Title

Sustainability Implications of Crop Rotations in California Rice Systems: Evaluating Agronomic, Economic, and Environmental Benefits and Tradeoffs

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Sustainability Implications of Crop Rotations with California Rice Systems: Evaluating Agronomic, Economic and Environmental Benefits and Tradeoffs

By

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Abstract

Rice lands are important agroecosystems for providing food for over half the world's population while also mimicking wetland environments which support wildlife habitat and are known for carbon sequestration. At the same time, rice lands are facing a number of challenges related to climate change, increased herbicide resistance, labor shortages, and market shift. In response, diversification of rice systems of historically rice dominated landscapes is becoming more common. Crop rotations are being proposed as a practice for California's rice sector to mitigate challenges related to herbicide resistance and water scarcity in the Sacramento Valley region. However, while crop rotations have been shown to support aerobic cropping systems with regards to weed control, soil health, and yields, switching between a flooded environment to an upland environment can be complex, and may compromise certain soil health related properties related to storing carbon and nitrogen. Furthermore, profitability of crop rotations with rice remains uncertain. Limited data exists on the benefits and tradeoffs of crop rotations with rice systems and their overall feasibility in the Sacramento Valley region. With the help of multiple collaborators, I assess the implications of crop rotations with rice systems by evaluating growers' perceptions and experiences on barriers to adoption, compare long term profitability of crop rotations with rice compared to continuous rice, and evaluate differences in soil health and agronomic factors between these systems.

In chapter one, I use semi structured interviews to gather a breadth of information from growers regarding the types of rotations that exist in California with rice, the benefits, and barriers to adoption growers' experiences with rotations, and the requirements for rotations to be successful. Crop rotations ranged in complexity and incorporated many upland crops such as tomato, sunflower, beans, safflower, vine seed, cool season forages, and more. I learned that multiple factors limit growers' ability to rotate including environmental limitations, lack of available contracts and markets for other crops, financial barriers, and limited experience and knowledge of other viable crops. Growers who rotated agreed that weed control and reduced reliance on herbicides were benefits of rotation, as well as soil health and economic benefits. In chapter two, I investigate the economics of crop rotations with rice systems by evaluating long-term profitability of crop rotations, one with tomato and sunflower, and one with safflower and beans, over a 15-year time frame, and show how rotational benefits and water scarcity events impact these outcomes. I used a Monte Carlo to randomly select variable costs based on data collected from growers and published work to account for economic uncertainty. I found that there is a high likelihood that crop rotations can be as or more profitable than continuous rice, under the assumptions of rotations providing increased rice yields and reduced herbicide inputs or under scenarios where fallowing becomes more common with continuous rice systems. However, there could be a substantial investment period for farmers depending on number of factors. In chapter three, I sample soil from 46 farmers' fields to assess differences in soil health and agronomic indicators between rotated and continuous rice fields, under both organic and conventional management. Furthermore, I evaluate tradeoffs between systems using a multifunctionality lens to assess system performance and effects on broader ecosystem service categories. This study found that crop rotations had reduced organic carbon and nitrogen pools, as well as less weed abundance and increased yields and minor elements. Organic rotated systems showed less soil health differences and had no significant changes with weed abundance. Conventional rotated fields had higher agronomic efficiencies with lower environmental and regulating services, compared to continuous rice systems.

Together this dissertation understands the role crop rotations can play for California rice sector, as well as the expected challenges and tradeoffs. Overall, this research confirms multiple benefits for crop rotations with rice systems and concludes that rotations should be considered as a tool for farmers to adapt to if challenges continue to persist. However, rotations are unlikely to become a common practice due to low feasibility. Outcomes of this research can be used for developing extension programing, supporting farmers decision making, and supporting policy goals.

Dedications

I dedicate this work to my fathers. My father Gary Rosenberg passed away June 2024, battling lung cancer taught me to believe in the basic goodness of human nature. My stepfather Robert Bennett passed away June 2017. He was and remains the smartest man I have ever known. Growing up in his presence shaped my love and respect for the intellect, and for the continuous pursuit of knowledge.

~

I dedicate this work to all the producers, farmers, and land stewards across the world.

It is through my time spent beside them, that I discovered so much of what we learn cannot be attainable in a classroom but must be experienced.

~

I would not have fathomed myself here today, and yet here I am.

And so, I dedicate this work to others like me, who came into this academic journey with a great doubt. "Believe in yourself and all that you are. You are braver than you believe, stronger than you seem, and smarter than you think" (A. A. Milne).

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Introduction

With a population projected to increase to over 9 billion by 2050 (FAO, 2009), we are challenged with the need to produce more food, while conserving resources and reducing our environmental impact. Extractive management practices currently dominate agricultural management practices which contribute to many climatic, social, and economic challenges. Large scale monocropping and industrial based agriculture has depleted soil carbon stocks and biodiversity, while increasing our dependents on external inputs such as fertilizers, pesticides, and herbicide (Lal, 2001; Ritchie & Roser, 2013) Agroecology seeks to understand ecological processes applied to agricultural systems to suggest management approaches that bring about more sustainable systems (Barrios et al., 2020). Diversification practices, such as crop rotation, is a foundational principle for management in agroecosystems (Tamburini et al., 2020). Diversification practices support ecological systems by increasing biodiversity, and therefore increasing functional diversity which supports synergies (Tamburini et al., 2020). For example, different species will attract a more diverse insect population to reduce input requirements. Similarly, crop rotation, can balance carbon and nitrogen dynamics through resource partitioning for more efficient nutrient cycling (Finney & Kaye, 2017; King & Blesh, 2018; Renwick et al., 2021; Tamburini et al., 2020). Furthermore, diversifying crops can change canopy architecture and timing of growth, which decreases weed's ability to compete, reducing the need for herbicide inputs (MacLaren et al., 2019). All these outcomes can support yields as well as provide a more diverse food landscape- which can benefit regional socioeconomic prosperity(Wezel et al., 2020).

While literature on the impacts of diversification, specifically crop rotations, continues to show multiple benefits, the majority of these benefits are determined in upland systems. Rice systems, Oryza *sativa*, dominated by aquatic or semiaquatic agroecosystems, in many ways, are more complex when it comes to crop rotation. In absence of oxygen, alternative electron acceptors are used during processes such as the decomposition of organic matter which has ramifications for N and C cycling as well as the availability of other nutrients, slowing down decomposition rates (Wei et al., 2019; Zhang et al., 2023). It is due to some of these biogeochemical differences that continuous cropping of rice systems can be continuously cropped without depleting soil nutrient reserved, maintaining sustainable yields for centuries (Cassman et al., 2002). Furthermore, rice environments offer crucial wetland habitat, an ecosystem threatened by land use change (Propper et al., 2023), while providing a primary source of carbohydrates for over half of the world's population (Fukagawa & Ziska, 2019). Therefore, rice landscapes on their own serve multiple functions for the environment, and society, and in some ways, may remain an exception to the rule of diversification.

Yet global rice systems, like aerobic systems, are under pressures from climate change, shifts in labor demands, water scarcity, and overuse of pesticide and herbicides. These challenges may be supported by rotating rice with other crops. Yet the feasibility of crop rotations with rice remains unclear. Rice has particular requirements for cultivation, typically requiring a flat surface for facilitating flooding, and a soil profile that inhibits percolation such as a high clay texture and hardpan environments that are often not as conducive for aerobic crops (Hill et al., 2006). Research shows that converting rice landscapes to upland systems can have major implications for both the environment as well as society, both positive and negative. Crop rotations can reduce methane emissions, and increase rice yields, but also can compromise carbon and nitrogen reserves by introducing oxygenated environments (Brye et al., 2017; Zhang et al., 2023).

California is one of a few states in the US with a robust rice sector, responsible for producing 2% of global rice and 20% of the US production (USDA/NASS, 2023). Nonetheless, challenges are occurring in this region, with regards to water scarcity and herbicide resistance issues, which makes maintaining productivity and profitability a challenge for rice growers (Brim-DeForest et al., 2020; Calrice, 2023; Hill et al., 2006) Crop rotations have been proposed as a way for mitigating these challenges as farmers can integrate drought tolerant crops and provide alternative forms of weed control mechanisms to herbicides. Yet, there is limited data on this topic, which make rice growers reluctant to practice crop rotations. Adaptive strategies are necessary to maintain a thriving rice sector in this region and diversification may be necessary as changing climates persist.

Two major questions arise when thinking about how crop rotations may or may not fit within a California rice system context. The first is, what is the overall feasibility of crop rotations in rice systems? This relates specifically to farmers willingness to adopt rotations. Rotations are difficult for rice growers to adopt, and the complexity of diversity means multiple factors may limit growers' ability to rotate. In my first chapter I focus on answering this feasibility question and explore what makes farmers want to rotate (what are the benefits), how farmers experience barriers to adoption and what the requirements for rotations to be successful are. In my second chapter I focus on feasibility through an economics perspective and explore economic barriers and overall profitability of crop rotations with rice. The second question that arises is what are the long-term effects of crop rotations on agronomic and environmental factors? This question focuses on understanding the different agronomic and soil health benefits and tradeoffs between continuous rice compared to rice-based crop rotations. While there may be certain benefits such as controlling weeds, or reducing inputs, there may be other long-term negative effects on soil functions like carbon and nitrogen retention.

An important aspect of developing this project was to integrate extension research and outreach methods in order to develop applicable findings for farming communities. Therefore, I begin my dissertation with a baseline assessment on crop rotations with rice systems, to learn from rice growers in the Sacramento Valley what rotations exist in the region and what the barriers and opportunities for crop rotation are in this region. My use of semi structured interviews allows to freely explore perceptions of rice growers and learn about their experiences. Furthermore, by beginning my research with a baseline assessment, I was able to build crucial relationships with rice growers whom I relied on throughout the entirety of my research. These relationships were foundational in order to integrate a participatory approach throughout my research design. Participatory research is the active participation of communities, who are the target focus of research outcomes, in the research process. I decided in this research that the most valuable, and realistic contribution farmers and stakeholders could participate was in the development stage of the research questions. Therefore, with the support of local farm advisors, I presented the findings of chapter 1 to growers and industry leaders and facilitated a multi stakeholder focus group which brought farmers together to define research priorities reflected in my other thesis chapters. The group decided on three major research objectives: 1) to investigate the economics of crop rotations, 2) understand the effects of crop rotation on soil health weeds and yields (UC Rice IPM Workgroup - Publications, 2023)

Economics is the largest factor influencing farmer decision making for or against adoption of new practice. Therefore, it was not surprising that growers wanted more information on the profitability and opportunity costs of crop rotations with rice. Different crops require different inputs and have different market prices. Furthermore, rotational crops are subjected to varying yields in rice environments compared to aerobic cropping system environments, thus impacts on net profitability are often times unclear (N. L. W. Chen, 2022; DeVincentis et al., 2020; *UC Rice IPM*, 2023). In my second chapter, I conduct a long-term cost benefit analysis to understand this profitability question better. To begin this study, I engage growers in the data collection, utilizing focus groups as a method for data collection, to help develop a cost of production framework for multiple crops commonly rotated with rice. Importantly, an output of this chapter was the development of an interactive cost calculator for farmers and other stakeholders to use online to investigate what profits and costs may look like for them if they were to switch out of rice to a rotation crop (UC Rice IPM, 2023)

In my third chapter, I investigate long-term benefits and tradeoffs with crop rotations, specifically how crop rotations influence soil health, rice yields, weeds, and inputs. While research shows rotations to support rice yields (S. Chen et al., 2012; X. He et al., 2023), none to my knowledge quantified nor confirmed these benefits in California. At the same time, crop rotations with rice are unique due to the switch between flooded and non- flooded environments and the effects of crop rotations with rice on soil health and weeds is uncertain. Literature has shown both positive and negative results when it comes to crop rotation effects on soil health (Brye et al., 2017; S. Chen et al., 2012; D.-C. He et al., 2021). While crop rotations have shown to support weed control in aerobic systems through increasing weed species diversity, limited research suggests these same effects when rotating between an aerobic and anaerobic environment. Pardo et al., 2021 shows that crop rotations can reduce the abundance of specific weed species, in the *Echinochloa* family, a semi aquatic grass which persists in both aerobic and anerobic environments, but aquatic species may not be affected by rotations, and further research is required to evaluate crop rotations impact on weed abundance (Adeux et al., 2022). While the main objective of this chapter is to quantify some of these major differences, I also decided to view my findings through a multifunctionality lens. To do this, I summarize how tradeoffs relate to different ecosystem services and discuss these tradeoffs in an easily interpretable multifunctional framework. For this chapter once again, I return to many of the growers, to use their fields as the focus of this study and include both organic and conventional fields.

California currently struggles with managing for multiple climate related goals for agriculture- water conservation, carbon sequestration, and biodiversity conservation (USDA/NASS, 2023). In most cases, these goals can be achieved congruently through increasing cropping diversity. However, rice systems, as discussed, are complex and many of the ecosystem services that rice environments provide may not be preserved when switching to an aerobic environment. I attempt to fill these knowledge gaps for California's' rice sector by integrating a mixture of methods and research approaches. My hope for this dissertation is twofold: The first is that it presents further knowledges to farmers so they can view crop rotations as a tool to integrate for whom and where it works well. I hope to define what the major economic risks are, and present the tradeoffs, benefits, and requirements for crop rotations in order to support growers in making informative decisions for their operations. The online support tool is an attempt at translating a fraction of this research to an applicable resource for growers to use. I end this work and each chapter by laying out where we need to continue to focus our efforts on the topic with regards to future research and outreach. The second hope is more personal. I believe this research represents a process and example of using diverse methods for extension motivated problem solving, one with farmers positionality, sociocultural and socioeconomic contents in mind. Through this academic journey, I have attuned myself to a specific goal for myself, to engage in a career in extension and research. Therefore, I write this dissertation not as an ending but as a beginning. This work was a trial of practice, and the intention is to continue to build upon my pursuit for knowledge in order to make a small difference in this world.

