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Addressing economic barriers to crop diversification in rice-based cropping systems



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Cropping system diversification is widely promoted to address global challenges. However, its economic performance compared to high-yielding monoculture represents a major knowledge gap. Using a combination of grower focus groups and Monte Carlo simulations, this research assessed the required changes in farm management and profitability of transitioning from continuous rice (*Oryza sativa* L.) to tomato (*Solanum lycopersicum* L.), sunflower (*Helianthus annuus* L.), beans (*Phaseolus vulgaris* L.), and safflower (*Carthamus tinctorius* L.) in California. Long-term outcomes of rotation scenarios were explored to provide insights into economic barriers to adoption, including rice rotated with sunflower and tomato and rice rotated with safflower and beans. Two additional scenarios reflected agronomic benefits of rotation and potential for climate risk adaptation. This research provides evidence that crop diversification can increase profitability over the long-term. Yet to achieve this goal, policies and incentives are required to overcome barriers such as additional investment, risk, labor, opportunity costs, and market access.

Rice (*Oryza sativa* L.) provides food for over 50% of the world's population while conserving wetland ecosystems¹. Globally, flooded rice systems have shown the potential to maintain high yields with continuous cropping over long periods of time, unlike monocropping in non-flooded soils which can lower yields, degrade soils, and contribute to environmental pollution^{1,2}. However, there are several global pressures forcing rice systems to diversify including pest management, climate change and water scarcity, labor demand shifts, and increasing agricultural costs of production^{3,4}. In reaction, research has focused on the implications of crop diversification in rice systems across multiple sustainability lenses^{5–7}. Crop diversification with rice is defined here as rotating flooded rice with non-flooded upland cash crops, which provides several agronomic benefits such as reduced pest pressure, improved soil health indicators, and increased crop yield^{5,8,9}. While each of these factors may increase profitability over time through a combination of reduced costs or increased revenue, the economic impacts of crop diversification remain a major knowledge gap¹⁰.

Cost-benefit analyses provide insights to help farmers make financial investments, assess risks of adopting new technologies, or quantify under what circumstances new management practices may be profitable^{11–13}. Furthermore, cost-benefit analyses are important to better understand barriers to adoption by assessing how different factors impact the costs of production as well as crop yields and revenue, both of which drive

profitability^{14,15}. Switching between flooded rice to a non-flooded crop introduces additional investment, labor, and financial uncertainty for several reasons^{7,16}. Rotation crops can produce higher returns, but may require higher costs for new equipment, land preparation, and irrigation infrastructure which may not necessarily lead to increased profits. In contrast, other crops may decrease revenue but save on production costs, increasing net gains.

Current research on the economic impact of crop rotations in rice systems is sparse^{10,17}. Some studies have taken place in tropical and sub-tropical climates, where an upland crop is planted in the fallow season or takes the place of the shorter season, secondary rice crop^{5–8}. In temperate regions of the United States, rice is grown as a summer crop with the primary production occurring in Arkansas, Louisiana, Texas, and California. Research on crop rotations with rice in the United States often comes from a pest management perspective, such as the infestation of weedy (red) rice, or concerning the impact rice has on the non-flooded crop^{18,19}. Less research has assessed the economic impacts of replacing summer rice with an alternative row crop, meaning less years of rice in the overall rotation. Investigating the level of farm management changes required to switch from continuous rice to a rice-based rotation including several years of rice followed by several years of a non-flooded summer crop is critical to understand long-term financial viability.

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Often economic studies in agriculture assess a single outcome without exploring how profits may change over time^{8,9,20,21}. The sequence of different crops grown in rotation over the long-term can be modeled using Net Present Value (NPV) to determine risk and profitability of different rotation scenarios^{22,23}. While additional costs can act as a disincentive, over time crop diversification can increase economic resilience and profit due to agronomic benefits such as higher yields^{14,17}. However, many cost-benefit studies focus on indirect benefits such as input savings from increased soil nutrients, yet rarely do they quantify indirect costs related to farmers needing to gain knowledge and skills or build relationships to access markets^{24,25}.

In the absence of experience, farmers need to sacrifice time spent learning a new system, rather than spending that time generating income elsewhere^{12,22,26}. This indirect cost is known as the opportunity cost²⁷. Here, the opportunity cost of these events is linked to the value farmers place on their own time, thus considering these costs can help identify additional barriers to adopting a new system. Traditional cost-benefit studies also fail to consider financial uncertainty due to variability in crop yield, operational costs on farms including irrigation and input requirements, and crop price. Sensitivity analysis can help illustrate the relative importance of different assumptions but cannot quantify the likelihood of outcomes due to economic uncertainty²². In contrast, probabilistic economic analysis, such as Monte Carlo simulations, can be a way to assess the risk of financial decisions by providing a distribution of possible outcomes based on many changing variables^{22,28,29}.

California produces rice on approximately 212,000 ha annually³⁰, roughly 95% of which is grown in the Sacramento Valley³¹. California rice landscapes are dominated by continuous rice planted each summer, requiring over 1500 mm for flood irrigation, followed by a flood or dry fallow in the winter months³². Less than 10% of rice lands are under some form of crop rotation^{33,34}. Recent challenges relating to water scarcity, herbicide resistance, and increasing input prices are threatening profitability by reducing planted area, crop yields, and increasing the costs of production³⁴. As an example, annual rice acreage has declined by 15–50% in recent years, mostly due to reductions in surface water availability³⁰. During 2022, the extent of fallowed rice fields corresponded to a revenue loss of about \$500 million, much of which was covered by crop insurance³⁵. Recent interviews with farmers suggest that rotations can increase profitability by diversifying the portfolio of crops grown, while decreasing input costs in rice for weed control and increasing rice yields³⁴. However, other farmers questioned the feasibility of rotations due to high clay soils and lack of equipment and markets.

In this study we assessed the economic performance and required changes in management for crop diversification in flooded rice systems. Crop rotation scenarios represented (i) high costs and revenue (rice – sunflower – tomato) and (ii) low costs and revenue (rice – safflower – beans), as compared with continuous rice. Furthermore, we included two scenarios that incorporated agronomic benefits of rotations and the ability to adapt to climate risks such as increasing water scarcity, considering recent trends where rice acreage has substantially decreased in drought years. The objectives were to determine: (1) costs of production, revenue, and profit ranges of individual crops compared to rice, (2) long-term profitability of

crop rotations based on probabilistic Monte Carlo simulations, and (3) explore how rotation scenarios reflecting increasing water scarcity (represented in the form of fallowing events in continuous rice) and farmer-reported agronomic benefits of rotation such as input savings and increased rice yields influenced profitability and risk. We hypothesized that additional costs for rotational crops such as equipment, labor, irrigation investments, and opportunity costs combined with a likelihood for low revenue will negatively affect profit outcomes for rotational crops on an annual basis, but that rotations can be more profitable than continuous rice in the long-term when accounting for rotational benefits and water scarcity.

Results

Required changes in management

The baseline system is continuous rice which is broadcast seeded with flood irrigation. Fields are leveled with a triplane and seed is flown on by airplane into standing water. After rice harvest, straw is incorporated into soil and a shallow flood is maintained over winter to promote decomposition and provide wildlife habitat. Growers deliver rice to a local elevator, so no marketing is required, allowing flexibility in rice acreage and yield levels for a given farm. All rotational crops are row crops grown on raised beds, thus focus groups reported that the biggest changes in management are related to land preparation, irrigation systems, and labor. When moving into a rotational crop following a previous rice crop, additional straw chopping and discing are required after rice harvest to minimize residues, and a winter flood is not usually done. Additional tractor work and labor are required in spring to remove levees, perform extra tillage to create a finer seedbed, and prepare beds with listing and shaping operations. Planting costs are often contracted out, increasing labor costs but decreasing equipment costs. For tomato, sunflower, and beans, contract labor is required for in-season weed control (manual hoeing). Furrow irrigation is used for safflower and beans, and sub-surface drip irrigation is used for tomato and sunflower. Despite lower water inputs compared to rice, furrow and drip irrigation systems have additional labor and investment costs. All four crops have opportunity costs related to the time it takes farmers to learn the new system and find new markets.

Relative production costs

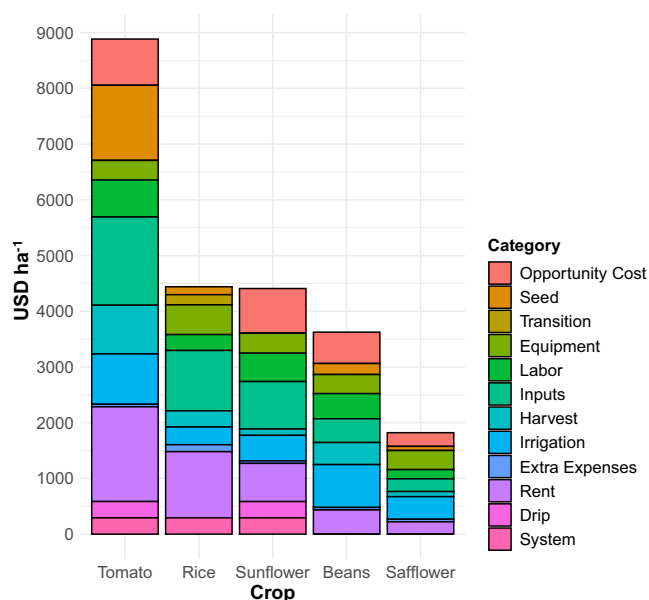
Tomato had more than double the total production costs compared to rice, regardless of whether capital costs, opportunity costs, investment and transition costs were included (Tables 1–3, Fig. 2). Meanwhile, sunflower and beans reduced normal production costs by 14–19%, whereas safflower reduced costs by 57% (Tables 1 and 2). Opportunity costs and labor costs were highest for tomato and sunflower, and seed costs and rent were highest for tomatoes. Yet, because tomato and sunflower had higher total costs, the relative impact of these categories in annual crop budgets was diminished. For rice, the largest costs were land rent and inputs which consisted of 27 and 22% of total costs, respectively (Fig. 1, Table 1). Rice irrigation was only 7% of total costs. Rice equipment costs were 12%, while labor costs were only 9% and transitional costs 4% of total costs. Tomato was the only crop with higher input costs compared to rice, although inputs comprised a smaller fraction of total costs for tomato (18%). Input costs were lower for all other

Table 1 | Mean values for all cost categories USD ha⁻¹ for each crop, including year-1 costs and switching in/out of rice (Transition)

Type	Opportunity Cost	Seed	Transition	Equipment	Cultural Labor	Inputs	Harvest	Irrigation	Irrigation Capital	Drip Line	Office Expense	Rent
Tomato	829	1348	-	351	665	1584	873	901	292	293	45	1700
Sunflower	804	-	-	357	508	852	113	458	292	292	45	685
Safflower	246	75	-	342	166	228	92	406	-	-	45	222
Beans	563	199	-	342	451	427	396	769	-	-	45	434
Rice	-	143	182	534	286	1080	291	318	293	-	125	1188

Table 2 | Minimum, maximum, and average costs, revenue, and profits for five crops without opportunity cost, capital costs, or costs for switching out of rice (considered operational costs)

Crop	Costs			Profit			Revenue		
	Min	Max	Mean	Min	Max	Mean	Min	Max	Mean
Tomato	6842	9153	7476	-595	5633	2114	7634	13079	9590
Beans	2532	3423	2996	-550	1741	256	2570	4759	3253
Rice	4232	4232	4232	-2358	2904	252	1874	7136	4485
Sunflower	2667	3629	3011	-644	2184	863	2581	5193	3874
Safflower	1220	1823	1574	-653	318	-256	1071	1712	1318

All units in USD ha⁻¹.**Fig. 1 | Breakdown of costs by each crop during transition years.** Cost breakdowns include investment and opportunity costs, indicated as Drip Tape, Irrigation System and Opportunity cost.

crops and comprised a lower fraction of total costs (19, 12, and 13% for sunflower, beans, and safflower, respectively). Similarly, tomatoes were the only crop with higher rent compared to rice. For all other crops, rent was lower than rice and a smaller fraction of total costs. Irrigation costs for tomato and sunflowers were 10% but increased to 21–22% of total costs for beans and safflower.

