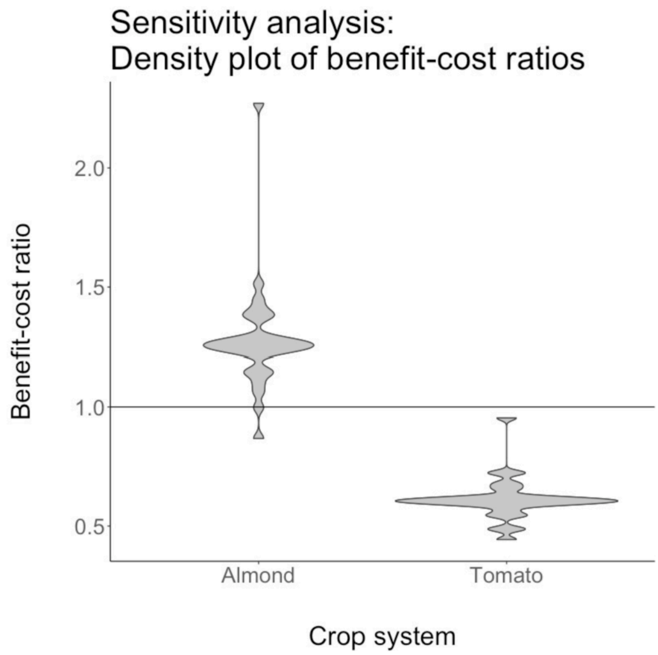

Fig. 2. Density distribution plot of results from sensitivity analysis of net present value models for growing winter cover crops in California. The analysis explored the impact of the range of prices for inputs to models for almond and tomato production systems.

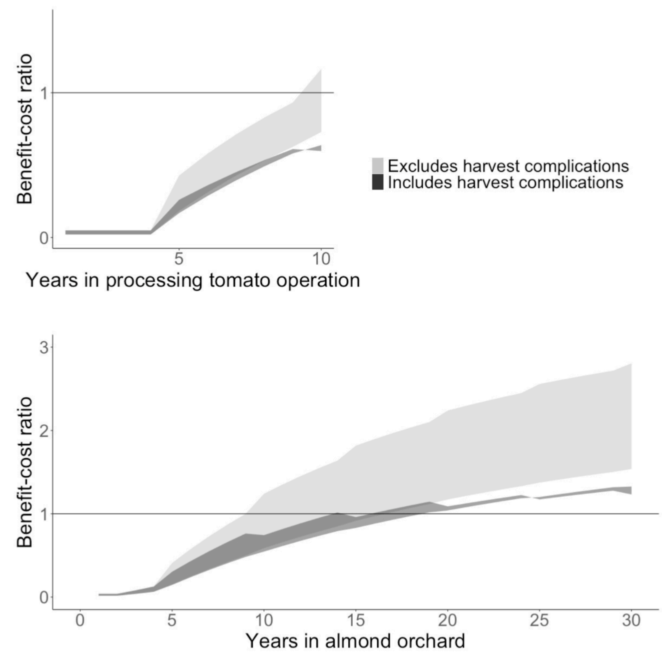

Fig. 3. Range of possible benefit-cost ratios experienced by specialty crop operations practicing winter cover cropping in California's Central Valley under baseline conditions.

These harvest complications were valued as infrequent revenue losses (see appendix).

These results led to further modeling to explore the impact of harvest complications. When this variable is *excluded* from the analysis, both crop systems experience an average benefit-cost ratio of 1 or greater and growing winter cover crops is profitable. However, if this variable is *included* in the analysis, the average benefit-cost ratios fall to 0.6 for tomatoes and 1.2 for almonds, indicating that total benefits eventually outweigh total costs for operations growing almonds, but not tomatoes (Fig. 3).

Growing winter cover crops in California's Central Valley can increase baseline profit for some operations. In average baseline conditions that include harvest complications every fifth year, perennial crop systems growing almonds can experience economic benefits between 14 and 19 years after the start and continuation of this conservation practice. Annual crop systems growing winter cover crops between crop rotations that include tomatoes do not see an economic return on average in the 10-year cycle that was modeled, unless harvest complications are removed from analysis. These results may not represent all tomato and almond operations because the baseline ratios are derived from *average* costs and benefits; farm-specific ratios would vary with site-specific factors. For example, if an operation experiences the upper-bound values for benefits and lower-bound values for costs, then benefits outweigh costs for both production systems after 9 years. The range of possible experiences that this model predicts for tomato operations (Fig. 3) is consistent with the reality that some annual crop farmers adopt winter cover crops, while the practice may not be profitable on average for everyone.