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Chapter 1 Crop rotations in California rice systems: Baseline assessment of barriers and opportunities[1]

1.1 Abstract

Flooded rice soils are unique in terms of maintaining soil fertility and long-term productivity, allowing continuous rice systems to contribute greatly to global food supply. Yet increasing herbicide resistant weed pressure, water scarcity, and other sustainability challenges suggest a need to explore options for cropping system diversification. However, little research has evaluated the current obstacles limiting diversification of rice systems in different contexts. We interviewed 42 rice growers in California to i) assess the perceived benefits and challenges of crop rotation in the context of California rice systems and ii) identify the factors influencing decision-making and barriers to adoption. Cropping systems ranged from high to low diversity across three different categories of growers (conventional rotations > organic > continuous rice). Key factors influencing the feasibility of rotations were soil limitations, production costs and productivity level of alternative crops, water and equipment requirements, market access, and regional differences. Generally, growers agreed that weed control and reduced reliance on herbicides were benefits of rotation. Similarly, growers who rotated described soil health as a primary benefit that decreases the need for fertilizer and pesticide inputs. However, there were many challenges to implementing rotations including heavy clay soils with poor drainage, lack of available contracts and markets for other crops, financial barriers such as land ownership and farm infrastructure (size of operation and available labor and equipment), and limited experience

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and knowledge of other viable crops. In terms of economic feasibility, those who only grow rice believed that other crops are less profitable, while those who rotate said that rotations increased profitability. Our research indicates that soil is an important limitation, but other economic, social, and cultural barriers also strongly influence the potential for the diversification of rice systems.

1.2 Introduction

Global rice (*Oryza sativa L.*) production is primarily characterized by continuous rice systems (single, double, or triple cropping intensity) (Cassman et al., 1995; Waha et al., 2020). For example, two rice crops per year are produced on approximately half of total irrigated rice area, which contributes more than three-quarters of total global rice production (Becker and Angulo, 2019).

Flooded rice systems have been practiced in lowland regions of Asia for hundreds of years, providing a number of sustainability benefits (Cassman et al., 1995; Wassman et al., 2019). Semi-aquatic environments such as these have different chemical and biological cycles compared to terrestrial ones (Bronson et al., 1998), thus flooded rice soils are unique in terms of their ability to maintain soil fertility and long-term cropping system productivity (Bronson et al., 1998; Pampolino et al., 2008). However, food production is not the only goal of multifunctional agriculture, and several biophysical, economic, and social drivers are contributing to the diversification of rice landscapes (Becker & Angulo, 2019).

Irrigated rice production in California is concentrated in the Sacramento Valley (Figure 1), produced on around 212,000 ha annually during the last 20 years (USDA NASS, 2021). California ranks second in the U.S. for total rice production, while maintaining the highest average yields (Hill et al., 2006a), currently ~ 9.6 Mg ha^{-1} and still increasing. The success of the commercial rice sector has been achieved due to the combination of a favorable climate (high solar radiation during summer months and cool nighttime temperatures), successful breeding programs, and timely cultural and pest management practices. California rice is often grown continuously under flooded conditions, mimicking natural wetland habitat, and thus is a major contributor of winter flooded wetland habitat for 3-6 million waterfowl, nearly 60% of all waterfowl migrating along the Pacific Flyway each year (Calrice, 2011). These semi-aquatic environments with clay soils and poor drainage differ substantially from other cropping systems in the Sacramento Valley, which consist of other summer annual crops or perennial forages in rotation.

Major challenges threatening rice production include herbicide-resistant weeds as well as unpredictability in water availability due to drought (Gebremichael et al., 2021; Hanson et al., 2014). California rice has the highest number of herbicide-resistant weed species compared to any other crop or region in the U.S. (Hanson et al., 2014). Moreover, weed species such as weedy rice (*Oryza spp.*) (Burgos et al., 2021), also known as red rice, pose significant challenges for weed management (Leon et al., 2019). At the same time, California's pesticide regulations limit the introduction of new herbicides and how herbicides can be applied (Hill et al., 2006). Due to the limited number of herbicides available, and the long timeline for the development of new chemical management tools, rice growers have limited options for control aside from increasing the number of applications, further exacerbating the problem. Meanwhile, California droughts have resulted in water use restrictions (Gebremichael et al., 2021; Hanak et al., 2019.). Gebremichael et al., (2021) found that fallow land in California's Central Valley tripled during drought years, from about 180,000 ha^{-1} in 2007 to 450,000 ha^{-1} in 2016. Similarly, rice acreage reduced significantly during peak drought years in California (2014, 2015, and 2021), corresponding with a 15, 18, and 22% decrease in rice area planted (Gebremichael et al., 2021; USDA-NASS, 2021).

Crop diversification is a fundamental principle for long-term agricultural sustainability (Cabell & Oelofse, 2012). In other systems, crop rotations have been shown to be a key management practice supporting weed control and inhibiting herbicide resistance (Beckie et al., 2004). Rotations allow for the use of different herbicide modes of action (Kayeke et al., 2017), while also allowing for the use of integrated weed management tools, including aerobic irrigation systems and cultivation techniques, which both help manage different weed species but are not normally utilized in rice weed management. At the same time, crop rotations have been cited as an effective way to conserve water resources. For example, Reba et al., (2017) found that maize, soybean, and cotton reduced season- long applied water by 66-80% compared to flooded rice in the Southern U.S. While there is no evidence to suggest that rice systems in California cannot continue to produce high yields, future success of the industry will depend on the development of new herbicides for weed control, continual release of improved rice varieties adapted to changing environmental conditions, and sufficient water availability. In this context, research exploring options for crop rotations would provide new knowledge on the potential advantages and disadvantages of diversification and the major barriers to adoption.

Diversification of farming systems is complex and constraints both on- and off-farm exist to disincentivize growers (Mortensen & Smith, 2020; Schoonhoven & Runhaar, 2018). In California rice systems, past research suggests that soil constraints are a major factor limiting growers' ability to rotate. More than half of rice area is considered "rice only" land, where other summer or winter crops fail due to poor yields and high input costs (Hill et al., 2006; Carter et al., 1994). These soils become waterlogged easily due to a high clay content or a cemented hardpan/claypan layer, resulting in significantly lower percolation rates (California Regional Water Quality Control Board, 2021; LaHue & Linquist, 2021). However, the remaining rice acreage varies in its suitability for rotations, with more opportunities in the southern Sacramento Valley: Colusa, Yolo, and Sutter counties (Carter et al., 1994) (Figure 1). Some rice growers in these regions are successfully rotating, often with summer field crops, yet little information is available regarding common crop rotation sequences and how different factors (e.g. soil characteristics, economics, equipment) influence crop choices. Moreover, no studies have assessed grower perceptions and experiences to provide insights into the feasibility of rotations based on environmental conditions and farm resources, as well as the potential benefits for rice systems.

Farming communities often have different forms of resources influenced by social, economic, cultural, and environmental forces (Flora et al., 2019; Rogers, 1983), which support their ability to adopt new farming practices. Understanding these forces, and how they impact grower decision- making at the farm level can be useful in informing and planning extension and research efforts to address community problems and needs (Emery& Flora., 2006; Lamm et. al, 2020). Semi-structured interviews, a method in which the interviewer has foundational predetermined questions, while subsequent questions are not planned in advance (Macmillan &

Benton; 2014; Merriam et al., 2016; Patton, 2005), can assist in gathering in-depth information about participants thoughts, experiences, and beliefs.

Our research explores how growers perceive the benefits and challenges of crop rotations in their farming systems, and how those benefits and challenges relate to social, economic, cultural, and environmental forces. Identifying how different factors enable or prevent rotations is required to support changes in policy, markets, and other structural barriers, all of which are beyond the control of individual farmers. This research does not imply that crop rotations are the only sustainable path forward, they should be considered as one tool among many that can be used to address challenges facing the rice sector. With this in mind, we interviewed 42 growers to address three major research objectives: 1) Assess the different types of rotations being used and understand how growers make decisions for different crop sequences, 2) Determine the perceived benefits growers experience with rotations, for both rotating and non-rotating growers, to assess the role they could play in addressing challenges in the future, and 3) Determine barriers and limitations for adopting rotations, as well as resources required for rotations to be successful, to inform future extension efforts.

Materials and Methods

1.3 California rice systems

For an overview of California rice systems and recommended production practices, see Hill et al., (2006) and the UCCE Rice Production Manual (2018). Briefly, most rice is direct seeded into standing water (referred to as water seeded) by plane. It is grown on natural flatlands that are laser- leveled to accurately manage water levels and reduce drainage, which is not suited for most row crops (Hill et al., 2006). Flooding is the most significant cultural practice for controlling weeds, with a depth maintained between 4-6 inches during the growing season. As crop rotations are not common, cultural and chemical weed control practices remain similar year to year, resulting in continuous selection pressure and the development of herbicide-resistant weed species. Analysis of the USDA cropland data layer indicates that around 10% of rice acreage is under rotation with annual crops (USDA NAS, 2021). Roughly 3% of the total annual rice production area is under organic management (USDA NASS, 2021). For organic systems, rice is not grown every year because summer fallowing combined with deep water and mid-season drainage is commonly used as a weed control practice (California Regional Water Quality Control Board, 2021). Without herbicides, organic producers are more likely to incorporate rotations to combat weeds. Some organic rotations include a cool-season cover crop which is either mowed down in spring or left through the summer in order to harvest the seed (Williams et al.,1992).

1.4 Interviews

We interviewed growers during summer and fall of 2020 in-person using semi-structured interviews to learn about grower's farming operations and their perceptions and experiences with rice rotations (Patton, 2005; Merriam, 2015). Interviews lasted between 30 minutes and an hour. Predetermined questions were developed independently for growers who rotated and those who did not rotate (full list in Supplementary Material). Interview questions addressed farming system decision-making and grower experiences, focusing on reasons supporting or preventing rotations, attitudes about the benefits and limitations of rotations and conditions required for succes (e.g. soil, equipment, farm infrastructure), and where growers seek information and advice on rotations. Specific questions were adapted or expanded on during each interview based on growers' unique responses to learn more about their situation and rationale. Questions were reviewed by five extension specialists and then pre-tested with a grower before implementation.

1.5 Participants

A baseline list of growers was identified and recruited through extension collaborators. Snowball sampling (Palinkas et al., 2015; Patton, 2005) and recommendations by the California Rice Commission and local rice cooperatives helped to diversify and obtain broader representation of participants beyond this initial list. Attention was placed on interviewing growers in the top rice producing counties: Colusa, Butte, Glenn, Sutter, Yolo, Yuba, Placer and Sacramento (NASS USDA, 2021) (Figure 1). Two interviews expanded into other regions including San Joaquin and Merced counties. We attempted to have more grower participation in counties with higher rice acreage to ensure results were representative.

Supplementary Table 1 displays the rice acreage in each county (and proportion of total rice area) as compared to the rice acreage managed by participants interviewed in each county (and proportion of total acreage managed by participants). While the averages were comparable, some counties were imbalanced because we were seeking an even number of growers who rotated or did not rotate for our interviews (i.e., there was some overrepresentation in Yolo County because more growers rotate there and some underrepresentation in Glenn and Colusa counties because fewer growers rotate there).

Out of 42 growers interviewed, roughly 47% (20) were continuous rice growers, while 28% (12) rotated using conventional production methods (not organic), and another 24% (10) were organic rice producers. On the one hand, we could not interview all growers who rotate, and on the other hand, the proportion of growers managing conventional rotations and organic rice is higher than reality. Hence outcomes and conclusions are representative of growers with similar profiles but cannot be extended to the whole rice sector. The number of growers interviewed in each county by grower group (continuous rice, conventional rotations, organic) is shown in Supplementary Figure 1. There were several growers who had both continuous rice fields as well as fields under crop rotation. These growers were important informants due to their dual experiences.

1.6 Data analysis

To analyze the information from interviews, conversations were recorded with grower permission and transcribed. Transcriptions were uploaded to NVivo12 (QSR international, March 2020), a qualitative coding software which was used to explore responses by analyzing themes and relationships. This method condenses large amounts of information from interviews into meaningful categories that can be summarized and interpreted (Merriam et al., 2016; Patton, 2005). The coding framework was inductive, based on similar responses being grouped until themes emerged (Glaser & Strauss, 1967; Thomas, 2006). This technique is considered a constant comparative analysis, commonly used to evaluate coded information, and increase validity (Boeije, 2002; Glaser & Strauss, 1967).

Coding was performed in multiple stages. In the initial stage, themes were broadly developed under 22 categories. During the second stage, we consolidated themes based on our major objectives and separated them by benefits, barriers, and types of rotations occurring, resulting in seven major categories. These themes were then translated into five major categories using the Communities Capital Framework. The Community Capitals Framework helps assess different types of community assets, known as capitals (Emery & Flora, 2006; Flora et al., 2019). This is an increasingly popular analytical tool to identify various conditions, resources, and relationships within a community and their contribution to sustainability (Lamm, et al., 2020).