The total investment for an irrigation system is estimated at \$4375 ha⁻¹, including the pump filter main line, and installment and material (Supplementary Table 10). Drip line total investment is estimated at \$875 ha⁻¹, or \$290 ha⁻¹ for each year. For tomatoes, the irrigation system and drip line were only 3% of total costs each year. Sunflower also shared the costs for the irrigation system and drip line, which represented 7% of total costs (Table 1). Equipment costs were less for all crops compared to rice, due to the assumption of contracting out field operations for rotation crops if rice equipment could not be repurposed for the job. Equipment costs for sunflower and tomatoes were 8 and 4% of total costs, respectively. For both beans and safflower, equipment represented 9 and 19% of total costs, respectively (Table 1). Compared to rice, labor costs were higher for tomatoes, sunflower, and beans. At the same time, sunflowers in California are grown for seed and marketed through contracts with seed companies, who often will be responsible for sharing certain labor costs³⁶. Labor for safflower was the lowest at only \$166 ha⁻¹ or 9% of total costs. Finally, opportunity cost was 18% for sunflower, 16% for beans, 14% for safflower, and 9% for tomato (Table 1).

Annual profitability with and without capital costs, opportunity costs and costs for transitioning in and out of rice

Average rice profits, revenue, and costs came to \$252 ha⁻¹, \$4491 ha⁻¹, and \$4485 ha⁻¹, respectively (Fig. 2A, Table 2). The Monte Carlo distribution suggested that roughly half the time (quartile ranges) profits for rice ranged between -\$61 ha⁻¹ and \$246 ha⁻¹, depending on the combination of costs, yield, and rice price, with revenue ranging between \$4171 ha⁻¹ and \$4478 ha⁻¹ (Supplementary Table 11). When ranking the profit of rotational crops compared to rice (without investment costs), the order of most profitable to least profitable was tomato > sunflower > rice > beans > safflower (Fig. 2). Excluding capital costs and opportunity costs, profits for tomato averaged \$2,114 ha⁻¹ with a quartile range between \$1350 ha⁻¹ and \$1962 ha⁻¹ (Fig. 2, Table 1). Sunflower profit came to \$863 ha⁻¹ with a quartile range between \$558 ha⁻¹ and \$862 ha⁻¹. Average profits for beans and safflower were \$256 ha⁻¹ and -\$256 ha⁻¹ respectively, with quartile ranges between -\$38 ha⁻¹ and \$188 ha⁻¹ for beans, and -\$364 ha⁻¹ and -\$263 ha⁻¹ for Safflower (Fig. 2A, Table 2).

When adding investment costs, which included capital costs, opportunity costs, and transitional costs for switching from rice to a rotation crop and vice versa, results changed substantially, with only rice and tomato remaining profitable. Profit for rice decreased to \$100 ha⁻¹ with roughly half of simulations falling between \$322 ha⁻¹ and \$9 ha⁻¹ (Supplementary Table 7). The order of most profitable crops also changed, with tomato > rice > beans > safflower > sunflower (Fig. 2B). Sunflower was impacted the most by extra costs, reducing average profit to -\$532 ha⁻¹ (quartile range between \$879 ha⁻¹ and \$537 ha⁻¹) (Supplementary Table 7). For sunflowers, the extra \$1,402 ha⁻¹ in investment costs increased total costs to \$4413 ha⁻¹. Tomato profit dropped to \$793 ha⁻¹ (quartile ranges between \$14 ha⁻¹ and \$662 ha⁻¹) with costs increasing by \$1370 ha⁻¹ (Table 3). Profit for beans came to -\$286 ha⁻¹ (quartile ranges -\$581 ha⁻¹ and -\$351 ha⁻¹) with costs increasing by \$562 ha⁻¹. Safflower average profit came to -\$506 ha⁻¹ (range -\$632 ha⁻¹ and -\$518 ha⁻¹) with costs increasing by \$250 ha⁻¹. The negative profits frequently observed for safflower and beans without extra costs, and safflower, beans, and sunflower with extra costs are driven by irrigation (water and labor) for all rotation crops and high labor for sunflower and beans. These cost components, combined with lower revenue than rice, especially safflower and beans (Table 1, Fig. 2), influence the likelihood of experiencing negative profit.

Long-term profitability of rotation scenarios

First, discounted annual net returns (DANR) for RRR (continuous rice) was compared to RSTT (sunflower and tomato rotation without benefits) and RSBB (safflower and beans without benefits) over 15 years (Fig. 3). With consistent profits each year for rice, DANR for RRR was stable and positive over the 15-year period. In contrast, RSTT showed a substantial drop in DANR due to investment in sub-surface drip irrigation and opportunity costs during year 2 (\$-5062 ha⁻¹) (Fig. 3). Similarly, DANR in RSBB decreased until year 4 due to opportunity costs for safflower and beans, and then again during years 8–10 during the second cycle of rotational crops (Fig. 3).

The cumulative NPV for RRR was \$3561 ha⁻¹ over 15 years (Fig. 4A, Supplementary Table 13). In RSTT, both tomato and sunflower had higher

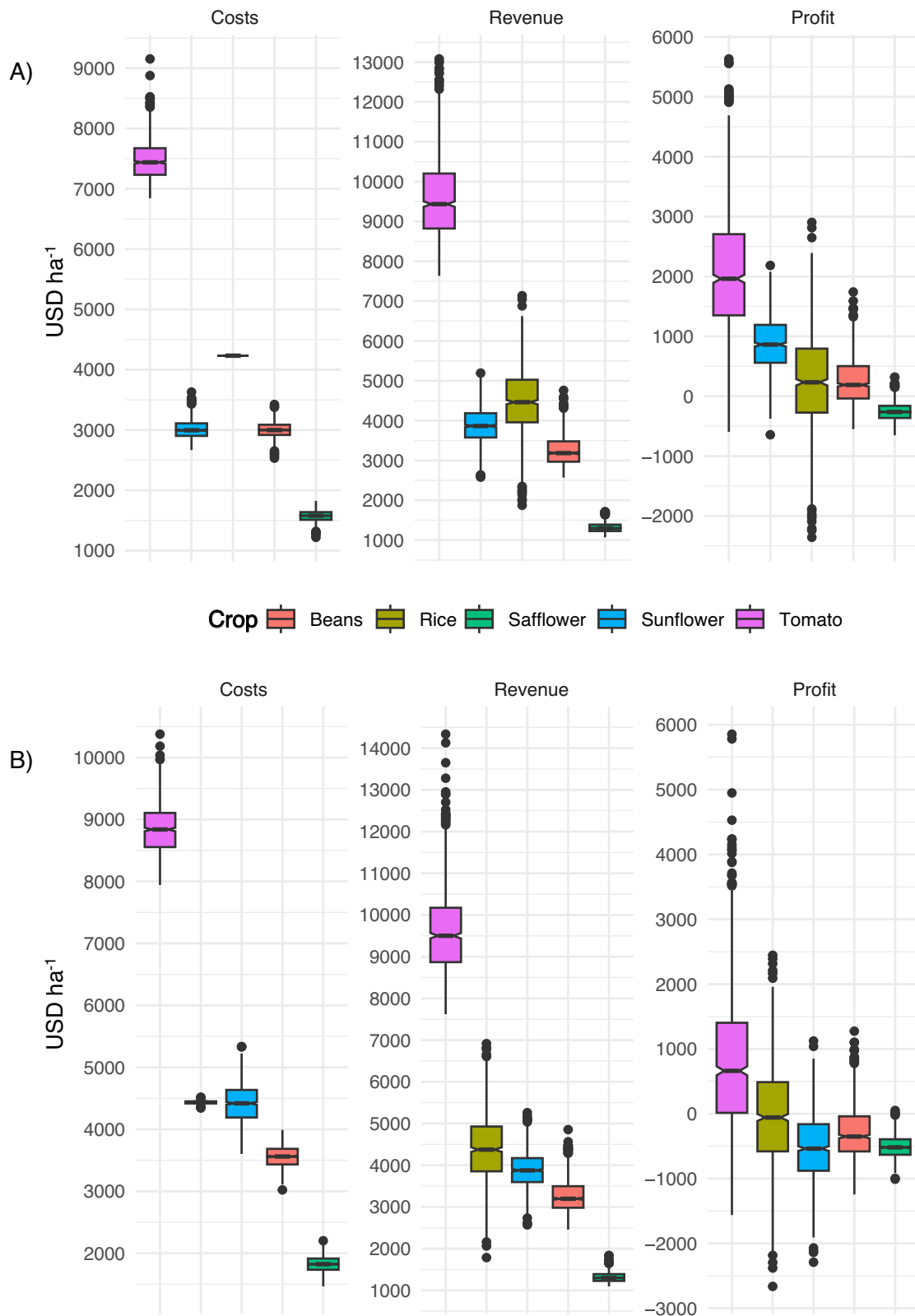


Fig. 2 | Estimated cost, revenue, and profit for each crop with and without extra costs. A, B All costs and profits are represented as a normal year without extra transitioning costs or investment costs. **B** All costs and profits are represented as years with transition costs and investment costs. This includes extra expenses to

reconstruct rice fields when switching in and out of rice, opportunity costs of the rotational crops, and irrigation investments. Monte Carlos simulations ($n = 1000$) reflect variability in cost and revenue assumptions. Revenue is the same in each scenario (**A** and **B**).