3.2. Counterfactual scenarios

The validated baseline models were adjusted to shed light on the future viability of winter cover cropping by simulating hypothetical changes in California's agricultural production and regulatory context. The resulting benefit-cost ratios challenge our second hypothesis that changes in climate, water access and policy can switch the economic viability of winter cover cropping (Table 3). For a majority of the scenarios, the benefit-cost ratios do not switch, and the value remains less than 1 for tomatoes and greater than 1 for almonds (Fig. 4). Almond orchards with winter cover crops appear to be resilient in this sense to regulatory disturbances, while processing tomato operations may require specific circumstances to experience profitability.

Climate change will challenge the economic viability of winter cover cropping in California. The climate change scenario 1 models the simultaneous occurrence of four climate changes and their related impacts to agricultural production. The cumulative benefit-cost ratios are below 1 for both crop systems, indicating that the combination of

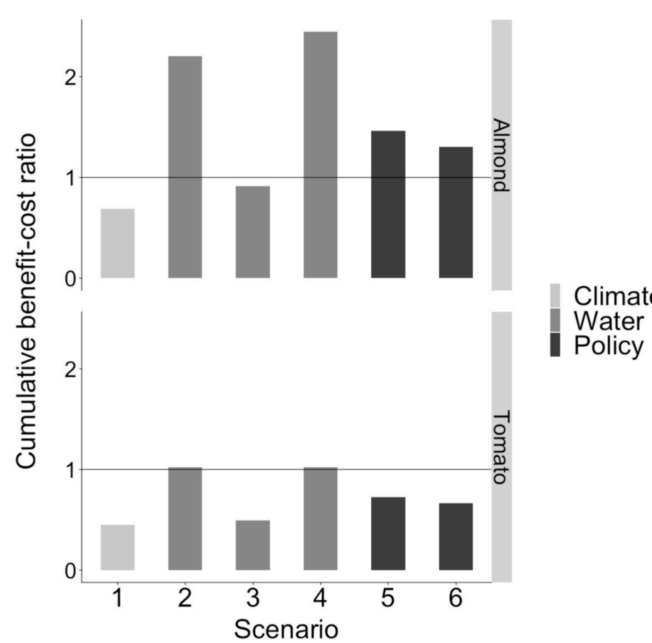

Fig. 4. Benefit-cost ratios of growing winter cover crops under various scenarios that simulate changes to California's agricultural landscape. This figure should be viewed in conjunction with Table 3 that references each scenario.

increased temperatures and frequency of extreme weather events cause the costs of cover cropping to increase more than the benefits in the face of climate change.

Winter cover cropping is profitable on average for tomato operations in two scenarios. First, growers will experience a net economic gain if winter cover crops cause a 30% reduction in summer irrigation requirements due to improved soil function. While this is an ideal scenario, it is important to consider because some farmers in the Central Valley report having had this experience. Second, a tomato grower can profitably grow winter cover crops if they experience *no* risk of harvest complications, as shown in scenario 4. However, they may suffer economic losses if late winter rains interfere with winter cover crop termination. Growers that experience harvest complications with tomatoes which prevent them from meeting the deadlines of inflexible contracts with canneries will not experience the same economic benefits of this land management practice, as shown in scenario 3.

There is opportunity for policy interventions and government subsidies to incentivize winter cover crop adoption, but the details of implementation require careful consideration of a grower's regulatory landscape. To encourage adoption, policies should offer incentives that are crop-specific because tomato and almond farmers do not experience the same degree of economic return from cover cropping with subsidies, as shown in scenario 5. The price point of subsidies to incentivize winter cover cropping must increase. Prices used to model subsidies in scenarios 5 and 6 were based on current rates offered by the USDA and historical price of carbon on the California market. The simulation of these subsidies did not help tomato farmers meet a breakeven point. Further variable manipulation showed that there are three subsidies that make winter cover cropping a profitable soil management strategy for tomato operations: a subsidy of at least $175 per acre annually or $550 per acre for the first three years of the practice or a subsidy that reflects a social price of carbon around $600 per ton, assuming that winter cover crops can sequester 0.3 tons of carbon per acre.

4. Discussion

The results of this research are critical for both producers and policy makers as they strive to meet the challenges of agricultural production under California's changing environment. For producers, winter cover crops can be economically viable under certain circumstances, but they should be considered a long-term investment. Almond operations appear to be resilient systems that could likely withstand the financial requirements of winter cover cropping, while tomato growers should more heavily weigh site-specific factors of their operations before investing in this practice. For policy makers, our findings show that access to sufficient government subsidies could increase winter cover crop adoption in both annual and perennial crop systems.