Ranking systems were then developed following qualitative coding guidelines (Merriam & Tisdell, 2016; Seidman, 2006; Strauss, 1987). Across all 42 growers, reference counts (n = the number of times a phrase or topic was mentioned) were used to determine the perceived importance of themes (Seidman, 2006; Strauss, 1987). Within-group analysis was conducted to reveal the gradations in different growers' perceptions and experiences with crop rotation benefits and challenges (Boeije, 2002; Glaser & Strauss, 1967). To determine these intergroup distinctions, we quantified the percentages of growers who mentioned a theme, as well as the average number of references within their groups, both of which assess importance or relevance of topics to participants (Dooley, 2007). Reliability and validity of findings was established through trustworthiness and credibility (Dooley, 2007). Results were shared within the research team and with growers. Thus, a credible triangulation of professional consensus that the most important findings resonated with experts and participants was established.

Results

1.7 Crop rotations practiced

Crop rotations ranged from diverse (more crops in rotation/more years producing rotation crops) to simplistic (less crops in rotation/more years producing rice) (Table 1). For example, diverse rotations tend to have rice in production for 1-2 years followed by numerous years of a variety of annual summer and winter crops. Below we group rotations into three broad types for discussion: rotations with row crops (warm season) (68% of growers), rotations with vetch (*Vicia* sp.) (41% of growers), and rotations with forage crops (cool-season and warm season) (27% of growers). While row crop rotations were often more diverse and managed conventional, rice-vetch rotations were considered simplistic and managed organically. However, sequences were highly flexible and dependent on weather, markets, soil characteristics, and landscape differences at the regional scale. Row crop rotations occurred primarily in southern counties, often described by growers as having diverse landscapes and lighter soils. Alternatively, most forage crop and vetch rotations occurred in northern regions, described as less diverse with heavier or constrictive soil.

Selection of individual crops for different seasons included considerations of irrigation and equipment requirements, production costs and profitability level, availability of markets and contracts, soil tolerance level, and the perceived benefits to the larger rotation (Table 2). Thus, each crop had different requirements and limitations. For example, some crops required different irrigation systems such as drip, flood, or furrow; and therefore, growers had to think about the logistics involved for switching between these systems. Certain crops, such as tomato, sunflower, vine-seed, and cucumber were more profitable, but had higher production costs and limited market access. Most low-cost production crops also tended to be less profitable, such as safflower and forage crops; however, markets for these crops were more accessible. These distinctions as well as the above regional and environmental differences all played a role in grower decision-making for different crop rotations.

Row crops

Row crop-rotations were reported in Sutter, Colusa, and Yolo counties (Figure 1). These growers used a mixture of warm-season crops such as sunflower (*Helianthus annuus L.*), safflower (*Carthamus tinctorius L.*), different beans (*Phaseolus vulgaris L., P. lunatus L.*, *Cicer arietinum L.*), corn (*Zea mays L.*), wheat (*Triticum* spp. *L.*), tomato (*Solanum lycopersicum L.*), melon, cucumber, and squash (*Cucurbitaceae* spp. L.). Cucurbits are grown for the fruit as well as the seed in this region (if grown for seed, growers use the common name "vine seed"). There was a group of growers who did not manage crops with higher production costs such as tomato or sunflower. Instead, these growers contract the production out to another entity to grow the crops for them. Table 3 includes representative quotes depicting row crop rotations.

Growers reported using sunflower or safflower normally as an intermediate crop, often to prepare the ground for a more profitable crop which would not do as well following rice. Recently growers explained how they have switched to sunflower, as the price of safflower has decreased. The opportunity for growing sunflower is more limited however, requiring an early-season contract. Although sunflower is more profitable, safflower was more logistically feasible,

Vetch

Vetch cover crops in rotation were reported in Sutter, Yolo, Yuba, and Butte counties (Figure 1).

A majority of organic growers (67%) cited using vetch in simple rice-vetch-rice rotations. Two organic growers rotated with row crops and integrated vetch in the fall, while only one conventional grower with rotations integrated vetch (Table 1). Grower responses suggest vetch is a low-risk, low-cost, low-value crop that can be used as a tool in rotations by itself or mixed with other cover crops. Growers reported that vetch added value to the larger rotation by increasing soil organic matter and nitrogen. Growers who only used vetch as a cool-season cover crop reported that their soils were not conducive for other crops, saying, "…we just do every other year rotation with a vetch seed crop, and these are on the soils that would be considered rice soils…"

Rotations with forage crops

Rotations with forage crops were recorded in Sutter, as well as some parts of Yuba County (Figure 1). In these regions, often growers reported that soils could not support tomatoes, and contracts for sunflowers were rare. These crops had relatively low production costs and used similar equipment to rice. Table 4 includes quotes illustrating example rotations using cool season forage crops.

1.8 Reported Benefits of Crop Rotation

Responses revealed five categories of benefits ranked as follows: weed control, soil improvement, economic benefits, conservation benefits, and disease and other pest control benefits (Figure 2). However, benefits were perceived differently depending on the group of growers. In general, organic growers and growers with conventional rotations discussed benefits more often than continuous rice growers (except for conservation benefits), represented both by the percentage of growers who mentioned the themes and the average number of references growers made about those themes (Figure 3). Organic growers attach more importance to weed control and soil improvement, conventional rotation growers attach more importance to weed control and economic benefits, and continuous rice growers attach more importance to conservation benefits.

Weed control (n=73)

Under this theme, growers discussed reducing weed populations, increasing yields, and reducing chemicals required for weed control. Growers reported that the longer a field is out of rice, the less intrusive weeds became; in contrast, the longer a field is in rice, the more common weeds became. A number of growers who rotated (both conventional and organic) declared that after rotations they saw an increase in yields and less weeds. Nonetheless, many growers who rotated still stated that weeds were increasing in their fields, despite describing weed control as a major benefit of crop rotations. Growers who had both continuous rice and rotated fields spoke often about the benefit of rotation in terms of reducing herbicide inputs saying, “Your chemical use is your highest cost in production so you’re decreasing that bill by having new ground.” These growers experienced a reduction in the number of spray applications needed to control weeds compared to their continuous rice operations.

Disease and other pests (n=14)

Some growers who held more diverse rotations (Table 1) highlighted benefits for weed, disease, and invertebrate pest control together. These growers valued rotations for their holistic contributions to the system. They “place a lot of value on building up the soil, and [viewed monoculture as] unhealthy for the pest world”. One farmer said, “Our farm, has been on a different path than most and we’ve had serendipitous results that we then capitalize on, which is why we started crop rotations.” Conversely, continuous rice growers did not reference other pest control benefits besides weeds (Figure 3).

Soil health (n=48)

Growers talked about a having a general soil health perspective, with rotations increasing fertility, and thereby reducing the need for inputs. This also included rotations increasing soil tilth and supporting remediation of alkalinity. Rice was cited as supporting summer beans like lima beans and dry beans in rotation if alkaline soils were an issue. Organic growers often spoke about the soil health and fertility benefits of rotations, with one explaining, “I’ve noticed the soil changing here for the better. This is our sixth year here and some of the fields going into rotation are coming out much better than they were in the past.” While another said, “We have some ranches, one ranch that we have had in the long-term organic rice and vetch seed rotation for 15-20 years and we don’t add any additional fertilizer.”

Economic benefits (n=35)

Economic benefits were discussed as rotations increasing profitability, increasing market diversification, and increasing rice yields.

"The third reason would be to maximize my profit I guess is the best thing to say, because there are some years when I don't make as much money on the rotational crop, but it leads to higher profit on my other crops, and I have less expenses."

Only two continuous rice growers referenced economics as a benefit of rotations. In contrast, they felt that rotations were not profitable (Figures 3). Economics, therefore, was seen as both an incentive for rotations and a constraint, depending on grower group.

Conservation (n=31)

Under the category of conservation, growers discussed how rotations had the potential to conserve rice ground, conserve water, and increase nesting habitat for wildlife. Regarding conserving rice ground, some growers mentioned how the recent limited water supply could be an incentive for rotations.

"[T]hey are talking about this voluntary agreement where folk in different areas are going to have to fallow land because there won't be ample water for the rice… if there was a way that the grower has a rotation crop that won't use any irrigation and rotate back and forth, that could keep the acres in rice producing well."

In the above quote, this grower argues that as more ground is fallowed due to water restrictions, rotating a drought-tolerant crop or cover crop in fields that would otherwise stay fallow may support the subsequent rice crop. In addition, growers mentioned rotations could potentially increase nesting habitat for birds by integrating cool-season crops like garbanzo beans, barley, wheat, and rye in fall and winter. Currently, there are efforts supporting the increase of upland habitat (non-flooded land) in fall for waterfowl to use as nesting ground (California Ricelands Waterboard Foundation, 2021).

1.9 Barriers for Adopting Crop Rotations

Responses revealed five major themes of barriers ranked as follows: environmental limitations, resource requirement limitations, economic constraints, cultural influences, and benefits of continuous rice (Figure 4). More continuous rice growers mentioned environmental and resource limitations (Supplementary Figure 2), and on average referenced environmental limitations the most.

Environmental limitations (n=73)

Environmental limitations were perceived as a major limitation by all growers. Environmental limitations had two major topics: soil limitations and the challenge of farming on floodplains. Often growers described their soils as “rice-only soils”, describing conditions with poor drainage, heavy clay, restrictive layers, and/ or saline or alkaline. Words like “adobe”, “black” “clay ground” and “hard panned” were used several times to describe these soils. Others described challenges from being near a flood basin or having a high-water table. Some described a combination of both soil limitation and flooding challenges.

"We planted some safflower one year, because the water district was only going to have a 50% supply, and the soil profile was too shallow. Safflower will have a root 5 to 7 feet deep and hit water, but some of those areas were hard panned at 3 feet, calcium looking stuff.
Same with wheat, we planted it on the heavy clay ground and a series of showers drowned it."

Regional differences in environmental conditions were apparent, with heavy clay soils generally decreasing the capacity for rotations in northern regions and lighter soils increasing capacity in southern regions. In the more southern regions, growers who rotated commented that "soils are definitely clay soils, but not as heavy as other areas, and so [they] grow other cops like tomatoes… [but only with the] advent of transplanting and drip irrigation".

"So, we don't rotate in our fields because well primarily because the soil type is only good for growing rice. As you get further out in different regions of the county, you're more likely to find rice ground that can either have trees or row crops or things like that, but our region where we grow our rice, rice is about the only thing that will grow there. That's the primary reason."

To support these claims, there were a group of growers who rotated but managed both continuous rice fields as well as fields under crop rotation. For these growers, decisions for continuous rice production were always made based soil differences.

"When we first started doing organic, I was under the impression that I could cover crop enough and plough down enough residues that I could make a row crop perform well in clay soil…but I could never achieve the yields that I could on a well-drained."

Six other growers had rotated fields and continuous rice fields, and made similar decisions based on soil differences.

Resource requirement limitations (n=61)

Resource limitations primarily dealt with on-farm challenges and infrastructure. Growers talked about lacking labor and management requirements to rotate with other crops, lacking correct equipment, and the logistics of switching from rice to alternative crops. Many rotation crops required more labor compared to continuous rice operations, and the investment was too costly. “I am not set up for sunflowers, I am a one-man operation. I do everything myself. Sunflowers take a lot more labor and you need different equipment.” Not only did rotations require more labor, but they also required more skill, time, and effort. To rotate, continuous rice growers had to transform their land and invest in new equipment.

> *“[T]he fields are made for rice, they’re laser leveled for flood irrigation the levies are in place, the on farm irrigation system is in place, the county irrigation system to get the water on to our farm is in place, we have the necessary heavy equipment, the tractors, the harvest combines specifically for rice, these are expensive pieces of equipment, and changing the makeup of the land to accommodate some other crop would be an extra expense, then taking on extra equipment that would be special for whatever crop we were to rotate, we would need to do that, and so when you’re talking about 1200+ acres to rotate that entire amount, or even some, would just require that extra work.”*

This quote illustrates the challenges associated with transitioning from continuous rice to a non-flooded crop. Although infrastructure development such as land-leveling and gravity fed irrigation networks have supported high-yielding rice production, consequently it has inhibited the integration of other crops. Logistics and costs are increased for switching the land grade, changing irrigation approaches, and managing different requirements for equipment.

Economic constraints (n = 43)

Four economic constraints were talked about including high investment costs, land costs, not having profitable options to rotate with, and limited access to markets. Some of the specific costs that were mentioned include the investments in new equipment, the opportunity cost to learn the rotation crop, the costs involved in increasing field slope and removing levies, purchasing new irrigation materials if drip irrigation was going to be used, and high land rental rates. Many growers explained that profitability is tied to rent and land costs which can be high, putting pressure on growers to maximize revenue on an annual basis.

> *"Economics, it's just not worth it. Like I said most of our land is on rented ground. It's not worth it to the landlord or to us to put in a typical rotation crop like safflower or wheat. At the end of the day, a bad rice crop pays more than a good safflower crop."*

As depicted by this quote, land ownership is a significant barrier for crop rotations. While growers who own land can be flexible with crop decisions, those with strict rental agreements may not have the capacity to produce a crop which is less profitable than rice, facing immediate financial pressures. Finally, the lack of available markets was mostly talked about by rice growers in areas where rice dominated the landscape. Many did not know where they could sell other crops like beans, tomatoes, or sunflowers. In addition, many of these rotation crops required a contract, which was not easy to get in rice-dominant regions. At the same time, growers who rotated in the past mentioned disappearing markets, such as sorghum, safflower, and sugar beet had pushed growers who rotated in the past into a monocrop rice system.