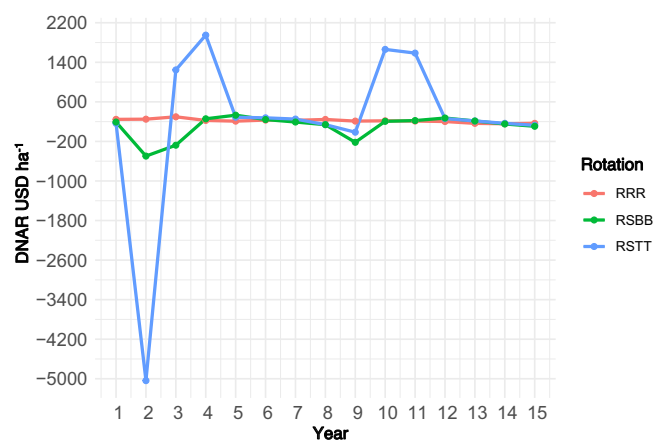


Fig. 3 | Discounted annual net returns (DANR) over 15 years. DANR shown for all three rotation scenarios: continuous rice (RRR), rice, safflower, and beans (RSBB), and rice, sunflower, and tomato (RSTT).

Table 3 | Minimum, maximum, and average costs and profits for five crops with opportunity costs, capital costs, and costs for switching out of rice

Crop	Costs			Profit		
	Min	Max	Mean	Min	Max	Mean
Tomato	7942	10377	8846	-1561	5855	793
Beans	3022	3990	3558	-2663	1274	-286
Rice	4343	4517	4433	-1596	2445	100
Sunflower	3603	5335	4413	-2290	1122	-532
Safflower	1464	2202	1824	-1009	50	-506

All units in USD ha⁻¹.

profits than rice, and therefore this rotation became \$170 ha⁻¹ more profitable than RRR after two rotation cycles, leading to a cumulative NPV of \$3731 ha⁻¹ (Fig. 4A). However, due to high investment costs, the break-even point for profitability with RSTT was not achieved until year 12 (Fig. 4A). In RSBB, although beans were as profitable as rice in individual years (Fig. 2A), safflower generated a loss of \$-256 ha⁻¹ each year it was grown, or \$-500 ha⁻¹ when accounting for opportunity costs (Table 2). Therefore, the combination of added opportunity costs in years 2–4 for RSBB (Fig. 3) and economic losses with safflower decreased its cumulative NPV by more than half compared to continuous rice (\$1643 ha⁻¹) (Fig. 4A, Supplementary Table 13).

When two years of fallowing was introduced into continuous rice (RRF) to account for climate risks causing water shortages (Fig. 4B), cumulative NPV decreased to \$2995 ha⁻¹ (Supplementary Table 13), representing a loss of \$566 ha⁻¹ over 15 years compared to RRR. With the added two years of fallowing in the baseline continuous rice system, RSTT became as or more profitable than RRF by year 11, but RSBB still remained less profitable.

When the anticipated agronomic benefits of crop rotation (10% increase in rice yields in the first two years returning to rice along with a 50% decrease in herbicide inputs) were incorporated into scenarios, both crop rotations (RSTT-benefit and RSBB-benefit) became more profitable than RRR over 15 years (Fig. 4C). The cumulative NPV of RSTT-benefit increased to \$5984 ha⁻¹ by year 15 (Supplementary Table 13), exceeding RRR by \$2423 ha⁻¹, with the break-even point for profitability achieved in year 10. Meanwhile, RSBB-benefit had a cumulative NPV of \$3970 ha⁻¹ (Supplementary Table 13), exceeding RRR by about \$400 ha⁻¹, with higher profits achieved between years 12 and 13. When the combined benefits of rotation for higher crop productivity and climate risk mitigation were

included (Fig. 4D), both rotations further increased cumulative NPV while decreasing the break-even point for profitability compared to RRR. For RSTT-benefit, cumulative NPV was \$2,989 ha⁻¹ greater than RRR with higher profitability achieved between years 9 and 10. For RSBB-benefit, cumulative NPV was \$975 ha⁻¹ greater than RRR with higher profitability achieved between years 6 and 7.

Risk assessment compared to continuous rice

Cumulative probability distributions provided evidence that 50% of the time NPV was at or above \$3561 ha⁻¹ and \$2995 ha⁻¹ for RRR and RRF, respectively (Fig. 5) after 15 years. The likelihood of being at or above these thresholds differed for the other rotation scenarios. Based on the Monte Carlo simulations, there was a 15% likelihood for RSBB to produce a NPV above RRF and about a 10% likelihood for it to produce a NPV above RRR. In contrast, RSTT showed a 65% chance of being more profitable than RRF and a 55% chance of being more profitable than RRR. When including the agronomic and climate risk mitigation benefits of rotation, the probability of RSBB-benefit having a higher NPV was 80–85% compared to RRF and 70% compared to RRR. Similarly, the probability of RSTT-benefit having a higher NPV was 95% compared to RRF and 90% compared to RRR.

Discussion

There is great interest in diversifying monoculture grain production systems to decrease environmental footprint, respond to climate change, and enhance economic opportunities for farmers^{4,9,17}. Our results provide a better understanding of the major changes in management and associated costs, as well as revenue and profitability ranges, for switching from continuous flooded rice to tomato, sunflower, safflower, and beans to explore options for rice-based rotations in California. Rice on its own had relatively high costs of production, but also higher revenue compared to the other crops except tomato, leading to stable profits (Table 2). Most farmers in this region specialize in continuous rice, meaning land preparation and crop management remain relatively similar year-to-year across large-scale operations, helping achieve economies of scale which is a major feature of simplified agricultural landscapes³⁷. Approximately 1100 rice farms generate over \$500 million of annual farmgate revenue, but larger farms over 200 ha⁻¹ in size account for 72% of total harvested area and rice sales despite representing only 37% of farming operations³⁰.

This research demonstrates that negative profits (relative to rice) are influenced by both revenue as well as cost savings, depending on the crop. While tomatoes had the highest costs of production, particularly with inputs, rent and custom seedling propagation (seed) (Fig. 1), they are still more profitable than rice on an annual basis (Fig. 2A, Table 2), suggesting the influence of high revenue outweighs any potential impact of costs. However, sunflower and beans show the highest sensitivity to fluctuation between being profitable and unprofitable when accounting for changes in costs (i.e., comparing outcomes for Tables 2 and 3). When adding in extra costs such as opportunity costs and capital costs, sunflower, originally 3.4 times more profitable than rice in Table 2, shifts to \$-532 ha⁻¹ in Table 3. Similarly, beans have the potential to become similar or more profitable than rice due to additional cost savings in the categories of irrigation or opportunity costs (Fig. 1, Table 1), however negative profits of \$-286 ha⁻¹ are likely to occur when capital and opportunity costs are included (Table 3). Therefore, for crop diversification to provide additional economic benefits in this context, switching from continuous rice to a non-flooded crop must either substantially decrease costs of production or increase revenues, especially considering the additional management and equipment requirements and the extra time needed to learn how to grow and market a new crop.

We hypothesized that higher financial requirements for equipment, labor, irrigation investments, and opportunity cost would impact profitability outcomes of rotational crops. Across 11 studies, He et al.¹⁷ reported that agricultural diversification in rice systems increased both production costs and revenue by about 30%, leading to no changes in overall cost-benefit ratio. Our results were more complex, indicating the economic

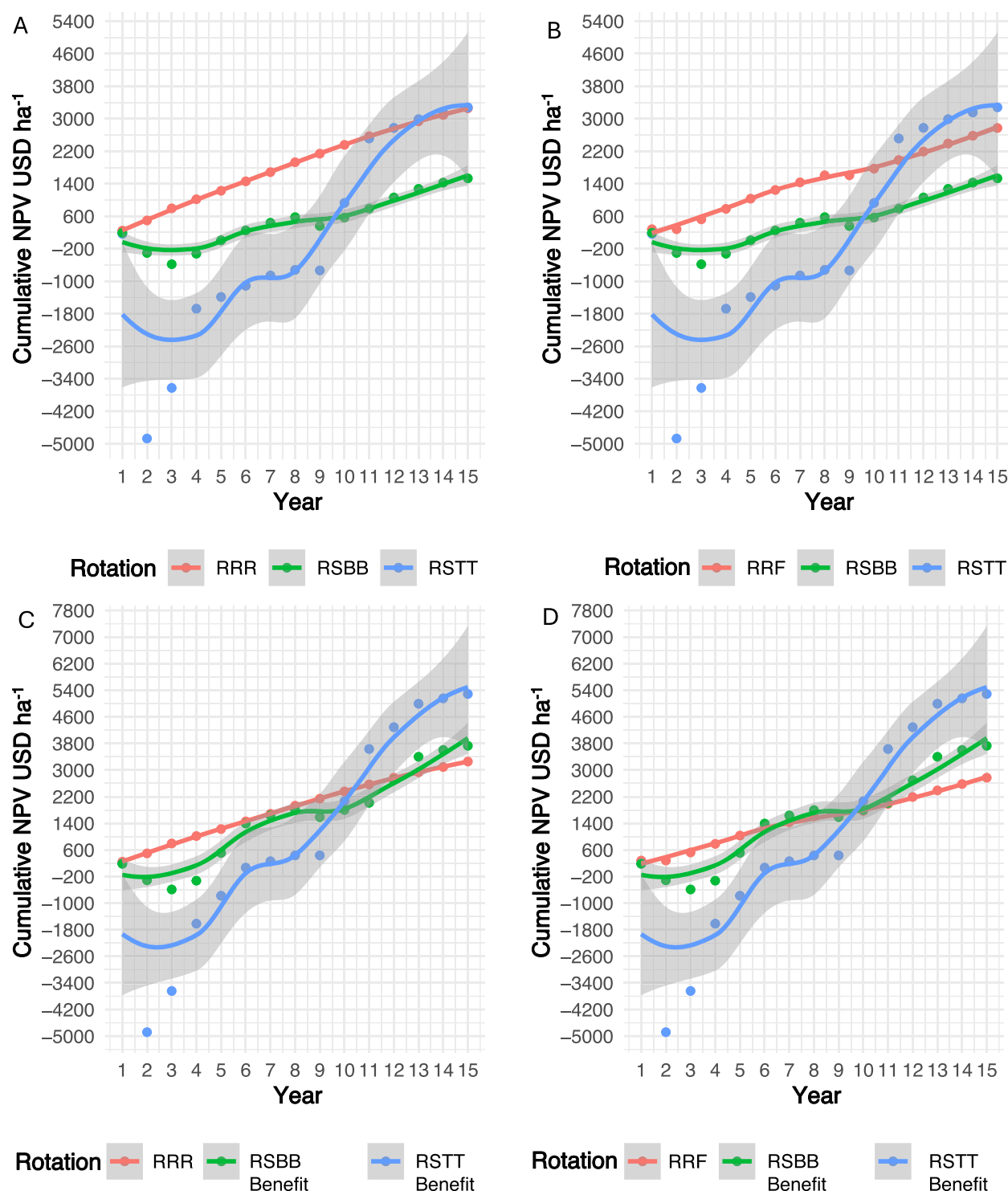


Fig. 4 | Cumulative NPV comparing different rotation scenarios. A continuous rice (RRR), rice safflower bean (RSBB), and rice sunflower tomato (RSTT), B rice with fallow (RRF), RSBB, and RSTT, C RRR and rotation scenarios with benefits (RSTT-benefit, RSBB-benefit), and D RRF, RSTT-benefit, RSBB-benefit.