4.1. Impacts for producers

To obtain positive net benefits from winter cover cropping, growers must consider a long planning horizon and value ecosystem services. We speculate that farmers should consider several on-farm implications of winter cover crops to ensure their profitability. First, the largest threat to winter cover crop profitability in processing tomatoes appears to be the potential for harvest complications with cash crops and subsequent contractual non-compliance. Potential solutions are to use warm weather cover crops that do not have the same management complications in response to late winter rains or to plant winter cover crops on a portion of the cropland, specifically that which will be harvested later in the summer. Winter cover cropping in tomatoes becomes a profitable practice without this threat, indicating that they could be a profitable investment if they are grown with the care and attention of a cash crop. This finding is relevant because the benefits of winter cover cropping clearly outweigh the costs for crop systems that are not beholden to predetermined dates of sale. There is ample opportunity for growers throughout California and the rest of the country to take advantage of the positive net present value of winter cover cropping as long as they do have flexible contractual requirements and can wait for the long-term return on investment.

California growers work within a complicated network of hydrologic constraints that may impact the profitability of winter cover cropping. If growers can reduce their summer irrigation requirements through the use of winter cover crops, the practice could pay for itself. In the northern part of the Central Valley, late winter rains that complicate termination of winter cover crops are more likely, but water is generally less expensive in this region. In the southern part of the Central Valley, late rains are less likely, while water can be significantly more expensive. Farmers in all parts of the Central Valley may have various water-related winter cover crop concerns.

4.2. Policy considerations

Policy interventions affect certain crop systems more than others, complicating the development of an incentive structure. Governmental programs that offer payments for ecosystem services could enhance the profitability of winter cover cropping in California, but, in light of our results, the payments likely need to be larger and more accessible than they have been in the past. According to our analysis, for an average tomato operation to profitably grow winter cover crops (holding all other variables constant), growers would need to receive a payment of nearly $550 for the first 3 years or $175 annually for 10 years. These values are significantly higher than the current rates provided through cost-share by the USDA for on-farm conservation practices, however they are on the scale of incentives currently available in California through the Healthy Soils Program by the California Department of Food and Agriculture. Only 6,000 acres of farmland in California annually received a subsidy for cover cropping from the USDA between 2015 and 2018 (personal communication with Hudson Minshew). High-value crops grown in California, such as tomatoes and almonds, are more expensive to produce than staple crops grown in the Midwest, where cover crop adoption is more common. Growers may adopt cover crops only if their subsidy covers a significant portion of their average annual operating costs.

Subsidies for the climate change mitigation effect of cover cropping could also enhance their profitability but require a ten-fold increase in the price of carbon. This may be feasible if law makers and society focus on the implementation of climate change mitigation policies and dedicate sufficient funds to incentivize sustainable agricultural practices.

These subsidies monetize ecosystem services provided by winter cover cropping, which include the indirect benefits of increased soil organic matter, reduced surface water runoff and soil-carbon storage. These indirect benefits are both felt by individual growers and have spillover effects to society at large. These benefits may be experienced by the next grower farming the land, who does not need to build up their soil carbon, a grower's downstream neighbor who has access to cleaner water or future generations that can rely on a consistent food supply amidst climate uncertainties.

4.3. Limitations and future work

Our work to understand cover crop adoption incentives can be expanded in future research. First, the model could be improved by including the monetary values of components of the budget that are difficult to quantify, such as changes in insect biodiversity, biogeochemistry and greenhouse gas emissions. For example, our model could more clearly address the complicated trade-off of using carbon: greenhouse gases are emitted when diesel-powered equipment is used to plant and terminate winter cover crops, but cover crops naturally sequester carbon in the soil. One could also explore the implications of alternative termination methods, such as grazing and forage. Additionally, the rich heterogeneity across growers is not captured in our analysis of average benefits and costs. The monetization process required simplifications and assumptions that may not reflect site-specific conditions for all specialty crop growers in California. Lastly, our results are location and crop specific to tomato and almond operations in the Central Valley of California and there is no prescription for all California farms. However, this model could easily be modified to different systems and locations with appropriate data.

Despite these limitations, this research provides significant contributions to the study of conservation agriculture practices by shedding light on the possible reasons for low adoption of winter cover cropping in California's specialty crop systems. It is the first modeling effort to evaluate the economic impact of cover cropping in these high-value crop systems in California and the results are relevant to many types of agricultural systems. This model improves on previous methodologies by validating parameter estimates and literature values through grower interviews and field datasets, ensuring that our research is grounded in reality. We use this novel method to analyze both the current situation *and* look to the future through counterfactuals that explore several possible futures of agricultural production.