Cultural influences (n=38)

Growers brought up statements around their identity and family background, their experience and knowledge, and their surrounding communities. Most growers came from a family that has either always rotated or always gown rice. This family background was an asset for the acquisition of knowledge and other resources. However, generally, continuous rice families lacked experience of how to incorporate rotations, as well as access to information about crop rotations. Alternatively, growers who rotate felt that rotations were built into their landscapes and diversity was all around them. Both groups expressed that “this is what we have always done”.

Continuous rice benefits (n=18)

The final limitation was described as the benefits of rice that would be lost by adopting rotations (e.g., how rice production supports wildlife habitat). Many continuous rice growers did not want to rotate because they valued the immense benefit rice lands provide for wildlife habitat. “Just everything that is great about rice. I love the fact that we are the stopping mark for the Pacific Flyway, and all these other critters, so, it’s a really great thing for the environment”.

Discussion

1.10 Factors for crop rotation decision-making

We interviewed 42 rice growers managing different types of operations in different regions to learn about their experiences and perceptions, providing insights into their motivation, decision-making process, and barriers to adoption for crop rotations in California rice systems. An important contribution of our work is that it covered the full range of perspectives, including growers who manage conventional rotations, continuous rice, and organic systems. Notably, all growers who rotated had different systems for different reasons (Tables 1 and 2). This is the first study to document that a wide range of crop rotations are practiced, and that the decision of whether to practice continuous rice or rotate is driven by a combination of the production environment, as well as broader cultural, social, and economic influences that collectively shape a rice farming system (Figures 2, 4).

Regional soil differences played a dominant role in how growers make decisions at the field-level for crop rotations. For example, no conventional rotations were found in Glenn and Butte County (Supplementary Table 1) and although organic producers were interviewed in Butte, rotations were limited to rice-vetch systems. Conventional growers who have both continuous rice fields and rotation fields, and organic growers who prioritize rice-vetch rotations have the knowledge, experience, and resources to rotate, yet still decide against using them in certain fields. Therefore, when considering the potential for crop diversification as a tool for California rice systems, an initial targeted approach is needed based on identifying soil properties that are conducive for rotations, followed by a flexible approach in terms of what alternative crops are grown, the length of time in or out of rice, and availability of markets and farm-level resources—all influencing the feasibility of rotations in different regions (Tables 1 and 2, Figure 5).

Different grower groups had different motivations for crop rotations which were reflected in how they identified rotational benefits (Figure 3). Organic growers placed an importance on rotations to support weed control and soil fertility, aligning with their management requirements for organic fertilizers and alternatives to herbicides for weed control. Conventional growers who rotated identified weed control and economics as a major benefit, aimed at reducing inputs and increasing rice yields. Continuous rice growers found rotations to be valuable for weed control, while conserving rice ground for future generations and increasing wildlife habitat. These outcomes are important for future recommendations and research as the ability for extension to communicate successfully across groups is key for supporting adoption (Lubell et al., 2014).

1.11 Barriers to Adoption

Given the limited rice area currently under rotation, it was surprising how many benefits growers identified, ranging from economic to environmental and short- to long-term processes (Figure 2). These experiences are consistent with scientific evidence regarding the benefits of crop rotation (Bommarco et al., 2013; Cook, 2006). Nonetheless, our research and others show that despite grower recognition of crop rotation benefits, a myriad of constraints limits their ability to diversify (Rodriguez et al., 2009; Spangler et al., 2020; Weisberger, 2021). In other words, while these benefits could in theory help address some of the major issues facing the rice sector including weed control, reducing herbicide inputs, conserving water, and increasing soil health and long-term profitability (Figure 2), our findings suggest there are valid reasons for not rotating in California rice systems, as many barriers appear to collectively outweigh the benefits

(Figure 4).

This research and others show constraints for diversification include inadequate labor and mechanization, cultural/social influences, economic constraints and marketing limitations, limited information or experience, land tenure relationships, and environmental incompatibility (Cutforth et al., 2001; Mortensen & Smith, 2020; Ranjan et al., 2019; Rodriguez et al., 2009; Schoonhoven & Runhaar, 2018). The combination of some or all these factors creates a production system that is unable to diversify at scale, or “locked-in” to monocropping practices (Morel et al., 2020). A key finding in our research is that diversification for rice systems is a complex issue, and even without soil constraints, other barriers and reinforcing factors are limiting growers’ ability to rotate, contributing to a system of “lock-in” (Morel et al., 2020; Mortensen & Smith, 2020). Clay soils with poor drainage have served as the primary rationale for continuous rice production for decades (Carter et al., 1994), and indeed, interviews revealed that growers have strong beliefs and experiences which suggests soil and environment dictate what crops they can grow, making it a dominant barrier (Supplementary Figures 2). Nonetheless, our research indicates that soil is not the only limitation, and other economic, social, human, and cultural factors play a role in decision-making and ability to adopt crop rotations (Figure 4).

Results such as these highlight the benefits of evaluating farmer perceptions and experiences to better understand barriers to adoption (Cutforth et al., 2001; Mortensen & Smith, 2020; Ranjan et al., 2019; Rodriguez et al., 2009; Weisberger, 2021). They can help inform research efforts and options for diversification in different context elsewhere. Becker and Angulo (2019) show there is currently a tension within intensified rice production systems in Asia, where resource limitations are forcing shifts out of rice to non-rice crops, transitioning towards more diversified systems. This includes socioeconomic drivers (new markets, off-farm employment, decreasing labor availability), technology advances (mechanization, direct seeding), and growing environmental pressures (water and carbon footprints) (Wassman, 2019). Our study suggests that to understand options for diversification in different contexts, research should not only account for biophysical factors such as soil, but also grower perceptions and broader social, cultural, and economic forces that determine feasibility.

1.12 Perceptions of profitability and the economics of crop rotation

In general, growers who currently rotate perceived more benefits of rotation compared to continuous rice growers. Similarly, one of the biggest areas of difference in this study was economics. Those growing continuous rice felt that other crops were not an option because they were less profitable, while those who rotate said that increased profitability through crop diversification was one of the main benefits of rotation. Based on these distinct perceptions, rotations may be more viable for certain production environments, allowing both continuous rice and growers who rotate to achieve long-term economic sustainability. Despite reports from other cropping systems showing that crop rotations can improve farm profitability and sustainability (Clark et al., 1999; Cook, 2006; Davis et al., 2012a), the fact that continuous rice growers did not discuss many benefits of rotations could also be because crop rotations would have negative outcomes given their environmental and economic circumstances.

Differing perceptions on profitability also reflect different economic timescales. Many continuous rice growers were concerned with seasonal returns, necessary to cover high rental rates and other operating costs. Therefore, they discerned profitability as end of the season revenue that was equal to or better than rice. Alternatively, many row crop growers viewed profitability across the whole system, implying that despite having lower yields in some years, this was often made up by higher yields in other crops and input savings in rice. Our findings demonstrate that growers' perceptions on profitability are matched with their conditions such as high rental rates, equipment limitations, and restrictive soils. Under these conditions, growers are doing the most economically sustainable thing by focusing on high rice yields, especially if they do not own land or had flexible leasing arrangements. However, profitability is determined by both inputs and outputs and other research on crop diversification shows that yields are not a defining factor of cropping system profitability, particularly in diversified systems (Olmstead & Brummer, 2008). Thus, even if California rice yields continue to increase, this may be negated by ever growing input costs as well.

1.13 Requirements for successful rotations

Our research provides an understanding of the requirements for successful rotations and identifies some strategies for overcoming barriers based on the practical experiences of other farmers. We developed a conceptual model to highlight certain requirements and conditions necessary for successful rotations (Figure 5) based on common rotational crops and their corresponding production requirements reported by growers (Tables 1 and 2). Such information is not currently available for the California rice sector, and it represents an initial step in identifying key levers that can be targeted through research and extension programs to enable diversification in the context of medium to large- scale systems.

To depict the complex relationships influencing crop rotation feasibility, we used the Community Capitals Framework to identify capitals that could help address different barriers to adoption (Figure 5). One of the foundational capitals in this framework is natural capital (Emery & Fey, 2006; Flora et al., 2019), which often is seen influencing the ability to build upon other assets. In our study, natural capital included soil and environmental conditions, which largely influenced four groups of secondary capitals, labeled in this study as economic, social, human, and cultural capitals. These capitals and the conditions influencing them (circles) are interdependent on each other, as depicted by the direction and connectivity of arrows.

For rotations to be successful, growers described soils as often being lighter and deeper which supported drainage, particularly with respect to row crop rotations. However, some growers who rotated still described their soils as heavy, sometimes having restrictive traits attributed to rice-only soils (Table 1). Therefore, although soil was a foundational asset that allowed for successful rotations, it was not the only requirement. Having appropriate resources such as equipment, were other important factors allowing for successful rotations (economic capital). Rotation growers came from families that always rotated (cultural capital), which passed down equipment, knowledge, and experience. Some growers had enough equipment to do all the work themselves, indicating a larger operation capacity (economic capital), and larger workforce and knowledge and experience with other crops (human capital). Others contracted out rotation crops to other farmers who brought their own equipment (social capital). One grower noted that rotations required a "mix-and-match of employees, equipment, land and markets… [and they are largely] dependent on the ability to form relationships and networks".

Drawing on our social capital pathway in the conceptual framework (Figure 5), having more diverse community networks has a positive influence on growers' ability to find connections to markets and contracts for rotation crops. Contractors and market access positively influences social capital, which increases crop rotation likelihood. Land ownership can also have a positive influence on social capital, providing growers an opportunity to rent out land to other farmers who grow rotation crops for them. These relationships and networks with other row crop growers were profoundly important social resources which increased their access to markets and allowed most rice growers who did not have the proper equipment or experience to integrate more profitable crops into their rotation. Alternatively, rigid, and high rental agreements negatively impact growers' ability to seek crop contracts, reducing the likelihood of rotation.

Literature pertaining to the Community Capitals Framework states that communities need an adequate supply of the required capitals for the adoption of sustainable practices to occur (Emery & Flora 2006). Our research supports this notion as growers who have access to certain assets can mitigate risk and overcome constraints. For example, soils with high clay content increase the risks involved in growing crops other than rice. However, having the correct equipment, knowledge, access to markets, and supportive communities decrease this risk.

1.14 Future directions

Understanding both the required resources for rotations to be successful, as well as barriers to adoption, are critical to inform future extension efforts. Interviews highlight the importance of soil limitations, but this barrier is neither easily addressed by growers or policy changes. Secondary factors influencing growers' ability to rotate are still impactful, and by targeting these less intractable barriers, we provide actionable recommendations from our work, placing emphasis on addressing opportunities related to economic, social, cultural, and human assets (Figure 5).

There is a need for new partnerships and approaches to problem-solving to explore crop rotations as an option for California rice growers. Prior work illustrates how the Community Capitals Framework can help identify which community assets are lacking, supporting program development that targets specific community needs and supportive interventions (Mattos, 2015). Programs which increase networking across different disciplines and actors are key for adoption of sustainable technologies, with new knowledge leading to increased innovation (Flora et al., 2019; Muringani et al., 2021; Takemura et al., 2014). For example, Ervin et al., (2019) demonstrated that social networking and connections among people, organizations, and groups were a key factor impacting growers' willingness to adopt integrative pest management options.

For rice growers, a program to increase social networking capability among row crop growers and rice farmers could stimulate learning and experimentation. Social assets are a key requirement for increasing knowledge and connections (Muringani et al., 2021), which might be improved if growers developed ties with the different groups. Furthermore, how complex or difficult a new technology is, and the extent that it can be tested without too much risk, are important factors that impact adoption (Rogers, 1983). There is immense risk that growers face when integrating other crops into their system in the form of higher labor demands, alternative equipment needs, and unknown markets.

Growers who do not rotate see the act of switching over to other crops as too costly and logistically challenging. To address these risks, programs that build capacity for alternative contracting agreements such as custom farming, crop share agreements, and equipment sharing programs, could decrease some of the large investments required to transition into rotational crops. Simultaneously developing incentives for growers to incorporate low-cost, and low-risk crops such as safflower, vetch, and beans would help increase crop rotation feasibility. These and other creative programs investing in the conditions under human, social, cultural, and economic assets in Figure 5 can help growers overcome certain barriers facing rotations (Emery & Flora 2006, Takemura et al., 2014).

Yet there are benefits of maintaining continuous rice, particularly in soils and environments most conducive to flooded conditions. In Asia there are concerns about the extent to which diversification of rice-based systems will influence sustainability. These systems have provided staple food for local cultures over hundreds of years, but a shift away from flooded soils will compromise some ecosystem services while enhancing others (Wassman, 2019). This research suggests that a landscape-scale approach is therefore crucial, where fields only capable of supporting rice need to be identified in California, while soils that are more adaptable to non-flooded crops should be targeted as potential options for crop diversification.

Our interviews provided several new insights but the impact of rotations on environmental and economic sustainability needs to be further evaluated. Research assessing soil properties to understand where rotations are possible at the landscape scale would help identify diversification opportunities while preserving soils that are most suitable for rice production. Due to differing perceptions about economics, evidence is required about the economic advantages or disadvantages of rotations under different conditions and the key factors influencing profitability. Growers also had different experiences with how rotations impacted weed control, thus research into how different rotations impact different weed species, and herbicide resistance over time would support better management decisions. Regarding soil benefits, growers discussed soils improving over time which contributed to increased yields and reduced nutrient input requirements, but further research should assess soil health under different types of rotations for both organic and conventional growers. It is important to understand how rotations may support water use efficiency as California faces continuous threats of drought. Safflower, beans, and sunflower were discussed as having a small water footprint, which could help address water scarcity and the decreasing available land base for planting rice. However, rice fields play a large role in offering wildlife habitat, and research should investigate tradeoffs between water conservation and wildlife habitat in what is traditionally understood as a semi-aquatic environment.