potential of rotational crops fell into two categories, with both higher and lower profits possible. Tomato represented an opportunity for higher revenue (\$9590 ha⁻¹) (Table 2), but required much greater investment in irrigation and labor, thereby increasing the costs of production (\$8846 ha⁻¹). Because the additional revenue more than offset the increase in costs, this high cost – high revenue approach contributed to the highest profits (\$793 ha⁻¹). Sunflower had similar revenue potential as rice but decreased costs in a normal year, helping it exceeds rice profits by \$604 ha⁻¹ when

investment costs were not considered (Fig. 2, Table 2). Results for safflower and beans were the opposite. Costs of production were \$875–2609 ha⁻¹ lower than rice which can decrease risk and provide advantages in large-scale capital-intensive farming systems. However, there was little opportunity for increased revenue, which resulted in beans achieving similar profit as rice and safflower consistently decreasing profit compared to rice in normal years (Fig. 2). Importantly, when additional investment and opportunity costs were included, both safflower and beans lost money in transition years

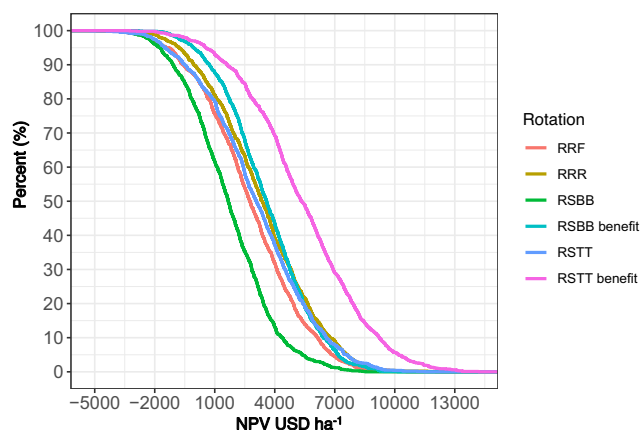


Fig. 5 | Probability of achieving above a certain Net Present Value (NPV) of six crop rotation scenarios at the end of the 15-year period. The NPV of RRF (Rice with fallow) and RRR (Continuous rice) at 50% are considered points of comparison when assessing profitability risk. RSBB = Rice with safflower and beans, RSTT = Rice with sunflower and tomato.

(\$-286 to -506 ha⁻¹). Thus, safflower and beans were characterized by low cost – low revenue – low profit.

Analyzing the required changes in management and their associated costs can provide insight into how economic factors act as a barrier to adoption for crop diversification. Labor costs were higher for tomato, sunflower, and beans (\$665, \$506, and \$449 ha⁻¹, respectively), relative to rice (\$389 ha⁻¹) (Fig. 1, Table 1) due to higher land preparation and manual hoe labor requirements (Supplemental Tables 6–9). An extra \$182 ha⁻¹ was required in the form of land deconstruction and field leveling when switching out of or into rice (Fig. 1, Table 1). Furthermore, irrigation labor was higher for rotational crops due to the higher labor demand for constructing and maintaining furrow wells and maintaining drip lines (Fig. 1, Supplemental Tables 1–5). Focus groups provided information that rice farmers who rotate will often use custom labor for the required tractor work, and therefore investment costs in equipment were not a substantial barrier in this study for rotational crops (Supplemental Tables 6–9). Realistically, certain regions may have more access to contract workers than others, and therefore human resource barriers may exist geographically³⁴. Research shows that operating costs are often higher for diversified farms, as they require equipment that may be used only at certain times of the year or only for specific crops, as well as more labor^{14,37}. In contrast, in a recent survey rice growers reported that labor requirements were a top priority affecting management decisions, along with water availability, profitability, and land stewardship³⁸. Most rice farms are family operations requiring little outside labor, which favors specialization and monocropping. Despite labor costs being higher for rotational crops, total costs remained lower, except tomato, further suggesting that financial barriers are not as important as human resources and time management requirements^{24,25,39}.

A strength of our study was quantifying opportunity costs, or the time farmers spent learning a new system and finding markets compared to generating income through rice^{12,26,27}. We hypothesized that opportunity costs would negatively influence farmer decision-making and the economic potential of rotational crops. Sunflowers had the highest opportunity costs relative to total costs (18% or \$810 ha⁻¹) (Fig. 1, Tables 1 and 3), mostly due to challenges in finding markets and contracts each season (Supplemental Tables 6–9). Tomato had an equally high opportunity cost at \$803 ha⁻¹, though this was a relatively low percentage of its total costs (Tables 1 and 3). The opportunity cost for tomato was mostly due to the time it takes to learn how to manage drip irrigation and find contract labor for planting (Supplementary Table 10). Our results are conservative because based on focus group outcomes, we assumed most of the labor for tomato, sunflower, and beans, including drip line placement, planting, and harvesting, was contracted out to

companies or neighbors (Supplementary Tables 6–9). Therefore, without these contracting agreements, both tomato and sunflower would have significantly higher opportunity costs if the rice grower was performing these operations. Carlisle et al.³⁷ discussed the need for “ecologically skilled labor forces” for farming communities to support the adoption of knowledge-intensive practices that tend to be aligned with more diversified systems. This could help address labor constraints and the extra time needed for learning new equipment and production practices and developing relationships for market access.

Comparing different cropping sequences and their corresponding cash flows helps illustrate how investment costs in early years may affect long-term profits, a key motivation in grower decision-making. Few agricultural studies have used a Monte Carlo analysis to assess the risk of different agricultural systems based on variable outcomes^{22,29,40,41}. Our results show that both rotation scenarios produced lower annual NPV when switching from rice to a rotational crop due to higher capital costs, opportunity costs, and transitional costs (Fig. 3). Yet, having tomatoes in the rotation for several years afterwards helped greatly increase NPV for RSTT, while profits for the rotation with beans and safflower (RSBB) never exceeded rice. Presenting these financial fluctuations and investment requirements is important for determining risk factors during years where farmers may have reduced annual income^{42–44}.

An important finding is the relatively long payback period, or time it would take to recoup investment costs and achieve net profits for crop diversification compared to continuous rice. Due to extra investment costs, which included opportunity costs for all crops and sub-surface drip irrigation for tomatoes and sunflower, RSTT only became more profitable than RRR by year 12 and RSBB was never more profitable. Although RSBB had much lower investment costs, it reduced profits by more than 50% compared to RRR by year 15 (Fig. 4A), suggesting lower feasibility for rice growers who are accustomed to relatively high costs of production, but also high rice yields and revenue on an annual basis. DeVincentis et al.²³ found that farmers in California may not see profits when adopting winter cover crops for 15 years or more, concluding that without external incentives, farmers were unlikely to adopt cover crops. This research and others demonstrate that integrating diversification practices such as crop rotations can reduce profits in the short-term due to high investment costs^{18,20–22,45,46}.

Capital costs (irrigation system and drip line) were the biggest financial investment impacting how fast profitability was realized when rotating with tomato and sunflower. Annually, capital costs were only 7% of total costs for RSTT when spread across their expected lifespan (15 years for the pump, and 3 years for drip line). However total investment was estimated to be on average \$4375 ha⁻¹ for the pump system and \$875 ha⁻¹ for drip line (Supplementary Table 10). Koech et al.⁴⁷ also found that financial constraints are major barriers to investing in irrigation technologies. Farmers will not invest in drip irrigation unless they can get multiple years of use out of it. Therefore, rotations with drip irrigation must remain out of rice for a longer period, which may also disincentivize farmers who specialize in rice. The rotation timeframe of only three years in this study may not be enough to invest in drip irrigation and should be considered a minimum. Tomato farmers will often keep drip lines in for 5 years or more to benefit from the value and reduce the required labor for removing and inserting drip lines⁴⁶. Safflower, sunflower, and beans had lower irrigation costs compared to rice (Table 1), and these crops can all be grown using furrow irrigation which requires less investment. Safflower and sunflower are also known to have very low water requirements, making them a viable option during reduced water years^{48,49}.

When the potential benefits of crop rotation were considered, the break-even point for profitability was reduced for both rotation scenarios (Fig. 4C). Assuming higher rice yields and lower herbicide costs, both rotations became more profitable than RRR after 10–13 years (Fig. 4C). Growers have reported yield benefits with rotation³⁴ but this is not a guaranteed outcome and further field research under different crop sequences and production conditions is required. Zhou et al.⁴⁵ found that crop rotation intensification practices increased rice yield by at most 4.6% while Feng et al.²⁰ found crop rotations with rape seed increased rice yield by 20%.

Meanwhile, White et al.⁵⁰ demonstrated that higher yields with lower input costs was a major determinant of rice profitability.

With the additional introduction of two fallow years in continuous rice, RSBB-benefit matched RRF profits after 6 years (Fig. 4D) and RSTT-benefit matched RRF after 9 years (Fig. 4D). This finding suggests that achieving higher profits may take longer investment and more financial security. While RSTT was much more profitable than RSBB over the 15-yr period, if agronomic and water-related benefits of rotation are realized, the break-even point was shortest for RSBB-benefit, suggesting it could be the most feasible option for farmers with limited time, capital, or human resources. This is because the combined production costs for safflower and beans were around 60% lower than sunflower and tomato. In terms of profit, RSBB-benefit only produced slightly higher cumulative NPV compared to RRR and RRF, but in terms of payback time, RSBB-benefit was the lowest at 6 years due to lower investment costs. The fact that break-even points are switched for rotations when including benefits highlights the different dynamics and interplay between long-term profitability, investment costs, and payback period. Zabala et al.¹⁴ found that crop choice rather than crop diversification practice was more important for economic impact. Our results suggest that profit depends on both the crop choice and agronomic benefits produced by diversification^{7,45,51–53}.

Exploring the probability of outcomes using Monte Carlo simulations provides a better understanding of the risk management farmers are facing. Under the presumption of following in RRF, RSTT-benefit and RSBB-benefit had a very high likelihood of being more profitable than rice (between 80 and 95%). However, without fallowing and without agronomic benefits, risk increases for rotations and RSTT had only a 55% or less chance of being as profitable as RRR, while RSBB was rarely as profitable as RRR (Fig. 5). These outcomes suggest that rice-based rotations including high cost – high revenue or low cost – low revenue crops are most likely to succeed financially over the long-term under the premise of rotational benefits related to enhanced crop yields and the ability to grow crops with lower water requirements when faced with water scarcity in drought years. For rotations to be successful, farms must also have the ability to withstand reduced profits for anywhere between 6 and 12 years, depending on the investment requirements and frequency of reduced water allocations causing fallowing in continuous rice (Fig. 4D). Having a break-even point of 6–12 years is a major disincentive for rotation, similar to outcomes for cover crops in DeVincentis et al.²³, and it becomes understandable why continuous rice continues to be the dominant practice.