5. Conclusions

This research highlights the importance of valuing soil management practices, such as winter cover cropping, to gauge their role in the changing agricultural landscape of California. A net present value model describes the economic value of winter cover cropping to shed light on barriers to adoption. The model confirms the hypothesis that winter cover crops have a long-term payoff because benefits accrue slowly over time. Winter cover crops are likely to be viable in almond and tomato operations that do not experience harvest complications. While climate change impacts may threaten the viability of winter cover cropping, benefits outweigh costs to a larger extent if growers receive sufficient subsidies to capture the societal benefit of ecosystem services and if they can reduce their summer irrigation requirements. Growing winter cover crops may have significant long-term benefits for individual farms and society as a whole in California and beyond.

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Appendix

Monetary values used in net present value models are explained in detail in the following paragraphs and Table 4.

A majority of the values described below are taken from the University of California Cost and Return studies for processing tomatoes in a crop rotation and an almond orchard (Duncan et al., 2016; Turini et al., 2018). Winter cover crops were estimated to be seeded on 100% of acreage for tomatoes fields and to cover 75% of possible acreage in almond orchards. All of the values described below were used to calculate the final values that were incorporated into a 10- or 30- year analysis, with all values discounted to the present value.

Direct costs were identical for every year of the analysis for processing tomatoes but varied for the almonds based on the year and what type of cover crop was being grown (annual vs. perennial). **Seed costs** were based on conversations with farmers, extension specialists and seed company representatives. The range in price describes the variety of potential seed mixes that are commonly used to winter cover crop in California's Central Valley and reflect seed mixes commonly used in annual and perennial systems. The mix for tomato operations was assumed to be a small grain forage mix (i.e. bell beans, winter peas, common vetch) purchased for $0.40–0.75 per lb. and planted at a rate of 60–120 lbs. Per acre. The mix for almonds was assumed to be a more expensive clover mix purchased for $1.00–2.15 per lb. and planted at a lower rate of 20–40 lbs. Per acre.

We assumed that **planting and terminating** winter cover crops only incurs labor costs. We estimated a farm worker would be paid a wage for machine labor and used wages from the Cost and Return studies. We assumed that this wage stays constant through the planning horizon. Planting labor costs were estimated to vary between 30 min and 1 h of wages for a farm laborer running a machine (Pratt et al., 2014), valued at $19.21 per hour for tomatoes and $20.51 per hour for almonds. Seed and planting costs were realized every year for tomatoes but only during the first 4 years of the almond operation. Termination (i.e. killing and incorporating winter cover crops) labor costs were estimated to be double that of planting for the entire tomato timeline and the first 3 years of the almond operation. Beginning in the fourth year for the almond operation, labor costs for termination were estimated to be 2–4 mows per season, valued at $15–25 per pass (Pratt et al., 2014).

Indirect costs were variable from year to year. We assumed that cover crops can **complicate harvests of cash crops** during the summer, as explained in the main text. Tomato growers risk delays in the emergence of tomatoes that could interfere with pre-determined weekly sales to tomato canneries, while almond growers may experience complications due to the presence of vegetation between tree rows that can interfere with hull harvest. The harvest complications were valued as revenue losses. Informed by grower interviews, we estimated the risk exposure of contractual noncompliance with tomato canneries between 5 and 30% of annual yield every 5 years. We assumed that once every five years there could be a late winter rain that complicates cover crop termination and leads to delayed planting. The risk exposure of harvest complications in almond orchards was estimated to be half that. Revenue losses were calculated based on data from the Cost and Return studies. We estimated returns of $55.50–85.50 per ton of tomatoes and $2.62 per lb. of almonds, and yield ranges of 43–73 tons per acre for tomatoes and 1000–3400 lbs. Per acre for almonds after year 6 (during full production). The yield ranges for almonds increase incrementally beginning in the third year.

Other indirect costs include **depreciation of equipment** and the **opportunity cost of time** spent learning how to cover crop. Equipment will depreciate more quickly if it is being used to cover crop in the winter, when it would otherwise be dormant. The depreciation costs were estimated to vary from 5 to 30% of annual capital recovery costs for equipment detailed in Cost and Return studies, $75 and $35.97 for tomatoes and almonds, respectively. The opportunity cost of time captures the value of time spent on behalf of the owner-operator learning to incorporate winter cover crops into his or her management system. This time may be spent making the decision to begin winter cover cropping (e.g. collecting relevant materials, reading, researching, attending workshops, talking with neighbors and fellow farmers) and implementing a new management plan (e.g. consulting with crop advisors and seed distributors, retrofitting equipment, disseminating instructions to crew members). The time was estimated to vary between 10 and 20 h every year for the first 5 years of winter cover cropping. The value per hour is the same as the hourly wages used to estimate the direct costs.