1.15 Conclusion

Rice growers we interviewed in the Sacramento Valley practice a wide range of crop rotations, and for the first time we summarized common rotation systems and influential factors in decision- making. Our interviews showed that different groups of rice growers (continuous rice, conventional rotations, and organic) perceive many benefits and barriers to crop rotation, some more applicable to certain groups than others. By focusing on the requirements for successful rotations, we identified different assets which can facilitate or limit rotation likelihood. We illustrate that although successful rotations are possible, they require certain social, economic, human, cultural and natural conditions, often missing from continuous rice growers' environments. For some influential factors, we found there are opportunities to address human, social, and cultural barriers through a community engagement approach, with a focus on developing new networks and programs (Chambers, 1994; Weisberger, 2021). Yet, like other studies on cropping system diversification, many of the barriers are complex and beyond growers' immediate control (e.g., soil limitations or available markets).

While identifying soils as a major barrier is important, this should not limit attempts to better understand other key obstacles or research opportunities to address sustainability issues through diversification. Further research should explore the implications of crop rotations, starting with identifying where and how much land may have potential to be rotated and looking at the mechanisms by which rotations support rice systems, as well as the tradeoffs. Ultimately program development will be necessary to help irrigated rice systems adapt to new resource limitations and sustainability challenges such as water resources and herbicide resistance. For the California rice sector, we have outlined opportunities for extension and future research possibilities to continue increasing knowledge on the advantages and disadvantages of rotations.

Figures

Figure 1. Map of rice growing areas in the Sacramento Valley of northern California, USA. Counties where grower interviews took place include (from northeast to southeast) Glenn, Butte, Colusa, Yuba, Sutter, Placer, Yolo, Sacramento, and San Joaquin. Map created by Luke Salvato. Data Source: USDA National Agricultural Statistics Service Cropland Data Layer. (2021). Published crop- specific data layer. https://nassgeodata.gmu.edu/CropScape/.

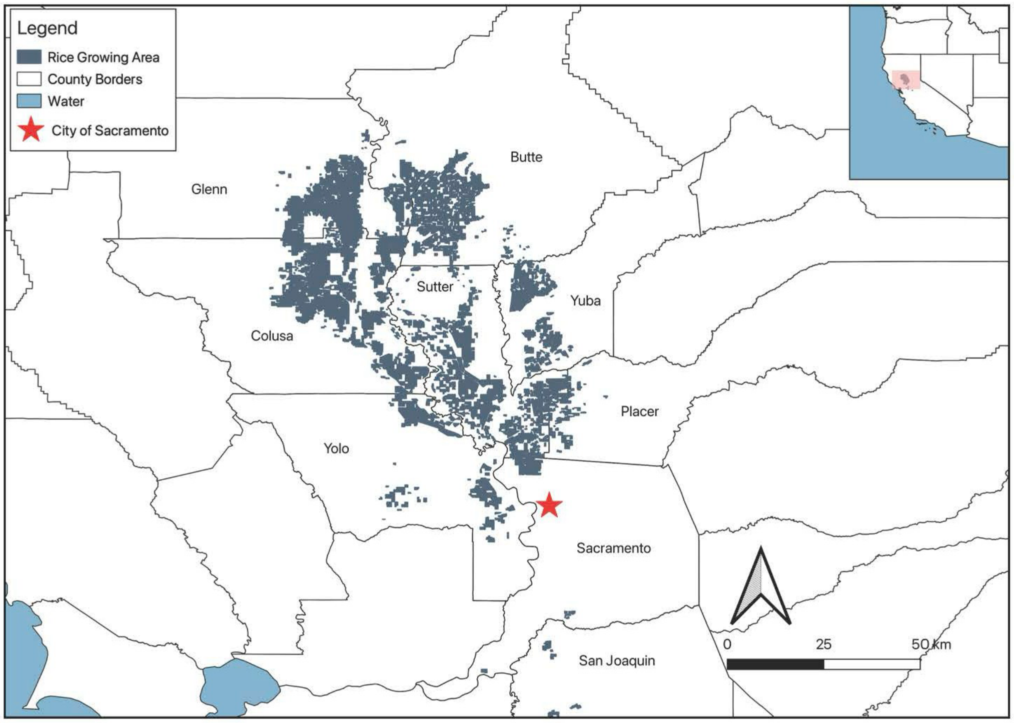


Figure 2. Perceived benefits of crop rotations in rice systems. The inner circle represents the major theme or benefit discovered through our qualitative analysis. The size of the inner circle is based on the number of references coded under each theme. The outer circle represents the different ways growers talked about the major themes. The relative size of each category corresponds with the number of times that category was discussed.

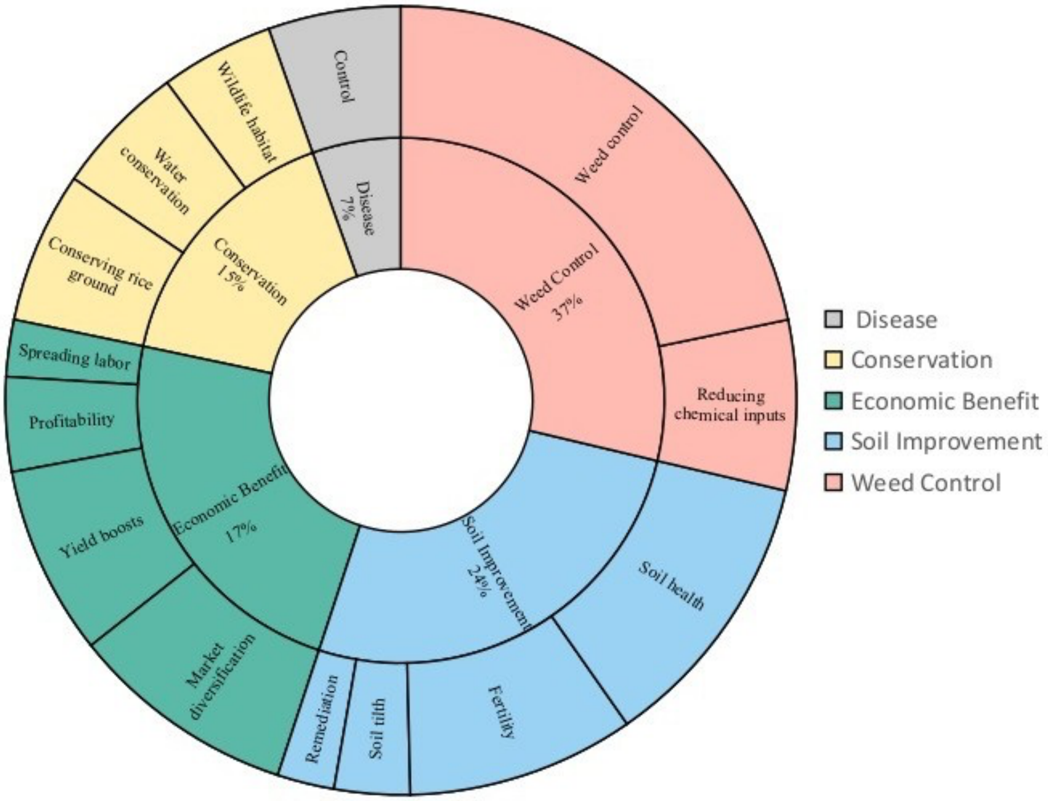


Figure 3. Barriers to adoption for integrating crop rotations into rice systems. The size of each square is based on the number of references coded under each theme (indicated by %). The rank of most significant barriers was: environmental barriers (included soil limitations and the risk of farming on floodplains), economic barriers (included the lack of markets for other crops, lack of other profitable options they could grow, prohibitive operational costs (cost of switching) and overhead costs), resource barriers (included on-farm limitations such as not having the correct labor or management capacity, lacking correct equipment, and not having enough land), cultural barriers (included family experiences and grower identity/values), and continuous rice benefits (includes wildlife habitat which rotations may compromise).

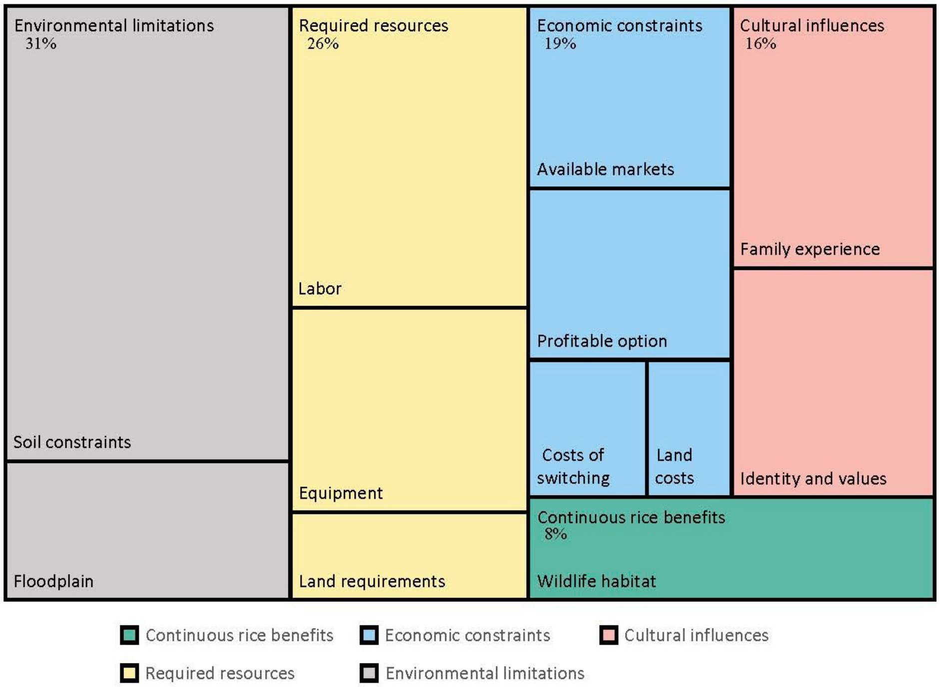
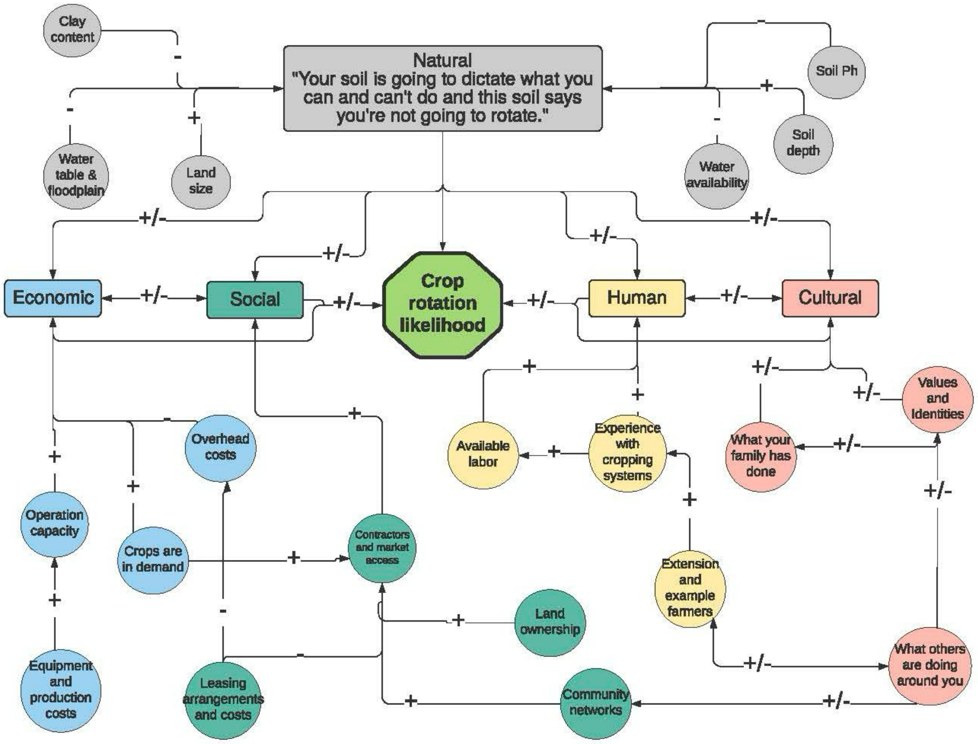


Figure 4. A conceptual model demonstrating major asserts for rice production and their influential conditions affecting the possibility for crop rotation. Natural capital is foundational and largely influences the other four. Secondary capitals were grouped into economic, social, human, and cultural categories (Flora et al., 2019). These capitals are interdependent on each other, depicted by the direction and connectivity of the arrows. Conditions that influence capitals are depicted as circles, the direction of the arrows indicate what they influence, and weather the relationship is positive or negative in terms of increasing or decreasing the likelihood for crop rotation, respectively. Some influential conditions such as “What your family has always done” can be either positive or negative depending on growers’ circumstances.



Tables

Table 1. Description of crop rotations for growers interviewed. Columns include, number of years commonly planted in rice and rotation crops, the type of operation (C= conventional or O=organic), the county where fields are located, surrounding landscapes, and grower description of their soil. Rotations are ranked with the most diverse rotations at the top (green - more crops in rotations/more years producing other crops) to the least diverse rotations at the bottom (yellow - less crops in rotation/more years producing rice).