There are limitations to our economic analysis and underlying assumptions. Financial circumstances are different for every farmer, and changes in important costs (e.g., irrigation) or revenue (e.g., crop yield or prices) would make rotations more or less feasible, hence results do not predict farm-level outcomes. We tried to capture such variability using Monte Carlo simulations based on grower-reported ranges for production costs and county-level changes in yield and crop prices. Although our interpretation regarding profitability above focused on average outcomes, the variability illustrated in distributions reveal more nuanced possibilities. For example, environmental constraints such as soil limitations have been cited as negatively impacting yields of rotational crops in rice fields^{33,34}. We accounted for lower yields by skewing the revenue distributions of rotational crops, helping test the hypothesis that this would negatively affect profitability. Yet, the lower quartile of simulations for tomatoes and sunflowers suggested these crops were still more profitable than the average for rice in a normal year (Fig. 2A). Thus at least a quarter of the time, even if these rotational crops experience high costs combined with low yields, they perform as well or better than continuous rice systems. This finding further illustrates that human resources and investment costs may be more of a limitation for integrating rotations in rice environments than revenue concerns. Furthermore, this study did not account for variability on every cost component. For example, fertilizer and fungicides were assumed to have fixed costs and are presented as their averages. Higher amounts of nitrogen applications may be required when rotating out of rice into a rotational crop. We don't have adequate data on how farmers may be using

fertilizer amounts in rotations with rice. This study did not account for the implications of fluctuations in these variables across the different cropping systems.

Opportunity cost was evaluated in this study as the sacrifice of time spent learning a new system, however, there are many other ways opportunity cost may be evaluated. Particularly, we did not add the opportunity cost of fallow events, given that farmers could potentially use that time to generate income elsewhere, we could have accounted for these costs. Farmers who rotate often acknowledge they choose to rotate when water allocations are not enough for rice but may be stretched out to grow other crops that require less water. At the same time, in times of water scarcity, rice growers may also decide to sell their water to other regions for a potentially higher profit than what the rice crop would provide, due to zero input costs. Both scenarios were not accounted for.

Oftentimes a higher discount rate between 7 and 10% may be chosen to assess the profitability of investments, while a lower discount rate evaluates CBAs from the perspective of society as a whole⁵⁴. While this study selected the use of a social discount rate, following that of similar studies in the region^{23,55,56}, the impact of the chosen discount rate can have an impact on net benefit over long time horizons⁵⁷. Similar CBAs for agriculture studies use a vast range in discount rates, between 2 and 10%^{54,58}. Dickenson et al.⁵⁵ shows that adjusting the discount rate between 3 and 7% had a moderate impact on overall NPV, suggesting this variable can contribute to overall decision making for farmers to change management. Future research should account for this by applying variability to the discount rate.

There are numerous crop sequences which farmers practice in this region that are not represented in our study. We focused on exploring options for farms dedicated to continuous rice and were less concerned with farms that grow primarily rotational crops, with fewer years of rice in rotation³⁴. While our economic assessment only included four rotational crops out of many, these crops were selected, in part, because they represented the extreme ranges of high or low profit potential. By investigating the factors influencing farmer decision-making on both ends of the spectrum (low cost – low revenue vs. high cost – high revenue), our results provide insight into the feasibility of rotational crops with moderate profit potential falling between these extremes. Further research should assess other crop sequences and different crop mixtures, as well as changing the number of years in rice and rotational crops, to understand how this may affect profit. Similarly, our scenarios did not include all potential benefits that rotations provide. In actuality, input savings could reach beyond herbicides and impact fertilizer and other input costs such as water, insecticides, and fungicides for both rice crops and rotational crops⁵¹.

Recent trends may influence the attractiveness and feasibility of rice-based rotations in California. Rice currently has more herbicide-resistant weeds than any other cropping system⁵⁹. Herbicide costs have increased from \$333 to 506 ha⁻¹ during 2015 to 2021^{60,61}. Continuous rice cropping with similar cultural practices has increased weed pressure and the corresponding need for chemical herbicides. Crop rotations have been shown to reduce resistance and decrease weed density^{2,5,59}. In addition, California rice farmers who rotate perceive major benefits for weed control³⁴. Alternating between flooded rice and non-flooded crops in a rotation could help manage the weed seedbank by recruiting different weed species under aerobic conditions and using herbicides with different modes of action in non-rice years.

Similarly, if water scarcity due to climate change remains a challenge, incorporating crops with lower water requirements could help farmers adapt to climate risks to maintain profitability. Surface water supplies depend on seasonal snowfall and predictions show a stark reduction in snowpack in coming decades, reaching up to 65% by the end of the century in a high-warming scenario. Hrozencik & Aillery⁶² acknowledge that measures including continued shifts in irrigated area, increased irrigation efficiency through system upgrades, and changes in regional cropping patterns are ways for increasing resilience under water supply scarcity. Information on the average water use of crops in California varies,

Rosenberg et al.³⁴ found that some common rotational crops in rice systems are known for their lower water requirements, such as safflower and sunflower, which require around 700–800 mm of irrigation⁶³ (Supplementary Tables 9–12). While there are multiple pathways of water movement off rice fields that make it difficult to compare net water use against other crops³², the applied water of the rotational crops evaluated here is generally estimated at half that of flooded rice, indicating an opportunity for water savings.⁶³ Alternatively, Salvato et al.³³ showed that over the last decade the amount of land fallowing has increased in response to water shortages. Land fallowing could provide similar benefits as rotation for rice yield and weed control, but little research has investigated this potential. Our results suggest that occasional fallowing has a minimal impact on continuous rice profits over 15 yr (\$566 ha⁻¹ reduction), if farmers attain preventative planting insurance which covers operational costs and overhead when uncontrollable events prevent farmers from planting (like drought or wet springs).

A recent survey indicated the top three reasons for growing rice are profitability, the crop was traditionally grown on farm, and stable markets³⁸. Beyond the economic barriers noted above, two important factors limiting the feasibility of crop rotations are market access and soil constraints. Focus group findings from this study provided robust qualitative knowledge regarding the socioeconomic factors affecting crop rotation decisions. Focus groups identified human resources, such as labor, time, and management requirements as key barriers, reinforcing findings from Rosenberg et al.³⁴ and other research on rotations^{25,37,39}. We attempted to quantify these factors under the category of opportunity cost, but further research may want to include other socioeconomic costs and barriers to expand the scope of findings. For example, many of the rotational crops considered have limited markets and may require contracts, so even if a farmer wanted to rotate, they may not be able to secure an outlet for the crop. Market contracts are limited for sunflower and beans due to limitations in consumer demand³⁴. Sunflower has a limited market because California produces hybrid seed rather than oil. There is also a geographical component to how contracts with seed buyers are determined, where fields must be a minimum distance apart to reduce cross-pollination. All these issues complicate market access in the region, reducing the ability for crop diversification.

Salvato et al.³³ determined that only 11% of continuous rice area has soil properties that are most conducive for rotational crops. Helping identify where rotations would be most feasible within this area could have rippling effects on food system sustainability by building more resilient regional farms^{64–66}. However, Esquivel et al.²⁵ found that factors supporting crop diversification include secure land tenure, adequate access to capital and resources, and access to markets, all of which are missing in continuous rice systems³⁴. Similarly, other cultural norms and broader structural forces such as policy, institutions, infrastructure, and global commodity markets have contributed to the simplification and specialization of cropping systems. As many of these structural constraints are beyond farmers' direct control, economic incentives and policy support are necessary to develop an enabling environment for crop diversification at the systems-level^{14,23,67}.

Methods

To achieve our objectives, we had two research stages. First, we discerned what labor, equipment, and management requirements were needed to switch out of rice into four major rotational crops and quantified their associated costs and benefits. These were incorporated into a detailed cost-benefit framework considering 11 management categories with between approximately 1–7 variables per category: opportunity cost, seed, equipment, field reconstruction (for transitioning from rice to a rotation crop and back to rice), labor, inputs, harvest, irrigation (including water and irrigation labor) and irrigation investments (including sub surface drip system and drip line), office expenses, and land rent. Second, we simulated the profitability of five long-term (15 years) rotation scenarios comparing two rice-based rotations to continuous rice with and without rotation benefits, as well as a scenario where rice is fallowed for 2 out of 15 years.

Data collection

This research integrated economic information from focus groups, state-wide cost of production studies^{36,46,61,68,69}, and farmer-provided partial budgets to accurately capture the variability in cost and revenue outcomes across rotational crops (Supplementary Tables 1–5). Any costs taken from University of California cost studies were adjusted for inflation⁷⁰.

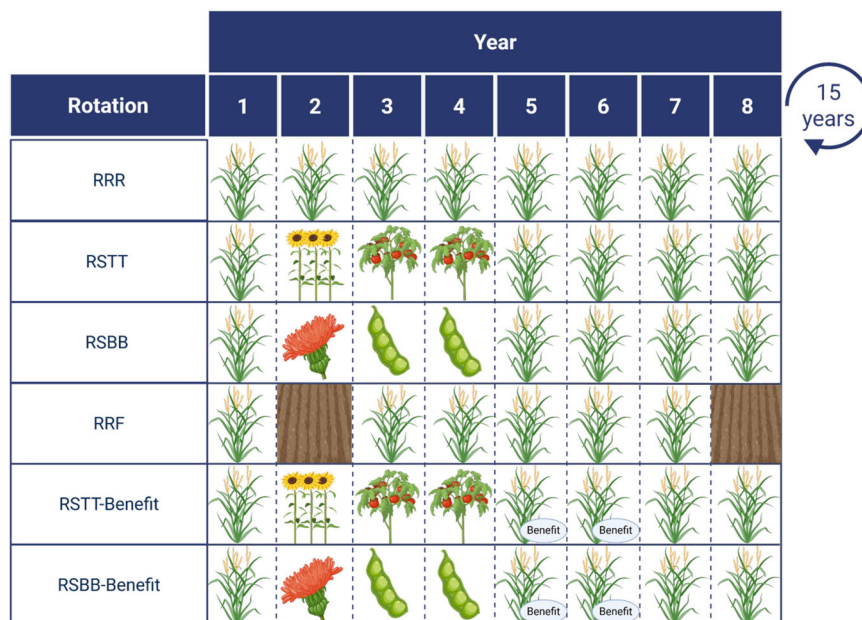
Focus groups were organized to learn what the associated costs of production were for converting a rice field into a rotation crop and discuss how those costs might change based on different circumstances. A total of four meetings were organized with 4–8 farmers attending each meeting. The four rotational crops considered in this analysis were tomato, sunflower, safflower, and summer dry beans. These crops are currently used in rice-based rotations in the region and were selected as feasible options based on farmer interviews³⁴. We developed a farm budget for each crop as a foundation for discussions (Supplementary Tables 1–5). Focus group questions covered the following topics: opportunity cost of time for learning the new cropping system requirements and marketing the crop, labor and equipment, overall profitability and input savings, irrigation requirements, land leasing scenarios, rotation sequences and others (Supplemental Tables 6–9). Each focus group session lasted between 1 and 2 h. At each meeting a projector was used so farmers could see the list of questions being asked, and the notes that were taken based on the discussions that took place. This ensured transparency and agreement between everyone on the important results that came out of each discussion (Supplemental Tables 6–9). This study, involving human participants, was reviewed and approved by UC Davis Institutional Review Board (1737326-1). Written informed consent for participation was not required for this study in accordance with the national legislation and the institutional requirements.