Direct benefits were identical every year beginning in the fifth year of consecutive winter cover cropping (Creamer et al., 1996). **Yield benefits** were estimated as a conservative 5% increase from the baseline yields for tomatoes and 2.5% for almonds to reflect agronomic benefits from improved soil health due to winter cover cropping based on grower interviews. **Soil erosion control** was estimated to be the foregone cost of new soil to replace soil lost due to runoff from fields, translated into U.S. dollars per lb. of potential soil lost per acre. On average, annual soil saved from erosion due to winter cover crops was estimated at 489.2 lbs. Per acre, which was valued based on the assumptions that top soil weighs 1300 lbs. Per cubic yard and is valued between $25–50 per cubic meter (Malik et al., 2000; Nearing et al., 2017; Pratt et al., 2014; Robinson et al., 2014). Fertilizer and herbicide cost savings were estimated to vary between 5 and 30% to capture the benefits of **nutrient cycling and weed control**, respectively. Fertilizer costs savings per acre were based on the prices per acre: $396 for tomatoes, $228.19 in the fifth year of almonds and $290.12 during full production after the sixth year for almonds. Cost savings for herbicide were $20 and $60.56 per acre for tomatoes and almonds, respectively. The benefit of **mycorrhizal fungi colonization** was estimated to be the foregone cost of added soil amendments, estimated to be 2–8 tons of compost per acre, valued at $14.58–72.91 per ton, every five years (Gravuer, 2016; Rahmani et al., 2004).

One variable differed between the models to address the different possible benefits for annual and perennial cropping systems. For annual tomato production, winter cover crops can improve soil structure and **reduce tillage** requirements to break up the soil surface and prepare the ground for transplanting in the spring. This benefit was estimated to be the savings associated with one less pass of machinery in winter cover cropped systems, valued using the same labor rate as in the direct costs. For perennial almond production, winter cover crops can provide an attractive pollination habitat for bees. Growers pay for beehives to pollinate almond trees every spring, and beekeepers may offer discounts to an orchard with cover crops that offer a more diverse foraging opportunity to the hive. These **beehive discounts** were estimated to be between 5 and 30% reduced costs that range from $94.16 in the third year to $470.81 after the sixth year based on prices from the Cost and Return study.

Indirect benefits were calculated similarly for both production systems. The benefit **of increased soil organic matter** captures the soil health improvements that winter cover crops provide. The monetary value per acre was based on the lowest and highest soil organic matter contributions from oil seed radish ($21.72) and crimson clover ($46.54), respectively (Pratt et al., 2014). Winter cover crops can also **reduce surface water runoff**, and subsequent pollution (Wyland et al., 1996). The range of prices for surface water discharge permits for the 2017–2018 fee schedule for California Code of Regulations TITLE 23. Division 3. Chapter 9. Waste Discharge Reports and Requirements was used as a proxy for savings from reduced surface water runoff because just 10% of ground cover can correspond to a 30% improvement in erosion control (California Code of Regulations, n. d.; Sarrantonio and Gallandt, 2003). The lowest value was $0.87 per acre and the highest value was $4.76 per acre.

The benefit of **soil-carbon storage** describes how winter cover crops can mitigate climate change by sequestering atmospheric carbon. The monetary value was estimated based on the carbon-sequestration potential of winter cover crops in California's Central Valley from the COMET Planner tool, which uses the DayCent crop model (Swan et al. n. d.). The model estimates 0.3 or 0.15 tons of carbon is sequestered per acre-foot of seeded cover crops and residual vegetation, respectively. These estimates were valued by multiplying them by a range of $14.54–75.10 per ton of CO_2, estimates for the social cost of carbon from California's carbon market (Auffhammer, 2018).

Table 4
List of raw values used to calculate costs and benefits associated with winter cover cropping in two specialty crop systems in California's Central Valley.