Rotation crops	Years in rice	Years out of rice	Operation	Rotation county	Surrounding landscape	Soil
Rice, sunflower, tomatoes, beans, vine seed and corn	1	4-6	C	Sutter	Diverse cropping region	Deeper loam soils
Rice, Alfalfa, barley, vetch, wheat	1	4+	O	Yolo	Field crop, row crop, and orchards	Lighter
Rice, beans, tomatoes, corn, vetch	1	4-5	O	Sutter	Diverse cropping region	Clay loam
Rice, sunflower, tomatoes, corn, rice	2-3	4-6	C	Sutter	Walnuts, and almonds	Lighter
Rice, beans	2	5+	C	Sutter	Diverse cropping region	Mix of heavy clay, sandy loam soils with alkali streaks
Rice, tomatoes, vine seed, wheat, sunflowers. Beans occasionally	4-5	4-5	C	Colusa	Diverse cropping regions	Light clay
Rice, safflower, or sunflower then tomatoes, melons, and wheat	4-5	4-5	C	Yolo, Colusa	Diversified crops, rotation common	Light in Colusa. The yolo not so heavy
Rice, barley, fallow, beans	1	3-4	O	Other	Cotton and alfalfa, some tomatoes	Heavy clay high salt
Rice, sunflower, corn and melons, some vine seed, some beans	2-3	3-4	C	Sutter	Some continuous rice, some row crop	Lighter soil, heavy clay, hardpan
Rice, vine seeds, cucumbers, squash, tomatoes	1-3	3-4	C	Colusa	rice in heavy clay and alkali areas, row crops in deeper soil	Deeper profile. for Glenn, heavy clay
Rice sunflower, garbanzo, tomatoes. Vetch and other cover crops	2-3	2-3	C	Colusa, Yolo	Savanna rolling oaks. Rotations in other areas	Very heavy Clays
Rice, tomatoes, corn, sunflowers, vine seed	2-3	2-3	C	Sutter	Diverse cropping region	Lighter soil
Rice, chickpea, tomatoes		2-3	C	Sutter	Rotations in area	lighter soils.
Rice, sunflower, or safflower, then contracts it out to tomatoes. Other crops, vine seed and beans	4-6	2-3	C	Colusa, Yolo	All rice in area, but there's other row crops grown	Colusa soil is heavy clay
Hay rotations- start out as alfalfa overseeded with orchard grass, rice	3 +	1-2	C	Sutter	Rice, livestock, and hay operations	Mostly heavy clay
Rice, beans, popcorn, wheat. Certain soils classified as "rice only soils" will only be rice and vetch rotations	1-3	1-3	O	Sutter	Rice, alfalfa, trees moving in	Heavy clay and Lighter soils
Rice, followed but cattle, fallow flood or rye, rice	1	1-2	O	Yuba	Rice and pasture	Heavy clay
Rice, pasture, some vetch, and oats	4-6	1	O	Yuba, Sutter	Rice and paster	Heavy clay
Safflower, corn, tomatoes, sunflower, beans, sorghum. Or organic rice-vetch-rice	5-10	1-2	O	Yolo, Butte, Colusa	Butte County is rice Yolo is mixed crops	sandy loam, most heavy clay
Rice-vetch-rice	1	0-1	O	Sutter	Mostly rice and livestock	Rice soils
Rice-vetch-rice, wild rice Past: sugar beets, wheat	1	0-1	O	Sutter	Primarily rice	Hardpan, heavy clay to clay-loam
Rice-vetch-rice Past: wheat and triticale	1	0-1	O	Sutter, Sacramento, Placer	Primarily rice and rangeland	Shallow soils with hardpan

Table 2. Summary of grower interviews for common rotation crops comparing profitability level, production costs, markets, soil tolerance, equipment, water usage, and rotation benefits. Assumption is that rice is water seeded.

	Tomato	Sunflower	Vine seed	Cucurbits	Beans (summer)	Corn	Safflower	Wheat	Oats	Rye	Barley	Vetch	Alfalfa
Season	Summer							Winter					Perennial
Equipment [a] (Irrigation) [b]	D (D or F)	D (L)	D (D or F)	D (D or F)	D (L)	D (F)	DP (L)	DP (F or FL)	DP (L)	DP (FL)	DP (FL)	P (N)	D (H)
Profitability [c] (Production costs) [d]	H (H)	H (H)	H (H)	H (H)	L (L)	L (L)	L (L)	L (L)	L (L)	L (L)	L (L)	L (L)	L (L)
Markets [e] (Contract) [f]	R (Y)	L (Y)	L (Y)	L (Y)	L (Y)	A (N)	A (N)	A (N)	A (N)	A (N)	A (N)	A (N)	A (N)
Soil Tolerance	Perception can't tolerate rice soils	May tolerate heavier soils	Prefers well drained soils	Prefers well drained soils	Prefers well drained soils	Prefers well drained soils	May tolerate heavier soils	Growers report poor yields and flooding in rice soils	May tolerate heavier soils	May tolerate heavier soils	May tolerate heavier soils	May tolerate heavier soils	None noted
Rotation Benefits	Rice following tomato does well	Intermediate crop	None noted	Flexible planting date	Can be intermediate and flexible planting date	None noted	Intermediate crop	Tomato growers like to follow wheat.	Can be mixed with vetch or for forage	May do better in rice ground	May do better in rice ground	Provides N, breaks down rice straw, offers wildlife habitat	Reported high rice yields following alfalfa

[a] Equipment: D = Crop requires different harvester and planter, DP =Crop requires different planter, P = Crop can be seeded by plane

[b] Irrigation: D= Drip, F = Furrow, L= Low irrigation, FL =Flood tolerant, N = No irrigation required, H =High water user

[c] Profitability: H = High, L = Low

[d] Production costs: H = High, L =Low

[e] Markets: R = Regional, L =Limited, A = Accessible

[f] Contract: Y =Yes, N =N. This refers to the ability to contract out the crop to other farmers who grow them, usually the grower will enter into a crop share agreement

Table 3. Illustrative quotes from row crop rotation growers and their corresponding significance.

Quote	Significance
"Right now, our three main crops are tomatoes, sunflowers, and rice. But we mix in some garbanzo beans, and we have some vine seed but that's just little stuff. Oh, and we have corn, so corn is in there, we have been trying to raise less corn because of the price." -Grower from Sutter County	In regions where rotations occurred with different row crops, growers had flexible rotations informed by markets rather than strict sequences.
"Typically, I farm half of the fields and rent around half of the land every year. And those change based on the crop rotation. The other half is farmed by someone else. For crop rotation purposes we like to have a field or two of tomatoes every year. Since I don't farm tomatoes, we contract them out to tomato growers."-Grower from Colusa County	Many growers who didn't have the knowledge or equipment to grow some of the more logistically challenging, yet profitable crops like tomatoes, or sunflower, remarked that they would contract them out to other farmers, taking on a landlord role.
"Typically, nobody really wants to plant a crop into a field that was just in rice because it is usually in bad shape… These crops help to "open up the soil, and then the tomato farmers like coming in after that." - Grower from Sutter County	Despite these rotations being flexible, Sunflower and safflower were often used following rice as a transition crop from a semi-aquatic environment to a terrestrial one.
"Dry beans grow with the natural moisture… if we get enough rain and we work the ground right you don't have to irrigate at all. Even this year, because we didn't have rain, we pre irrigated [then we] didn't irrigate [after]." -Grower from Sutter County	In response to wet springs, some growers would choose to plant different dry beans. These crops often didn't need to be irrigated and could be planted later into the year.

Table 4. Illustrative quotes from growers describing cool-season rotations practiced in rice systems.

Description	Rotation
“What we do is grow organic rice one year, the next year after harvest, grind up the stubble, flood it and let the ducks in there all winter. The next spring flood it some more, get water grass to grow get all the weeds to grow then cut that off for hay. Then about the first of September disc everything up, relevel it getting it ready to plant rice again and plant rye grass and hopefully we can irrigate the rye grass up. The next spring, we make a cutting of that rye gras hay. So, the next spring we cut the rye down bale it and feed it to cows.” – Grower from Yuba County	Rice cattle-fallow-rye-rice
“We have rotated rice from irrigated pasture and vice versa.” ‘I have followed cattle, it’s awesome. I have come in and put rice fields in cattle pasture…the amount of nitrogen in the soil from [the] manure is all I can explain… I mean it’s just healthy. It’s crazy and I use a lot less nitrogen on it.”- Grower from Sutter County	Irrigated pasture-rice
“We do rice the first year, barley the second year, and then fallow, or dry beans the third year, and then back to rice. We have rice in for 1 year at a time. So, after we harvest the rice, we plant the barley around November, then following summer we harvest the barley, and prep the ground and it will either be fallowing, or it will be planted into dry beans the following spring. And then dry beans are harvested late July or August, then the ground is prepped for rice.” -Grower from Merced (Other) County	vinter barley-dry beans-rice
“We have certain ground that is in hay that will probably go into rice next year. That would typically start as alfalfa and then after three seasons or so we overseed it with orchard grass. We have a retail hay business, if we didn’t have that I don’t know if it would be worth it to get it at wholesale prices. It also keeps people busy…. you definitely saw a yield benefit…if you ever see the rice field the first three years after alfalfa, it’s just a nitrogen bomb.” -Grower from Sutter County	Hay/alfalfa-rice

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Chapter 2 Economic analysis of rice-based crop rotations in California

2.1 Abstract

As challenges related to climate change, weed pressures and other economic issues increase, crop rotation may become an important but challenging practice for California rice farmers who typically have continuous rice systems. This research assessed the economic barriers to adoption and potential for achieving profitability by comparing four common rotational crops in the context of California's Sacramento Valley tomato (*Solanum lycopersicum* L.) sunflower (*Helianthus annuus*), beans (*Phaseolus vulgaris*), safflower (*Carthamus tinctorius*) to rice (*Oryza sativa*). Using a combination of focus groups and Monte Carlo simulation methods we explore the range of economic components - profits, costs, and gross income (revenue)- that farmers can expect when rotating rice with these crops. We then tested multiple long-term (15-year) rotation scenarios with a combination of crops with i) high cost and revenue, ii) low-costs (rice, sunflower, tomato), and ii) low costs and revenue (rice, safflower, beans) and compared outcomes with continuous rice systems. Scenarios tested the hypothesis that rotations with rice can be profitable over the long term when accounting for benefits such as decreased inputs and increased rice yields, as well as under circumstanced of increased fallowing years due to water scarcity events.

Results: Economic barriers were crop-specific when considering annual costs and returns Investments in drip irrigation for tomato and low revenue concerns for beans and safflower are significant barriers for adopting these crops. Opportunity costs (time for finding markets and learning new systems) did affect profit in year one, while labor costs were higher for rotational

crops. However, all rotational crops, except tomato, had lower costs suggesting financial barriers are less of a concern than human resources and management considerations when switching out of rice into rotational crops. Long-term scenarios suggest that farmers are likely to succeed in profits when rotating over the long term, under the premise of rotational benefits and increasing water scarcity years.

However, there could be a substantial investment period for farmers between 6-12 years depending on investment considerations and opportunity costs, and fallowing events. This research shows evidence that if current trends continue to increase within the California rice sector, crop rotations would be an economically viable option and support farmers ability to adapt to changing environments.

2.2 Introduction

Flooded rice (*Oryza sativa* L.) provides food for over 50% of the population while conserving wetland ecosystems (Chen et al., 2012). Rice has shown the potential to maintain high yields after continuous cropping over long periods of time, unlike non-flooded cropping systems where monocropping can lower yields, degrade soils, and pollute the environment (Altieri, et al., 2009; Chen et al., 2012). However, there are a number of global pressures forcing rice systems to diversify including climate change and water scarcity issues, labor demand shifts and global events increasing agricultural costs of production (Siagian et al., 2019; Wassmann, 2019). In reaction, research has focused on the implications of diversifying rice systems across multiple sustainability lenses (Assefa et al., 2021; Banjara et al., 2022; Upadhaya et al., 2022). Crop rotations with rice systems, defined here as converting from a flooded rice field to a non-flooded cash crop and back, has shown a number of agronomic benefits such as reduced pest and disease pressure, improving certain soil health indicators, and increasing crop yield (Assefa et al., 2021; Huang et al., 2021; Macedo et al., 2022), all of which may increase profitability over time through a combination of savings and increased revenue.

Financial considerations are a dominant factor driving farmer decision-making (Carlisle, 2016; DeVincentis et al., 2020). Cost-benefit analyses can provide insights to help farmers make financial investments, assess risks of adopting new technologies, or describe under what circumstances new management practices may be more profitable (Alcon et al., 2021; Kuwornu et al., 2018; Newton et al., 2012). Furthermore, cost-benefit analyses are important to better understand barriers to adoption by viewing how different factors impact the costs of production as well as crop yields and associated revenue, both of which drive overall profitability. For example, DeVincentis et al. (2020) found that profitability for integrating winter cover crops in California specialty crops was dependent on a number of factors including irrigation savings, access to financial subsidies and severity of climate change impacts on the cash crop yield. Switching between a flooded environment for irrigated rice to a non-flooded crop brings even more uncertainty for profit outcomes. Rotation crops may produce higher returns, but often require higher costs for changes in equipment, land preparation, and irrigation which may not necessarily lead to an increase in profit. 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 has mainly focused on tropical and sub-tropical climates, where a second crop is planted in the fallow season, without replacing the rice crop (Assefa et al., 2021; Banjara et al., 2022; Huang et al., 2021; Upadhaya et al., 2022). Less research has assessed the economic impacts of replacing rice in the summer months with an alternative row crop. In temperate regions of the United States, rice is grown as a summer crop with the primary production occurring in Arkansas, Louisiana, and California. Research on crop rotations with rice in the United States often comes from a pest management perspective, or with respect to the impact rice has on the non-flooded crop (Carroll et al., 2020; Pardo et al., 2021). There has been no research to our knowledge that has investigated the economic impacts of switching from a continuous rice system to a rice-based rotation including several years of rice followed by several years of non-flooded summer crops.