Comprehensive crop budgets were developed and informed by the focus group outcomes, including costs of production and revenue. There were eleven categories of production costs: opportunity cost, seed, equipment, field reconstruction (for transitioning out of and into rice), labor, inputs, harvest, irrigation (including water and irrigation labor) and irrigation investments (including sub surface drip system and drip line), office expenses, and land rent. We used both average values and approximate ranges (high/low) for each variable, with different assumed distributions, to capture the full range of possible outcomes. Beyond focus groups, data was also taken from University of California Cost of Production Studies as well as partial budgets from farmers (Supplementary Tables 1–5). Revenue was calculated based on average county yields and crop prices³⁰. Prices were taken across an 8–10-year time frame to control for inflation. Yields were taken between counties over multiple years to account for yield variation across regions. Values were then multiplied together to retrieve minimum, maximum, and average revenue values.

Hypothetical farm and economic assumptions

We modeled our rotation sequences based on common practices in the region, where rice-based rotations often include up to 5 years of rice before rotating to other crops³⁴. However, it should be noted that rotation types can vary widely. In some cases, rice is grown only once every 5 years^{33,34}. The assumptions of the hypothetical farm used in this study are meant to represent an average continuous rice system in the Sacramento Valley that is being converted to include rotational crops. Hence, the farm is built for continuous rice production, with no other equipment for rotational crops. The University of California Cost of Production Study assumes an average rice farm is 324 ha. In our study, the equipment used for rice is repurposed at times for land preparation of rotational crops. Other operations using row crop equipment including specific tillage requirements, bedding, seeding, and laying dripline are assumed to be custom hired. The farm is irrigated by district water through flooding gates, and no sub-surface or furrow irrigation infrastructure exists. Therefore, this assessment assumes an initial investment in drip irrigation infrastructure (assumed here as capital costs) for tomato and sunflower, and extra labor for furrow irrigation development. No extra capital costs are assumed to be required for safflower and

Fig. 6 | Crop rotation scenarios over an 8-year period and corresponding abbreviation. Rotation sequences were repeated to account for a 15-year period. RSTT (Rice Sunflower Tomato, Tomato), RSBB (Rice, Safflower, Beans, Beans), RRR (continuous rice), RRF (Rice, Rice, Fallow), RSTT-benefit (RSTT + 10% increase rice yield and herbicide input cost reduction), RSBB-Benefit – (RSBB + RSTT + 10% increase rice yield and herbicide input cost reduction).



beans. For further information on assumptions for seed, water, and labor see Supplementary Note 1.

Transitional costs: Transitional costs include costs that are needed to transition a rice field into a non-flooded row crop or transitioning out of a row crop back into a flooded rice crop. These costs entail extra costs for breaking down/building levies, adding contours or slope to the field/leveling the field, and extra tillage passes to prep a field that has been under flooded conditions for multiple years, and extra straw management requirements when not using a winter flood for straw decomposition.

Opportunity costs: Opportunity costs in this study are values that refer to what a grower would have to give up when rotating out of rice. We measured opportunity cost based on how growers value their own time, and the time it would take for them to learn how to grow a new crop or find new markets. Information was sourced from focus groups, with many farmers valuing their time at \$50 h⁻¹, which was in a similar range as DeVincentis et al.²³ who used an hourly wage of \$25 h⁻¹. We set the minimum and maximum for how the farmers value their time between these two numbers and assumed a minimum and maximum number of hours spent learning the system and finding markets based on qualitative information from the focus groups, then multiplied those values together.

Tractor/equipment costs: We followed the same tractor and equipment depreciation costs as the University of California cost of production studies^{36,46,66,68,69,71}. These studies use a capital recovery cost as an amortization rate for the asset (Supplementary Note 1).

Irrigation: Most tomato farmers in the region have transitioned from furrow to sub-surface drip irrigation. This includes farmers who rotate tomato with rice³⁴. Therefore, sub-surface drip was assumed to be used for tomato⁴⁶. Sunflower is often grown either on furrow or with sub-surface drip³⁶. We assumed sub-surface drip since it was in a rotation with tomato. The beans and safflower rotation were assumed to be furrow irrigated due to low revenues that typically do not cover the investment costs for sub-surface drip^{68,69}. These assumptions were reinforced by the focus groups as well as cost studies. Irrigation costs include labor to manage irrigation, applied water, and any costs for maintaining furrows or managing flood boxes. All of these are incurred on an annual basis and do not require material purchases that depreciate over time.

Drip irrigation capital costs: Drip irrigation capital costs are separate from irrigation costs. The capital costs for irrigation include infrastructure for ground water pump, and drip line, which this material lasts for multiple years. Investment in a pump and filter system, main lines, and drip line are

considered capital costs and depreciate over time. We assumed a full depreciation value at the end of the 15-year use cycle with no salvage costs remaining (Supplemental Table 10). For the annual assessment, the irrigation system (which includes everything except the drip line) total cost is divided by 15 and added to tomato sunflower and rice, while the drip irrigation lines costs are divided by 3 because they were used for three years and added under tomato and sunflower costs. For the NPV model (described below), the drip system investment is captured in the first year of switching into a rotational crop, and the drip line full cost is captured at the beginning of each rotational crop cycle because the tape is used for the three years of the rotation.

Rotation scenarios evaluated

We evaluated the long-term profitability of multiple rotation scenarios, including two rice-based rotations compared to continuous rice over 15 years, as well as scenarios including anticipated rotation benefits in terms of higher crop productivity and climate risk adaptation (Fig. 6). Continuous rice (RRR) is the baseline for this region and considered the control for this study. Each rotation included two seasons of shifting out of rice into non-flooded crops - a rotation with sunflower and tomato (RSTT) and one with safflower and beans (RSBB) (Fig. 6). Fifteen years was chosen to simulate two full rotation cycles which included both years with normal costs and budgets which include opportunity costs, capital costs, and added expenses for transitioning in and out of rice (hereafter referred to as extra costs), allowing enough time to determine when profitability is realized. For rotation crops, years 2 and 3 include additional irrigation investment costs and opportunity costs, while years 4, 9, 10, and 11 are considered 'normal' years and do not include extra costs. For rice, years 1, 5, 9, and 12 are transitioning years into or out of rice and contain extra costs, while years 6, 7, 8, 14 and 15 are 'normal' rice years and do not include transitional costs.

We explored additional scenarios for all three systems related to agronomic benefits and the potential to adapt to water scarcity caused by climate change. To account for agronomic benefits due to rotation, RSTT and RSBB were assumed to experience a 10% rice yield increase and 50% reduction in herbicide cost in specific years (RSTT-benefit, RSBB-benefit). Focus groups specified that these benefits occur mostly in the first 2 years of returning to rice from the rotation crop (Supplemental Tables 6–9), hence these effects were incorporated during years 5, 6, 13, and 14. To explore the ability for crop rotation to mitigate climate risks related to water scarcity, RRR was assumed to experience two years of fallowing due to water

Table 4 | Distribution assigned to each cost benefit component and supporting rationale for Monte Carlo simulations. More details on sources for assumptions, cost ranges, averages, and standard deviations can be found in Supplementary Tables 1–5

Cost-benefit component	Distribution used	Assumption
Rice		
Revenue	Normal distribution	Most growers have average yields.
All costs	-	No ranges used for RRR
Herbicide costs - benefits		Averages, min and max were decreased by 10%
Transitioning Rice		
Remove or rebuild levees	Skewed high cost around the mean	Assumes this task would take more time when rotating
Disk and chop	Normal distribution	Most growers experience average cost
Irrigation box repair	Normal distribution	Most growers experience average cost
Custom work GPS field leveling	Normal distribution	Most growers experience average cost
Rotation crops		
Revenue	Skewed low revenue around the mean	Assumes yields would likely be lower than in non-rice producing fields
Rent	Skewed high cost around the mean	Region may lean slightly higher on crop share percentages trending
Drip irrigation infrastructure costs year 1	Uniform distribution	Variable costs between the low and high
Drip tape	Uniform distribution	Variable costs between the low and high
Water in-season	Normal distribution or skewed lower around the mean	Crop specific: Most growers have an average water cost, or rice fields will retain more water reducing applied water needs
Drip irrigation labor	Normal distribution	Most growers will experience average labor cost
Install furrow irrigation	Skewed lower cost	Assumes could be done by a neighbor for lower cost
Furrow irrigation labor	Skewed lower cost around the mean	Assumes regional costs slightly lower
Insecticide and fungicide custom apply	Normal distribution	Most growers will experience average cost
Herbicide custom apply	Normal distribution	Most growers will experience average cost
Custom cultivation	Normal distribution	Most growers will experience average cost
Labor-pre plant operations	Skewed high cost around the mean	Likely to experience higher cost due to more tractor work required because of compaction and high clay content.
Custom work planting	Normal	Most growers will experience average cost
Custom work pre-planting	Normal or skewed high cost around the mean	Crop dependent
Tractor	Skewed high cost around the mean	Likely to experience higher cost due to more tractor work required because of compaction and high clay content.
Hoe labor	Skewed high cost around the mean	Growers may experience higher weeds
Opportunity cost	Uniform distribution	Assumes variable experiences with how people value their time

shortages (RRF). Fallow years were represented by no costs and no revenue for years 2 and 14 in RRF, assuming rice farmers received insurance coverage for preventative planting when water allocation was scarce. This frequency was chosen based on the number of years in the past 15 where total rice acreage planted was reduced by at least a threshold of 20%³⁰.

Data analysis

Annual budgets capturing variability among annual costs and revenue and select capital costs were developed for each crop. Monte Carlo simulations were performed to evaluate the annual profitability of each crop individually, followed by a cost benefit analysis for each crop rotation over a period of 15 years (Fig. 6). Monte Carlo simulations are a tool used for cost benefit analysis to introduce uncertainty by selecting randomly sampled values for input variables based on set parameters^{22,28,72}. The Monte Carlo simulations included 1000 iterations of each crop in the rotation, or 15,000 iterations over the full rotation scenario. During each Monte Carlo run, random values were drawn from a specified distribution (described below) to quantify how uncertainty in input parameters influenced economic outcomes across a plausible range of conditions^{22,73}. Minimum, maximum, and averages for each distribution of outcomes were then derived to compare cost benefit outcomes. All data analysis was performed using (R) programming language (version 2023)⁷⁴.