	Budget components	Raw data used in calculations (per acre)			Sources
		Low	High	Description	
Processing tomatoes					
Costs	Seed	$0.40	$0.75	price per lb. of seed	1
		60	120	lb. cover crop seed	1
	Planting (labor)	30	60	minutes of labor	1,3
		$19.21	$19.21	hourly wage	2
	Termination (labor)	60	120	minutes of labor	1,3
		$19.21	$19.21	hourly wage	2
	Harvest complications with cash crops	5	30	% of yield loss every 5 years	1
		$55.50	$85.50	return per ton tomatoes harvested	2
		43	73	tons per acre harvested	2
	Depreciation of machinery	5	30	% of annual capital recovery costs depreciated	1
		$75.00	$75.00	annual capital recovery costs for equipment	2
	Opportunity cost of time spent learning to grow cover crops	10	20	hours of learning	1
		$19.21	$19.21	hourly wage	2
Benefits	Increased yield	5	5	% increase	4
		$55.50	$85.50	return per ton tomatoes harvested	2
		43	73	tons per acre harvested	2
	Soil erosion control	489.2	489.2	lbs. topsoil lost without cover	3,5,6
		$25.00	$50.00	price of cubic yard topsoil	7
	Nutrient cycling	5	30	% of fertilizer savings	1
		$396.00	$396.00	price of fertilizer	2
	Weed control	5	30	% of herbicide savings	1
		$20.00	$20.00	price of herbicide	2
	Mycorrhizal fungi colonization	2	8	tons of compost avoided	8
		$14.58	$72.91	price per ton of compost	9
	Reduced tillage operations	$15	$25	price per pass	1
	Increased soil organic matter	$21.72	$46.54	value of soil health improvements	1,3
	Reduced surface water runoff	10	30	% of ground cover	10, 11
		$0.87	$4.76	surface water discharge permits	12

(*continued on next page*)

Table 4 (*continued*)

	Budget components	Raw data used in calculations (per acre)			Sources
		Low	High	Description	
	Soil-carbon storage	0.3	0.3	tons of sequestered carbon	13
		$14.54	$75.10	price per ton of carbon	14
Almonds					
Costs	Seed	$1.00	$2.15	price per lb. of seed	1
		20	40	lb. cover crop seed	1
	Planting (labor)	30	60	minutes of labor	1,3
		$20.51	$20.51	hourly wage	15
	Termination (labor)	60	120	minutes of labor	1,3
		$20.51	$20.51	hourly wage	15
		2	4	mowing passes	1
		$15	$25	price per pass	1
	Harvest complications with cash crops	2.5	15	% of yield loss every 5 years	1,3
		$2.62	$2.62	return per lb. almonds harvested	15
		182	618	lbs. almonds per acre harvested at year 3	15
		364	1236	lbs. almonds per acre harvested at year 4	15
		727	2473	lbs. almonds per acre harvested at year 5	15
		1000	3400	lbs. almonds per acre harvested at maturity	15
	Depreciation of machinery	5	30	% of annual capital recovery costs depreciated	1
		$35.97	$35.97	annual capital recovery costs for equipment	15
	Opportunity cost of time spent learning to grow cover crops	10	20	hours of learning	1
		$20.51	$20.51	hourly wage	15
Benefits	Increased yield	2.5	2.5	% increase	4
		$2.62	$2.62	return per lb. almonds harvested	15
		182	618	lbs. almonds per acre harvested at year 3	15
		364	1236	lbs. almonds per acre harvested at year 4	15
		727	2473	lbs. almonds per acre harvested at year 5	15
		1000	3400	lbs. almonds per acre harvested at maturity	15
	Soil erosion control	489.2	489.2	lbs. topsoil lost without cover	3,5,6
		$25.00	$50.00	price of cubic meter topsoil	7
	Nutrient cycling	5	30	% of fertilizer savings	2
		$228.19	$228.19	price of fertilizer at year 5	15
		$290.12	$290.12	price of fertilizer at maturity	15
	Weed control	5	30	% of herbicide savings	2
		$20.00	$20.00	price of herbicide	15
	Mycorrhizal fungi colonization	3	8	tons of compost avoided	8
		$14.58	$72.91	price per ton of compost	9
	Discounted beehives	5	30	% of beehive savings	1
		$94.16	$94.16	price of beehives at year 3	15
		$188.32	$188.32	price of beehives at year 4	15
		$376.65	$376.65	price of beehives at year 5	15
		$470.81	$470.81	price of beehives at maturity	15
	Increased soil organic matter	$21.72	$46.54	value of soil health improvements	1,3
	Reduced surface water runoff	10	30	% of ground cover	10
		$0.87	$4.76	surface water discharge permits	12
	Soil-carbon storage	0.3	0.3	tons of sequestered carbon years 1–3	13
		0.15	0.15	tons of sequestered carbon after year 4	13
		$14.54	$75.10	price per ton of carbon	14

Monetary values based on:

1 Conversations with farmers, extension specialists, and seed company representatives
2 Turini et al. (2018)
3 Pratt et al. (2014)
4 Creamer et al. (1996)
5 Malik et al. (2000)
6 Nearing et al. (2017)
7 Robinson et al. (2014)
8 Rahmani et al. (2004)
9 Gravuer (2016)