Often economic studies in agriculture assess a single profit outcome without exploring how profits may change over time (Feng et al., 2021; Huang et al., 2021; Macedo et al., 2022; E. G. Smith et al., 2013). The sequence of different crops grown in rotation over the long-term can be modeled using a Net Present Value analysis (NPV) to determine profitability over time. For example, DeVincentis et al. (2020) found that farmers 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 (Cai et al., 2019; Carroll et al., 2020; Chen, 2022; Fang et al., 2021; Smith et al., 2013; Zhou et al., 2023). While additional costs can disincentivize farmers, in the long-term these rotations can increase economic resilience and profit due to diversification benefits. However, while many studies using a cost benefit analysis (CBA) focus on indirect benefits such as input saving from increased soil nutrients, rarely do they focus on indirect costs related to gaining knowledge and skills or building relationships to access markets. In the absence of experience, farmers need to sacrifice time spent learning a new system, rather than spending that time generating income elsewhere (Chen, 2022; Kuwornu et al., 2018; Lien, 2003). 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.

Moreover, traditionally CBA's do not consider financial uncertainty There is often uncertainty in many operational costs on farms, such as crop yield, irrigation, and input requirements. Sensitivity analysis can help illustrate the relative importance of different assumptions but cannot quantify the likelihood of outcomes due to economic uncertainty (Chen, 2022). Probabilistic economic analysis, such as Monte Carlo analysis, can be a way to assess risk of financial decisions based on many changing variables, providing a distribution of outcomes (Chen N., 2022; Johansen, 2010; Mahdiyar et al, 2016). Few agricultural studies have used a Monte Carlo analysis to simulate this change and assess the risk of different agricultural systems based on variable outcomes (Asci et al, 2014; Chen, 2022; Mahdiyar et al, 2016; Gryze et al., 2010).

California produces rice on approximately 212,000 ha annually (NASS USDA, 2023), with roughly 95% of this grown in the Sacramento Valley (Geisseler & Horwath, 2016). Recent challenges relating to water scarcity, herbicide resistance, and increasing input prices are threatening profitability by reducing crop yields and increasing the costs of production. As an example, rice acreage planted has reduced significantly across the state (2014 -15%, 2015 -18%, 2021 -22%, 2022 – 50%) mostly due to reductions in water availability via surface water (California Rice Commission, 2022, NASS USDA 2023). During 2022, the extent of fallowed land corresponded to a revenue loss of about $500 million, much of which was covered by crop insurance (Smith, 2022). As climate change and water scarcity remain a challenge for California, rice farmers may need to grow other crops to maintain production. While information on average water use of crops in California vary, focus groups with rice farmers found that some of the common rotational crops are known for their minimal water requirements, such as safflower and sunflower, which require on average 0.123 - 0.308 ha/m^2 (1-1.5 acre/ft) of water compared to 0.617 ha/m^2 (5 acre/ft) for rice (Supplementary material). Recent interviews with farmers suggest that rotations can increase profitability by diversifying the portfolio of crops grown, while decreasing input costs for weed control and increasing rice yields (Rosenberg et al., 2022). However, at the same time, other farmers questioned the feasibility of rotations due to high clay soils and lack of equipment and markets, making rotations less profitable than continuous rice (Rosenberg et al., 2022).

Little financial information exists to support our understanding of the economic risks for rice-based crop rotations and how economic components and rotational benefits may affect long term profitability and farmer decisions. That we know of, no research has focused on crop rotations with rice systems in the context of California. In this study we assessed the profitability of two rice- based rotations compared to continuous rice, with the two rotations representing either a combination of a high-revenue, low-cost crops or low-revenue, low-cost crops to explore a wide range of possibilities. 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 combinations of cost and revenue, and 3) How water scarcity scenarios (represented in the form of fallowing events) and farmers-reported benefits of rotation such as input savings and increased yields may influence profit. We hypothesized that 1) Certain 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 2) Rotations can be more profitable than continuous rice in the long-term when accounting for rotational benefits and water scarcity.

2.3 Materials and Methods

To achieve our objectives this research had two research stages. First, we discerned what the labor demand and human resources, equipment, and management requirements were needed to switch out of rice into four major rotational crops and quantified their associated costs and benefits. Second, we simulated the profitability of five long-term (15 years) rotation scenarios comparing two rice-based rotations to continuous rice as well as a scenario where rice is fallowed for 2 out of 15 of those years using Monte Carlo analysis.

2.4 Data collection

This research integrated focus groups, statewide cost studies from the University of California (Agriculture & Resource Economics UC DAVIS, 2023), and farmer-provided partial budgets for developing our data set in order to accurately capture the variability in cost and revenue outcomes.

Focus groups

Data collection for economic analysis often includes historical data, published work, collected expense reports, whole farm budget reports based on example farms, or the use of surveys (Alcon et al., 2021; Evans et al, 2000). Less often used in economic studies are focus groups, where an organized meeting is held with selected individuals for their representative knowledge. Focus groups can be a way to explore different community experiences (Yayeh, 2021). The four rotational crops considered in this analysis were tomato, sunflower, safflower, and beans. These crops are currently used in rice-based rotations in the region and were selected as feasible options based on farmer interviews (Rosenberg et al., 2022). We developed a farm budget for each crop as a foundation for discussions (Supplementary Material Tables 1-5). Focus groups were organized to learn what the associated costs of production were for switching out of rice into each 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. Focus group questions covered the following topics: Opportunity cost of time for the new cropping system requirements and marketing, labor and equipment, overall profitability and input savings, irrigation requirements, land leasing scenarios, rotation sequences and others (Supplemental Material 15-17). Each focus group lasted between 1-2 hours. 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 from each question posed. As an example, Table 1 summarizes the information from the focus group on tomato and their correlating topics.

Partial budget development

Comprehensive crop budgets were developed including costs of production and revenue. We used both average values and ranges (high/low), with different assumed distributions (further discussed under *Monte Carlo Simulation*) for each variable in each crop budget, to capture the full range of outcomes. Sources were comprised of University of California cost of production studies, partial budgets from farmers, and focus group data (Agriculture & Resource Economics UC DAVIS, 2023). There were nine categories of production costs related to opportunity cost, seed, equipment, field reconstruction (for transitioning out of and into rice), labor, inputs, harvest, irrigation, extra expenses, and rent. Revenue was calculated based on county yields and average crop prices (USDA/NASS,2023).

2.5 Model construction

We modeled our rotation sequences based on common practices in the region (Rosenberg et al 2022). Rotation decisions are affected by markets, changing input costs, and availability of resources. Therefore, rice-based rotations in California are diverse and flexible, with the potential of including both high and low revenue crops. For example, farmers who can integrate drip irrigation, generally focus on high revenue crops like tomatoes and sunflower. Less used, but easier to rotate into are low revenue crops such as beans and safflower. It is common for rice-based rotations to include up to 5 years of rice before rotating to other crops (Rosenberg et al., 2022). However, it should be noted that rotation types can vary widely. In some cases, rice is grown only once in every 5 years (Salvato et al., 2024; Rosenberg et al., 2022). We evaluated the long-term profitability of two rice-based rotations compared to continuous rice over 15 years (Table 2). The comparison for the region is continuous rice (RRR), which is considered the control for this study. Each rotation included two cycles of shifting out of rice into non-flooded crops and then back into rice - a rotation with sunflower and tomato (RSTT) and one with safflower and beans (RSBB) (Table 2). Fifteen years was chosen to simulate two full rotation cycles to assess the effect of transitioning in and out of rice and allow enough time to see if and when profitability is realized (Table 2). From the rotational sequence (Table 2), year 2 and 3 include year-one costs for rotational crops. These years have extra costs associated with opportunity costs for all rotation crops and sub-surface drip irrigation investments for tomato (Figure 3 A). Years 4, 9, 10, and 11 are considered 'normal' years for rotational crops and do not include opportunity cost or investments. Years 5, 8, 12 and 15 are transitioning years into or out of rice and contain transitioning costs. Year 6, 7, 13 and 14 are 'normal' rice years and do not include transitional costs

2.6 Rotation benefits and climate impact scenarios

We explored an additional scenario for all three systems related to rice benefits and water scarcity: RRR was assumed to experience two years of fallowing due to water scarcity (RRF). RSTT and RSBB both were assumed to experience a 10% rice yield benefit and a 50% reduced herbicide costs (RSTT-benefit, RSBB-benefit). Focus groups helped to quantify these benefits and specified that they occur mostly in the first 2 years of returning to rice from the rotation. (Supplemental Material Tables 16-18). In these scenarios, rotation benefits and climatic impacts assumed that rice yield would increase during years 5, 6, 12, and 13, and input costs for herbicides would decrease by half for those same years. Fallow years were represented by no costs and no revenue for two years of rice out of 15 in years 2 and 15, assuming that farmers received insurance coverage for preventative planting during years when water allocation is 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% (USDA/NASS 2023).

To assess profit across time, Net Present Value (NPV) projects all of future cash flows for a CBA. NPV uses a discount rate to account for the time value of money.

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

Where NPV is Net Present Value, P is revenue minus costs, t is time of cashflow (year), and i is the discount rate. A discount rate of 0.02 was used based on the average interest rate over 20 years from Federal Reserve historic data (FRED, 2023) Any costs taken from historic UCANR cost studies were also adjusted for inflation (US Inflation Calculator, 2023).

2.7 **Monte Carlo simulation**

A Monte Carlo approach takes a simulation and introduces uncertainty by repeating it with randomly sampled values for input variables based on set parameters (Chen, 2022; Johansen, 2010; Martínez-Paz et al., 2014). In this study, parameter values were set as either normal distributions, uniform distributions, or skewed distributions. The majority of the variables with unknown values had their parameter distributions set to normal because it was assumed that it was more probable the value lied closer to the mean (Chen N., 2022). However, from focus groups certain values, such as revenue, were set skewed based on qualitative data, such as, in common heavy clay rice soils, farmers often will experience lower yields for row crops. Uniform distributions were set for opportunity costs.

A budget for each crop presents all the costs and revenue occurring over one year (annual budget) at an acre scale. The cash flow, or NPV, is each annual budget called over a period of 15 years. The CBA then is one simulation of the 15-year cash flow. The monte Carlo then runs this simulation 1,000 times, which means calling the annual budgets 15,000 times. During each run a value is randomly picked from each unknown variable within the set distribution and used to calculate the CBA (Chen N., 2022; Almansa & Martínez-Paz, 2010) (Supplemental information A). In this study we ran the simulation 1000 times in order to have a representative sample across all possible combinations of values. All model development was done using R-studio (R development Core Team, version 2023).

2.8 Individual crop analysis for a 'normal' year and year-one

Individual crop budgets were run under the Monte Carlo parameters to attain distributions of total cost, revenue, and profit for an "normal" year in the rotation. A 'normal' year does not include costs from initial investments from year one for the farmers' time (opportunity cost), irrigation infrastructure, and rice transitioning costs (Figure 1 A). We then replicated the Monte Carlo with these extra costs assumed under a year one-transitioning scenario (Table 2) (Figure 1 B). First, we describe the mean values as well as the 25% 50 % and 75 % quartiles to show the likely ranges of these economic components for each crop based on the distribution outcomes (Figure 1 A, Supplementary Material table 6-9). Then, we compare cost and profit which include extra costs (Figure 1 B, Supplementary Material Tables 10-12). Next, we present all costs by category, including extra costs, for each rotational crop and compare these categories to rice (Figure 2, Supplementary Material Tables 13-14). All units are in US $/ac unless otherwise noted.

Results

2.9 Cost, revenue, and profit for a 'normal' year

In this study, rice is the baseline for comparison. Presented below are the mean values for each economic component (cost revenue and profit) for each crop of the rotation, along with the Monte Carlo created quartile ranges for each crop, starting with rice (Figure 1A). These mean values and the quartile ranges can be seen as what growers would expect to experience in a normal year, and do not include year one investments or transitional costs. In an 'normal' year rice profits, revenue, and costs came to \$113, \$1,797, and \$1,684, respectively (Figure 1 A). The Monte Carlo distribution suggests that roughly half (quartile ranges) of rice farmers may observe anywhere between \$35 and \$194 in profit for rice, with revenue ranges between \$1,693 and \$1,852 and cost ranges between \$1,693 and \$1,852 (Supplementary Material table 6-9).

When comparing profit of the rotational crops to rice, results show, in order of most profitable crop to least, tomatoes > sunflower > beans > rice > safflower (Figure 1 A). In a 'normal' year tomato profits were \$567 for tomato, though quartile ranges anywhere between, \$269 and \$850 in profits. Sunflower profit came to \$472, with a quartile range between \$353 and \$590. Beans and safflower average profit was \$131 and \$-56 respectively, with ranges between \$-46 and \$273 for beans, and \$-102 and \$-12 for safflower. Costs are highest in tomato (\$3,251), with ranges between \$3180 and \$3359; followed by beans (\$1,175), with ranges between \$1142 and \$1211; then sunflower (\$1,076), ranging between \$1035 and \$1119 and finally safflower (\$581), with ranges between \$547 and \$614 (Supplementary Material Table 6-9).