In this study, each cost component was assigned a normal, uniform, or skewed distribution (Table 4). Most variables were assigned a normal distribution, with the assumption that values were normally distributed around the mean, unless focus group outcomes provided information that suggested values were often higher or lower than average²². For the defined normal distributions, we developed them around the minimum and maximum and the mean, provided by University of California cost studies (Supplementary Tables 1–5). The standard deviation was calculated as the (maximum – minimum)/4 using the range rule⁷⁵. From focus group qualitative data, certain values, such as revenue, or tractor work, were skewed around the mean a (Table 4). For example, a skewed distribution was used for revenue (crop yields) under furrow irrigation because in heavy clay rice soils, farmers often will experience lower yields. All skewness parameters were set around the mean using the `rsnorm`, $\xi = 2 / -2$. In the context of the `rsnorm` function, setting $\xi = 2$ generates random numbers from a skew-normal distribution⁷⁶. Uniform distributions were set for opportunity costs, with the assumption that individuals valued their own time with equal variability between the minimum and maximum. Ranges were not available for four cost components, including the cost for applied water for tomato, the cost of pre plant custom work for sunflower, harvest hauling costs for sunflower, and herbicide application custom

work for safflower. For these costs, the mean was multiplied by 0.04 to estimate the standard deviation⁷⁶ (Supplementary Tables 1–5).

Individual crop budgets were run under the Monte Carlo parameters to attain distributions of annual costs, revenue, and profit. An annual analysis was conducted without investment costs to provide insight on an overall summary of operational costs, revenue, and profits for each crop. A second analysis was conducted with capital costs, opportunity costs, and transitional costs to determine their impact on profit. Capital costs were assumed as irrigation investment for the drip system and drip line and are expressed as the annual depreciated amount incurred by each crop in the RSTT rotation (Supplementary Table 10). Mean values as well as the 50% quartile ranges are used to demonstrate the variability of these economic components for each crop (Supplementary Table 11).

The long-term cumulative cash flow, or cumulative NPV is represented by a sequence of annual crop budgets over 15 years for each rotation scenario. To assess profit across time, NPV projects all future cash flows using a discount rate to account for the depreciation of money over time (Equation 1):

$$NPV = \sum \frac{P_t}{(1+i)^t}$$

Where NPV is Net Present Value, P is revenue minus costs, t is time of cashflow (year), and i is the discount rate (Equation 1). A social discount rate of 0.03 was used based on historical averages of the Federal Reserve⁷⁷, as well as recent regionally relevant economic literature^{23,54,55}. The federal funds rate influences other interest rates such as longer-term interest rates for mortgages, loans, and savings⁷⁷. Related to NPV, discounted annual net returns (DANR) involve calculating the value of future cash flows⁷⁸. While cumulative NPV reveals profitability over time, the DANR offers insight into annual profit and loss fluctuations that may be expected at different time points.

Data availability

Data generated during this study and used for analysis are available in the supplementary material. The code used for Monte Carlo analysis in R software (Version 2023) is available from the lead author upon reasonable request.

Code availability

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References

- Chen, S. et al. Effect of long-term paddy- upland yearly rotations on rice (*Oryza sativa*) yield, soil properties, and bacteria community diversity. *Sci. World J.* **2012**, e279641 (2012).
- Altieri, M. *The Ecological Impacts of Large-Scale Agrofuel Monoculture Production Systems in the Americas* (Sage Journals, 2009). <https://doi.org/10.1177/0270467609333728>
- Siagian, D. R., Shrestha, R. P., Shrestha, S., & Kuwornu, J. K. M. Factors driving rice land change 1989–2018 in the Deli Serdang Regency, Indonesia. *Agriculture* **9**, Article 9 (2019). <https://doi.org/10.3390/agriculture9090186>
- Wassmann, R. Environmental Footprints of Modernization Trends in Rice Production Systems of Southeast Asia. In *Oxford Research Encyclopedia of Environmental Science* <https://doi.org/10.1093/acrefore/9780199389414.013.230> (2019).
- Assefa, Y. et al. Crop diversification in rice- based systems in the polders of Bangladesh: Yield stability, profitability, and associated risk. *Agricult. Syst.* **187**, 102986 (2021).
- Banjara, T. R., Bohra, J. S., Kumar, S., Ram, A. & Pal, V. Diversification of rice–wheat cropping system improves growth, productivity and energetics of rice in the Indo-Gangetic plains of India. *Agricult. Res.* **11**, 48–57 (2022).
- Upadhaya, B. et al. Diversification of rice-based cropping system for improving system productivity and soil health in Eastern Gangetic Plains of India. *Agronomy* **12**, Article 10 <https://doi.org/10.3390/agronomy12102393> (2022).
- Huang, Q. et al. Higher economic benefits and changes in soil fertility due to intensifying winter crop rotation in double-rice cropping systems. *Appl. Soil Ecol.* **157**, 103773 (2021).
- Macedo, I. et al. Intensification of rice-pasture rotations with annual crops reduces the stability of sustainability across productivity, economic, and environmental indicators. *Agricult. Syst.* **202**, 103488 (2022).
- Beillouin, D., Ben-Ari, T. & Makowski, D. Evidence map of crop diversification strategies at the global scale. *Environ. Res. Lett.* **14**, 123001 (2019).
- Alcon, F. et al. Cost benefit analysis of diversified farming systems across Europe: Incorporating non-market benefits of ecosystem services. *Sci. Total Environ.* **912**, 169272 (2024).
- Kuwornu, J. et al. Cost-benefit analysis of conventional and integrated crop management for vegetable production. *Int. J. Vegetable Sci.* **24**, <https://doi.org/10.1080/19315260.2018.1457585> (2018).
- Newton, A. C. et al. Cost-benefit analysis of ecological networks assessed through spatial analysis of ecosystem services. *J. Appl. Ecol.* **49**, 571–580 (2012).
- Sánchez, A. C., Kamau, H. N., Grazioli, F. & Jones, S. K. Financial profitability of diversified farming systems: A global meta-analysis. *Ecol. Econ.* **201**, 107595 (2022).
- Zabala, J. A. et al. Crop diversification practices in Europe: An economic cross-case study comparison. *Sustain. Sci.* **18**, 2691–2706 (2023).
- Zhou, Y. et al. Shifting rice cropping systems mitigates ecological footprints and enhances grain yield in central China. *Frontiers* **13**, Retrieved, 2023, from <https://www.frontiersin.org/articles/10.3389/fpls.2022.895402/full> (2022).
- He, X. et al. Agricultural diversification promotes sustainable and resilient global rice production. *Nat. Food* **4**, 788–796 (2023).
- Carroll, S. R., Le, K. N., Moreno-García, B. & Runkle, B. R. K. Simulating soybean–rice rotation and irrigation strategies in Arkansas, USA using APEX. *Sustainability* **12**, 6822 (2020).
- Pardo, G., Mari, A. I., Aibar, J. & Cirujeda, A. Do crop rotations in rice reduce weed and *Echinochloa* spp. Infestations? Recommendations for integrated weed control. *Agronomy* **11**, 454 (2021).
- Feng, H., Wang, T., Osborne, S. L. & Kumar, S. Yield and economic performance of crop rotation systems in South Dakota. *Agrosyst Geosci. Environ.* **4**, e20196 (2021).
- Smith, E. G. et al. The profitability of short-duration canola and pea rotations in western Canada. *Can. J. Plant Sci.* **93**, 933–940 (2013).
- Chen, N. L. W. *Cost Benefit Analysis Using Monte Carlo Simulations on Regenerative Agricultural Practices of Growing Processing Tomatoes in California's Central Valley* <https://dash.harvard.edu/handle/1/37373335> (2022).
- DeVincentis, A. J. et al. Using cost-benefit analysis to understand adoption of winter cover cropping in California's specialty crop systems. *J. Environ. Manag.* **261**, 110205 (2020).
- Carlisle, L. et al. Organic farmers face persistent barriers to adopting diversification practices in California's Central Coast. *Agroecol. Sustain. Food Syst.* **46**, 1145–1172 (2022).
- Esquivel, K. E. et al. The “sweet spot” in the middle: why do mid-scale farms adopt diversification practices at higher rates? *Front. Sustain. Food Syst.* **5**, <https://www.frontiersin.org/articles/10.3389/fsufs.2021.734088> (2021).