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Table 4 (*continued*)

10	Sarrantonio and Gallandt (2003)
11	Wyland et al. (1996)
12	Section 2200.6. Annual Agricultural and Irrigated Lands Fee Schedule (2017–2018)
13	COMET Planner tool by Swan et al. (n.d.)
14	Auffhammer (2018)
15	Duncan et al. (2016)

References

Aguilera, E., Lassaletta, L., Gattinger, A., Gimeno, B.S., 2013. Managing soil carbon for climate change mitigation and adaptation in Mediterranean cropping systems: a meta-analysis. Agric. Ecosyst. Environ. 168, 25–36. https://doi.org/10.1016/j.agee.2013.02.003.

Aldieri, L., Kotsemir, M., Vinci, C.P., 2019. The role of environmental innovation through the technological proximity in the implementation of the sustainable development. Bus. Strat. Environ. 1–10. https://doi.org/10.1002/bse.2382. July.

Auffhammer, M., 2018. Quantifying economic damages from climate change. J. Econ. Perspect. 32 (4), 33–52.

Bai, Y., Ochuodho, T.O., Yang, J., 2019. Impact of land use and climate change on water-related ecosystem services in Kentucky , USA. Ecol. Indicat. 102 (January), 51–64. https://doi.org/10.1016/j.ecolind.2019.01.079.

Bergtold, J.S., Ramsey, S., Maddy, L., Williams, J.R., 2017. A review of economic considerations for cover crops as a conservation practice. Renew. Agric. Food Syst. 1–15. https://doi.org/10.1017/S1742170517000278.

Bitsch, V., 2005. Qualitative research: a grounded rheory example and evaluation criiteria. J. Agribus. 23 (1), 75–91.

Blanco-Canqui, H., Shaver, T.M., Lindquist, J.L., Shapiro, C.A., Elmore, R.W., Francis, C. A., Hergert, G.W., 2015. Cover crops and ecosystem services: insights from studies in temperate soils. Agron. J. 107 (6), 2449–2474. https://doi.org/10.2134/agronj15.0086.

California Code of Regulations. Annual Agricultural and Irrigated Lands Fee Schedule., Pub. L. No. Section 2200.vol. 6.

California Department of Food and Agriculture, 2018. California Agricultural Statistics Review 2017-2018.

Carlisle, L., 2016. Factors influencing farmer adoption of soil health practices in the United States: a narrative review. Agroecology and Sustainable Food Systems 40 (6), 583–613. https://doi.org/10.1080/21683565.2016.1156596.

Creamer, N.G., Bennett, M.A., Stinner, B.R., Cardina, J., 1996. A comparison of four processing tomato production systems differing in cover crop and chemical inputs. J. Am. Soc. Hortic. Sci. 121 (3), 559–568.

DeVincentis, A. J., Sandoval-Solis, S., Zaccaria, D., Rice, S., Gomes, A., Maskey, M. L., et al.). Quantifying the Hydrologic Impact of Winter Cover Cropping in California.

Duncan, R.A., Holtz, B.A., Doll, D.A., Klonsky, K., Sumner, D.A., Gutierrez, C.A., Stewart, D., 2016. Sample costs to establish an orchard and produce almonds. UCCE ANR Agricultural Issues Center.

Ewel, J.J., 1999. Natural systems as models for the design of sustainable systems of land use. Agrofor. Syst. 45 (1/3), 1–21. https://doi.org/10.1023/A:1006219721151.

Frances, C.M., Baldos, U., Hertel, T., Diaz, D., 2017. New science of climate change impacts onagriculture implies higher social cost of carbon. Nat. Commun. https://doi.org/10.1038/s41467-017-01792-x.

Ghadim, A.K.A., Pannell, D.J., 1999. A conceptual framework of adoption of an agricultural innovation. Agric. Econ. 21 (2), 145–154.

Gravuer, K., 2016. Compost Application Rates for California Croplands and Rangelands for a CDFA Healthy Soils Incentives Program.

Hanak, E., Lund, J., Dinar, A., Gray, B., Howitt, R., Mount, J., et al., 2011. Managing California's Water from Conflict to Reconciliation. Public Policy Institute of California.

Jury, W.A., Vaux, H., 2005. The role of science in solving the world's emerging water problems. Proc. Natl. Acad. Sci. Unit. States Am. 102 (44), 15715–15720. https://doi.org/10.1073/pnas.0506467102.