26. Lien, G. Assisting whole-farm decision-making through stochastic budgeting. Retrieved November 15, 2023, from https://www.researchgate.net/publication/222518108_Assisting_whole-farm_decision-making_through_stochastic_budgeting (2003).
27. Becker, S. W., Ronen, J. & Sorter, G. H. Opportunity costs-an experimental approach. *J. Account. Res.* **12**, 317–329 (1974).
28. Johansen, A. M. Monte Carlo Methods. In P. Peterson, E. Baker, & B. McGaw (Eds) *International Encyclopedia of Education* 3rd edn (pp. 296–303). (Elsevier, 2010). <https://doi.org/10.1016/B978-0-08-044894-7.01543-8>.
29. Mahdiyar, A., Tanatabaee, S., Mehnagh, M., (2016). *Probabilistic private cost-benefit analysis for green roof installation: A Monte Carlo simulation approach* | Semantic Scholar. Retrieved November 15, 2023, from <https://www.semanticscholar.org/paper/Probabilistic-private-cost-benefit-analysis-for-A-Mahdiyar-Tabatabaee/2b326e47088d9c77556e577521>
30. United States Department of Agriculture National Agricultural Statistics Service (USDA NASS) QuickStats Ad-hoc Query Tool. Retrieved Dec 13, 2024, from <https://quickstats.nass.usda.gov/results/0E2F62A4-BF73-3297-A8AB-D1C227E1E9B5>
31. Geisseler, D. & Horwath, H. W. (2016). Rice Production in California. http://geisseler.ucdavis.edu/Guidelines/Rice-Production_CA.pdf
32. Linquist, B., Hill, J., & Swelam, A. Water balances and evapotranspiration in water and dry-seeded rice systems. *Irrig. Sci.* **33**(2015) Pagination 375–385. <https://doi.org/10.1007/s00271-015-0474-4> (2015).
33. Salvato, L., Pittelkow, C., O'Geen, T., Linquist, B. (2023). *A Geospatial Assessment of Crop Rotation and Soil Properties for Rice Systems by Luke Salvato, Cameron Pittelkow, Toby O'Geen, Bruce A. Linquist.* SSRN. (2023). Retrieved November 15, 2023, from https://papers.ssrn.com/sol3/papers.cfm?abstract_id=4354774
34. Rosenberg, S. et al. Crop rotations in California rice systems: assessment of barriers and opportunities. *Front. Agron.* **4**. <https://www.frontiersin.org/articles/10.3389/fagro.2022.806572> (2022).
35. Smith, A. D. (2022). *Big Drop in California Rice Acres*. Retrieved, September 2023 from <https://asmith.ucdavis.edu/news/big-drop-california-rice-acres>
36. Long, R. et al. *Sunflower Hybrid Seed Production in California* (2018) <https://escholarship.org/uc/item/14k450p6>
37. Carlisle, L. et al. Transitioning to sustainable agriculture requires growing and sustaining an ecologically skilled workforce. *Front. Sustain. Food Syst.* **3** <https://www.frontiersin.org/articles/10.3389/fsufs.2019.00096> (2019).
38. Kanter, J. et al. Setting research and extension priorities for agronomic crops in California. *Calif. Agric.* **78**, 88–99 (2024).
39. Calo, A., & Master, K. T. D. After the incubator: factors impeding land access along the path from farmworker to proprietor. *J. Agricult. Food Syst. Commun. Dev.* **6**, Article 2 (2016). <https://doi.org/10.5304/jafscd.2016.062.018>
40. Asci, S., Vansickle, J., Cantiffe, D. (2014). *Risk in Investment Decision Making and Greenhouse Tomato Production Expansion in Florida*. International Food and Agribusiness Management Association 17. Retrieved, from https://www.researchgate.net/publication/270571623_Risk_in_Investment_Decision_Making_and_Greenhouse_Tomato_Production_Expansion_in_Florida
41. Gryze, S. et al. *Simulating greenhouse gas budgets of four California cropping systems under conventional and alternative management on JSTOR.* 20. <https://www.jstor.org/stable/25741349> (2010).
42. Bradfield, T., Butler, R., Dillon, E. J., Hennessy, T. & Loughrey, J. The impact of long-term land leases on farm investment: Evidence from the Irish dairy sector. *Land Use Policy* **126**, 106553 (2023).
43. Harwood, J., Heifner, R., Coble, K., Perry, J., & Somwaru, A. Managing risk in farming: concepts, research, and analysis. *United States Department of Agriculture, Economic Research Service, Agricultural Economics Reports* (1999).
44. Miller, A., Dobbins, C., Pritchett, J., Boehlje, M. (2004). Risk Management for Farmers. DOI: 10.22004/ag.econ.28640 Retrieved November 15, 2023, from <https://ageconsearch.umn.edu/record/28640/?ln=en>
45. Zhou, Q. et al. Winter crop rotation intensification to increase rice yield, soil carbon, and microbial diversity. *Heliyon* **9**, e12903 (2023).
46. Miyao, G., Aegerter, B., Summer, D., Stewart, D. Sample Costs to Produce Processing Tomato in the Sacramento Valley & Northern Delta, Sub-Surface, Drip Irrigated. University of California Cooperative Extension. Department of Agriculture and Resource Economics. Davis, CA. (2017). coststudies.ucdavis.edu/en/
47. Koech, R., Haase, M., Grima, B. & Taylor, B. Barriers and measures to improve adoption of irrigation technologies: A case study from the Bundaberg region in Queensland, Australia*. *Irrig. Drainage* **70**, 909–923 (2021).
48. Long, R., Light, S., Light, E., Galla, M., Murdock, J. Sample Costs to Produce Sunflowers for Hybrid Seed in the Sacramento Valley, 2019. University of California Cooperative Extension. Department of Agriculture and Resource Economics. Davis, CA. coststudies.ucdavis.edu/en/
49. Peterson, C., Pittelkow, C., Lundy, M. (2022) *Exploring the Potential for Water-Limited Agriculture in the San Joaquin Valley*. Public Policy Institute of California. Retrieved November 15, 2023, from <https://www.pplic.org/publication/exploring-the-potential-for-water-limited-agriculture-in-the-san-joaquin-valley/>
50. White, M., Heros, E., Graterol, E., Chirinda, N., & Pittelkow, C. M. (2020). Balancing Economic and Environmental Performance for Small-Scale Rice Farmers in Peru. *Front. Sustain. Food Syst.* **4**. <https://www.frontiersin.org/articles/10.3389/fsufs.2020.564418>
51. Bowles, T. M. et al. Long-term evidence shows that crop-rotation diversification increases agricultural resilience to adverse growing conditions in North America. *One Earth* **2**, 284–293 (2020).
52. Davis, A. S., Hill, J. D., Chase, C. A., Johanns, A. M. & Liebman, M. Increasing cropping system diversity balances productivity, profitability and environmental health. *PLOS One* **7**, e47149 (2012).
53. Lin, B. B. Resilience in agriculture through crop diversification: adaptive management for environmental change. *BioScience* **61**, 183–193 (2011).
54. Guerriero, C., Pacelli, A. *Cost-Benefit Analysis of Environmental Health Interventions, Chapter 7 - Discounting Benefits and Costs*, Academic Press, Pages 129–143, ISBN 9780128128855, <https://doi.org/10.1016/B978-0-12-812885-5.00007-X> (2020).
55. Dickinson, D. et al. Cost-benefit analysis of using biochar to improve cereals agriculture. *GCB Bioenergy* **7**, 850–864 (2015).
56. Herrera, Axel, Ellen M. Bruno, and Cristina Lazcano. 2025. "The Profitability of Regenerative Viticulture in Sonoma County, California." ARE Update 28: 5–8. University of California Giannini Foundation of Agricultural Economics.
57. Li, Qingran & Pizer, William A., 2021. Use of the consumption discount rate for public policy over the distant future. *J. Environ. Econ. Manag.* Elsevier, **107** (2021).
58. Komarek, A. M., Li, L. & Bellotti, W. D. Whole-farm economic and risk effects of conservation agriculture in a crop-livestock system in western China. *Agricult. Syst.* **137**, 220–226 (2015).
59. *Integrated Weed Management. UC Statewide IPM Program (UC IPM)*. Retrieved November 3, 2025, from <https://www2.ipm.ucanr.edu/agriculture/rice/Integrated-Weed-Management/> (2023).
60. Espino, L. A., Muters, R. G., Buttner, P., Klonsky, K., Stewart, D. & Tumber, K. P. Sample Costs to Produce Rice, Sacramento Valley, Rice Only Rotation. University of California Cooperative Extension. Department of Agriculture and Resource Economics. Davis, CA. Coststudies.ucdavis.edu/en/ (2015).

61. Espino, L. A., W. Brim-DeForest, M. Leinfelder-Miles, B. A. Linquist, P. Buttner, J. Murdock, D. Stewart, D. A. Sumner Sample Costs to Produce Rice in the Sacramento Valley 2021. University of California at Davis Cost and Return Studies. Retrieved November 3, 2025 from <https://coststudyfiles.ucdavis.edu/uploads/pub/2021/11/03/2021ricesacramentovalley.pdf> (2021).
62. Pathak, T. B. et al. Climate change trends and impacts on California agriculture: a detailed review. *Agronomy*, 8, Article 3. <https://doi.org/10.3390/agronomy8030025> (2018).
63. Hrozencik, A., & Aillery, M. *Trends in U.S. Irrigated Agriculture: Increasing Resilience Under Water Supply Scarcity*. U.S. Department of Agriculture. (2021). Retrieved November 15, 2023, from <https://www.ers.usda.gov/publications/pub-details?pubid=102927>
64. California Department of Water Resources. Statewide Agricultural Water Use Data 2016–2020. (2004). Available at: <https://data.cnra.ca.gov/dataset/agricultural-water-use-data-2016-2020>
65. Emery, M., & Fey, S. *Using Community Capitals to Develop Assets for Positive Community Change* 19 (2006).
66. Emery, M. & Flora, C. Spiraling-up: mapping community transformation with community capitals framework. *Commun. Dev.* **37**, 19–35 (2006).
67. Blesh, J. et al. Against the odds: network and institutional pathways enabling agricultural diversification. *One Earth* **6**, 479–491 (2023).
68. Long, R., Lundy, M., Klonsky, K., Stewart, D., Sample Costs to Produce Beans, Common Dry Variety Double Cropped in the Sacramento Valley, 2014. University of California Cooperative Extension. Department of Agriculture and Resource Economics. Davis, CA. coststudies.ucdavis.edu/en/
69. Munier, D. et al. Sample Costs to Produce Safflower in the Sacramento Valley, Irrigated-Bed and Dryland-Flat Planted. University of California Cooperative Extension. Department of Agriculture and Resource Economics. Davis, CA. coststudies.ucdavis.edu/en/ (2011).
70. *U.S. Inflation Calculator*. *Coin News Media* (2024). Retrieved 2023, October 12 from <https://www.usinflationcalculator.com/>
71. McDaniel, T., Soto Mas, F. & Sussman, A. L. Growing connections: local food systems and community resilience. *Soc. Nat. Resour.* **34**, 1375–1393 (2021).
72. Martínez-Paz, J., Pellicer-Martínez, F. & Colino, J. A probabilistic approach for the socioeconomic assessment of urban river rehabilitation projects. *Land Use Policy* **36**, 468–477 (2014).
73. Almansa, C. & Martínez-Paz, M. J. What weight should be assigned to future environmental impacts? A probabilistic cost benefit analysis using recent advances on discounting. *Sci. Total Environ.* **409**, 1305–1314 (2011).
74. *Posit Software, PBC formerly*. Retrieved October 18, 2023, from <https://www.posit.co/> (2023)
75. Ramirez, Alfredo and Cox, Charles (2012) “Improving on the Range Rule of Thumb,” *Rose-Hulman Undergraduate Mathematics Journal*: Vol. 13: Iss. Article 1. Available at: <https://scholar.rose-hulman.edu/rhumj/vol13/iss2/1>
76. Fernandez, C., Steel, M. F. J. On Bayesian Modelling of Fat Tails and Skewness, Preprint, 31 pages (2000).
77. Fernández, C. & Steel, M. F. J. On Bayesian Modeling of Fat Tails and Skewness. *J. Amer. Statist. Assoc.* **93**, 339–371 (1998).
78. Laitinen, E. rkki Discounted cash flow (DCF) as a measure of startup financial success. *Theor. Econ. Lett.* **09**, 2997–3020, <https://doi.org/10.4236/tel.2019.98185> (2019).

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Author contributions

S.R. was the lead researcher, responsible for developing the questions, facilitating grower focus groups, developing partial budgets and analyzing the data, as well as writing the research article, with oversight from C.P.; W.B.-D. also supported in facilitating focus groups. W.B.-D. and S.R. conceptualized the study, guided the research and analysis, and helped write the research article. W.B.-D., B.L., L.E., K.A.-K., and M.L.-M. provided a feedback and reviewed drafts of the article. All authors contributed to the article and approved the submitted version.

Competing interests

The authors declare no competing interests.

Additional information

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