Klonsky, K., Livingston, P., 1994. Alternative systems aim to reduce inputs, maintain profits. Calif. Agric. 48 (5), 34–42.

Kremen, C., Merenlender, A.M., 2018. Landscapes that work for biodiversity and people. Science. https://doi.org/10.1126/science.aau6020.

Lu, Y.C., Watkins, K.B., Teasdale, J.R., Abdul-Baki, A.A., 2000. Cover crops in sustainable food production. Food Rev. Int. 16 (2), 121–157. https://doi.org/10.1081/Fri-100100285.

Malik, R.K., Green, T.H., Brown, G.F., Mays, D., 2000. Use of cover crops in short rotation hardwood plantations to control erosion. Biomass Bioenergy 18 (6), 479–487. https://doi.org/10.1016/S0961-9534(00)00016-7.

Nearing, M.A., Xie, Y., Liu, B., Ye, Y., 2017. Natural and anthropogenic rates of soil erosion. International Soil and Water Conservation Research 5 (2), 77–84. https://doi.org/10.1016/j.iswcr.2017.04.001.

Nordhaus, W.D., 2017. Revisiting the social cost of carbon. In: Proceedings of the National Academy of Sciences, 201609244.

Pathak, T.B., Maskey, M.L., Dahlberg, J.A., Kearns, F., Bali, K.M., Zaccaria, D., 2018. Climate change trends and impacts on California agriculture: a detailed review. Agronomy 8 (3), 25.

Pratt, M.R., Tyner, W.E., Muth, D.J., Kladivko, E.J., 2014. Synergies between cover crops and corn stover removal. Agric. Syst. 130, 67–76.

Prokopy, L.S., Floress, K., Klotthor-Weinkauf, D., Baumgart-Getz, A., 2008. Determinants of agricultural best management practice adoption: evidence from the literature. J. Soil Water Conserv. 63 (5), 300–311. https://doi.org/10.2489/63.5.300.

Rahmani, M., Hodges, A.W., Kiker, C.F., 2004. Compost users' attitudes toward compost application in Florida. Compost Sci. Util. 12 (1), 55–60. https://doi.org/10.1080/1065657X.2004.10702158.

Robinson, D.A., Fraser, I., Dominati, E.J., Davíðsdóttir, B., Jónsson, J.O.G., Jones, L., et al., 2014. On the value of soil resources in the context of natural capital and ecosystem service delivery. Soil Sci. Soc. Am. J. 78, 685–700. https://doi.org/10.2136/sssaj2014.01.0017.

Rodriguez, J.M., Molnar, J.J., Fazio, R.A., Sydnor, E., Lowe, M.J., 2009. Barriers to adoption of sustainable agriculture practices: change agent perspectives. Renew. Agric. Food Syst. 24 (1), 60–71.

Sarrantonio, M., Gallandt, E., 2003. The role of cover crops in North American cropping systems. J. Crop Prod. 8 (1–2), 53–74. https://doi.org/10.1300/J144v08n01_04.

Soil Health Institute, 2019. Progress Report: Adoption of Soil Health Systems Based on Data from the 2017 U.S. Census of Agriculture.

Swan, A., Easter, M., Chambers, A., Brown, K., Williams, S. A., Creque, J., et al.). COMET Planner: Carbon and Greenhouse Gas Evaluation for NRCS Conservation Practice Planning.

Turini, T., Stewart, D., Murdock, J., Sumner, D.A., 2018. Sample Costs to Produce Processing Tomatoes. University of California - Division of Agriculture and Natural Resources.

Usda, N.R.C.S., 2019. Quick Spreadsheet of the Most Common Indexes and Discount Rates. Retrieved from. https://www.nrcs.usda.gov/wps/portal/nrcs/detail/national/cntsc/?cid=nrcs143_009709.

Vukicevich, E., Lowery, T., Bowen, P., Urbez-Torres, J.R., Hart, M., 2016. Cover crops to increase soil microbial diversity and mitigate decline in perennial agriculture. A review. Agron. Sustain. Dev. 36 (3) https://doi.org/10.1007/s13593-016-0385-7.

Watt, D., 2007. On becoming a qualitative researcher: the value of reflexivity. Qual. Rep. 12 (1), 82–101. Retrieved from. http://nsuworks.nova.edu/tqr/vol12/iss1/5.

Wyland, L.J., Jackson, L.E., Chaney, W.E., Klonsky, K., Koike, S.T., Kimple, B., 1996. Winter cover crops in a vegetable cropping system: impacts on nitrate leaching, soil water, crop yield, pests and management costs. Agric. Ecosyst. Environ. 59 (1–2), 1–17.