2.10 Cost and profit with year-one and transitional costs

Above describes economic components of each crop without additional year one costs. Below reviews these components adding in these extra costs (Figure 1 B). Adding in extra costs, including irrigation investments, opportunity costs, and field reconstruction costs, affects crop profit (Figure 1 B, Supplementary Tables 10-12). Rice, due to extra costs for switching in and out, drops to a profit of $80 and roughly half of farmers may observe anywhere between $-1 and $164. Costs increased to $1717 and a range of $1712 and $1720, suggesting an average increase of only $33 (Supplementary Tables 10-12). Overall costs are lower for each rotational crop (except for tomato) compared to rice (Figure 1A and B).

When comparing profit of the rotational crops which include extra costs, results are different than in a 'normal' year. In order of most profitable crop to least, sunflower > rice> beans > safflower > tomato (Figure 1 B). Sunflower profits during year-one is $150 (range between $6 and $296), with costs coming to $1402, an increase of $326. Beans profit during year-one came to $-112 (range $-300 and $45) with costs coming to $1492, an increase of $254. Safflower profit during year-one came to $-205 (range $-252 and $-160), with costs coming to $731, an increase of $150. Tomato profit was $-1384 (range between $-1713 and $-1098) and costs came to $5228, an increase of almost $2,000 (Supplementary Tables 10-12).

2.11 Cost categories including year-one and rice transitioning costs

Here we show a breakdown of individual cost categories and how they contribute to total costs and how this compared to rice (Figure 2, Supplementary Material 13-14). Cost categories include opportunity costs, seed, straw management, equipment, labor, inputs, harvest irrigation, extra expenses, and rent (Figure 2). For rice, the largest costs are inputs which consist of 33 % of total costs ($497). Rent is a second substantial category for rice ($475 or 31%). Rice irrigation costs are only 14% of total costs ($206). Rice equipment costs are 10% for rice ($213). Labor costs are only 3% for rice ($43). Finally straw management 5% ($75). Extra costs for switching in and out of rice are included in straw management costs (Supplementary Material Table 5).

Input costs for rice are only exceeded by tomato ($685) although this comprises a smaller fraction of tomatoes total cost (13%). Inputs are lower for all other crops, and also comprise of a lower fraction of rotational crops total costs. Sunflower has inputs comprising 28%, corresponding to $392. Beans and safflower inputs are $235 and $118 corresponding to 16%. Comparing rent category, again tomato is the only crop with higher rent compared to rice, but it comprises of a smaller fraction of tomato total cost (13% or $680). For all other crops rent is lower than rice, and a smaller fraction of their costs 19% for sunflower ($273), 12% for beans ($174), and 12 % for safflower ($90).

However, irrigation costs for tomato, including year-one investments is 43% of total costs, compared to rice which is only 14% of total costs. The majority of tomato irrigation costs are materials for pump installment, on average costing $1,750 for installment and material (Table 1). Beans also has higher irrigation costs then rice ($308) and comprises 21 % of total costs. Sunflower and safflower have substantially lower irrigation costs compared to rice ($185 and $162 respectively). Safflower has such low total costs that irrigation still comprises a large percentage (22%), while for sunflower irrigation is only 13% of total costs.

Equipment costs are less for all crops compared to rice. Equipment costs for sunflower and tomatoes are $140 which is 10% and 3% of their total costs respectively. For both beans and safflower equipment represents 18% of costs ($134). Equipment costs are substantially lower in this context because the assumption is rice farmers will contract tractor work out to others (Supplementary Material 13-14).

Compared to rice, labor costs are much higher for tomato ($213 or 4%) and beans ($120, 8%) but lower for both sunflower and safflower. Sunflowers' labor costs are only (25$, at 2%) and safflower labor costs are only 6% of total costs ($43). While these values seem low, Sunflower in California is grown for seed and marketed through contracts with seed companies, who often will be responsible for sharing certain labor cost (Agriculture & Resource Economics UC DAVIS, 2023). In addition, rotation crops have an opportunity cost of transitioning, up to 23% of sunflowers total costs, translating to $323. Opportunity cost is 16 % for beans ($227), 14% for safflower ($100) and 6% for tomato ($326) (Supplementary Material 13-14).

2.12 Long term models and scenarios

The first scenario presents NPV for our baseline scenario, represented by RRR (continuous rice) compared to RSTT (sunflower and tomato rotation without benefits) and RSBB (safflower and beans without benefits), evaluated over 15 years (Figure 3 A). When representing NPV each year, we see that some years are positive and some negative (Figure 3 A). RSTT shows a substantial drop in profit due to investment costs during year 2 and 3 ($ -1,340) (Figure 3 A). RSBB rotation leads to drop in profits until year 4 due to opportunity costs and then again during years 8-10 due to low revenue (Figure 3 A).

The second scenario presents the cumulative NPV for the three baseline scenarios (RRR, RSTT and RSBB) (Figure 3 B). The cumulative 15-year average for RRR was $1,516 (Supplementary Material Table 15). In RSTT, both tomato and sunflower receive higher average profit than rice during the years they are in rotation and therefore over time this rotation becomes more profitable than rice which leads to a cumulative NPV of $1,581 (Figure 3 B). RSTT exceeds RRR by $65, and profit is not achieved until year 12 (Figure 3 B). In RSBB, beans are as or slightly more profitable than rice by about $20 (Figure 1 A), but safflower has a loss of $-56, which is 169$ less than rice (Figure 1 A), therefore, the combination of added opportunity costs in years 2-4 (Figure 3 A) and the low profit returns by safflower causes RSBB to never achieve more net profits than rice by year 15, with a cumulative NPV of only $852 (Figure 3 B, Supplementary Material Table 15).

The third scenario includes two years of fallowing brought on by water scarcity years for the continuous rice model (RRF) (Figure 3 C). RRF presented with a cumulative NPV of $1,301 (Supplementary Material Table 15), which is a loss of about $215 over 15 years, compared to RRR. With the added two years of fallowing, RSTT become more profitable between 10 and 11 years rather than 12, but RSBB remains less profitable.

A fourth scenario compares rotations with assumed benefits (RSTT- benefit and RSBB-benefit) to RRR (Figure 3 D). Assumed benefits include a 10% increase in rice yields in the first two years returning to rice along with a 50% decrease in herbicide inputs. RSTT-benefit has a cumulative NPV of $2535 by year 15 (Supplementary Material Table 15). RSTT-benefit exceeds

RRR by $1,019 and profits were also achieved between years 9 and 10 rather than year 12. RSBB-benefit has a cumulative NPV of $1,833 (Supplementary Material Table 15). RSBB-benefit exceeds RRR by $317 and profit is achieved between years 11 and 12.

In the fifth scenario, we compare RSTT-benefit and RSBB-benefit to RRF (Figure 3 E). RSTT-benefit exceeds RRF by $1,234 and profit is achieved between year 8 and 9. RSBB-benefit exceeds RRF by $532 by year 15 and profit is achieved between year 6 and 7.

2.13 Risk assessment for achieving profits higher than continuous rice

We can assume roughly half of farmers (50%) would achieve NPV at or above $1516 and $1301 for RRR and RRF respectively (Figure 4) by the end of 15 years. Comparing NPV outcomes, we evaluated the likelihood of being at or above these amounts for the other rotation scenarios (Figure 4). Based on our simulations, there is about a 15 % chance for RSBB to be above RRF and about a 10% chance of being above RRR. RSTT on its own shows a 65% chance of being more profitable than RRF and about a 55% chance of being as profitable as RRR. RSBB-benefit is between 80 and 85% chance of being more profitable then RRF and about 70% chance of being more profitable than RRR. RSTT-benefit is 95% likely to be more profitable then RRF and more than 90 % likelihood of being more profitable than RRR.

Discussion

2.14 Are economic components barriers for adopting rotational crops for rice farmers?

We find that economics is a barrier for rotational crops in different ways for different crops.

While low revenue is a barrier for adopting beans and safflower, financial requirements of investing in irrigation is a barrier for tomatoes. Our results provide a better understanding of the major cost components, as well as revenue and profitability ranges for switching over to tomato, sunflower, safflower, and beans in a rice-based rotation in California (Figure 1 and 2). Rice on its own showed relatively low costs of production and a moderate revenue compared to the other crops, tending to the middle in profits (Figure 1A). In 'normal' years, sunflower and tomato exceed rice profits by $464 and $359 respectively, while beans barely exceeding rice with a large variation ($-43 and $273), suggesting higher risk factors for farmers to adopt beans (Figure 1 A). Safflower presents with a constant loss in profit compared to rice suggesting farmers are not going to achieve direct economic benefits from safflower.

Furthermore, when accounting for opportunity costs and irrigation investments, rice profits moved up in relative profitability, exceeded only by sunflower (Figure 1 B). Changes in production practices when switching between rice and a rotational crop, and their associated costs provide insight into how economics acts as a barrier for adoption of rotational crops. We hypothesized that higher financial requirements for equipment, labor, irrigation investments and opportunity cost, would impact profitability outcomes. However, results were more complex, and crop dependent. 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 substantial in this study, and are not a major barrier (Figure 2, Supplemental Material Tables 13-14). Realistically, certain regions may have access to contract workers more than others, and therefore geographical barriers may exist for these needs.

Labor was higher for both tomato and beans ($213 and $120 respectively), relative to rice ($43) (Figure 2). These extra labor costs are mostly due to a higher pre-plant land preparation and manual hoe labor requirements (Supplemental Material Tables 16-18). An extra $33 for labor was required in the form of land deconstruction and field leveling when switching out of or into rice (Figure 2, Supplementary Material Table 5). Furthermore, irrigation labor was higher for rotational crops due to the higher labor demand for constructing and maintaining furrow wells and maintaining drip lines (Figure 4, Supplementary Material Table 5). 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 (Carlisle et al., 2019; Sánchez et al., 2022). Importantly, while categorically costs for labor were higher for rotational crops compared to rice, total costs remained lower for most crops, except tomato, suggesting that financial requirements are not as much of a barrier as the human resources and time management requirements (Calo & Master, 2016; Carlisle et al., 2022; Esquivel et al., 2021).

Irrigation costs were a substantial financial investment impacting profitability. We found that 43% of tomato costs were irrigation costs, the majority of which are materials for pump installment, on average costing $1,750 for installment and materials (Figure 2). Koech et al. (2021) found, similar to our results, that financial constraints are major barriers for investing in irrigation technologies. For these reasons, 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 of time, which may also disincentive rice farmers. However, safflower and sunflower both had a lower overall irrigation cost than rice. These crops are also known to have very low water requirements, making them a viable option during reduced water years (Peterson, C. et al., 2023; Long et al., 2019).

We hypothesized that opportunity costs would have an impact on farmers' decisions to invest in time spent learning and finding markets. Sunflowers presented with highest opportunity costs relative to total costs (23%, or $327) (Figure 2), mostly due to the challenges farmers would have finding markets and contracts each season (Supplementary Material Tables 16-18). Tomato had a high opportunity cost as well at $326, though this was a relatively low percentage of its total costs (Supplementary Material Table 14). The opportunity cost for tomato was mostly due to the time it takes to learn how to manage drip irrigation (Table 1). Based on focus group outcomes, we assumed most of the labor for tomato, sunflower, and beans, including drip placement, planting, and harvesting, was contracted out to companies or neighbors (Supplementary Material Tables 16-18). Therefore, without these contracting agreements, both tomato and sunflower would have a significantly higher than estimated opportunity cost. Carlisle et al. (2019) discusses a 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 research suggests for conventional systems, there may be opportunities to increase contracting agreements to reduce the need for learning new systems, which may reduce economic barriers.

However, the reality of market access is complex in the region of study. Market contracts are limited for sunflower and beans due to limitations in consumer demand. In terms of sunflowers, the limited market is also because California produces seed, rather than oil. There is also a geographical component to how contracts with seed buyers are decerned. There is a minimum distance that fields have to be apart from one another in order to reduce cross-pollination. All of these issues make market accessibility in Sacramento Valley region of California complex, and this reduces farmers abilities to diversify.

Environmental constraints such as soil limitations have been cited as negatively impacting yields of rotational crops in rice fields (Rosenberg et al., 2022; Salvato et al., 2023). Therefore, we hypothesized that a likelihood of lower yields with rotational crops would negatively affect profits of rotations. We accounted for these effects in our yield estimates by skewing our revenue distributions low for each rotation crop. Salvato et al., 2023 determined only 11% of the continuous rice area has soil properties that are conducive for rotational crops. Our research modeled the probability for lower yields by providing a range from low revenue to high revenue and skewing revenue low. An important finding of our research is that the lower quartile of the profit distributions for tomato and sunflower can be more profitable than average profit for rice (Figure 1). In other words, combinations of high costs and low yields in these other crops may still perform as well or better than continuous rice systems. While further research should investigate the yield gaps when growing alternative crops in rice soils, these findings further illustrate that human resources and investment costs may be more of a limitation for integrating rotations in rice environments than revenue concerns with tomato and sunflower. The low revenue from beans does have the potential to affect profit. The 25% quartile showed profit as $-46, despite having lower overall costs of production compared to rice (Figure 1, Supplemental Material Tables 7-9). Safflower is always less profitable than, despite having much lower costs of production, suggesting revenue is an important barrier for safflower as well (Figure 1).

2.15 Long-term profitability of rice-based rotations

Our long-term analysis shows how profit fluctuates over time, with and without rotational benefits, and the likelihood of achieving those profits due to variability in costs and returns. Information such as this is crucial for understanding and motivating grower decision making. By displaying profit annually (Figure 3 A), we provide a more accurate financial summary for farmers. Presenting these financial fluctuations is important for determining risk factors during years where farmers may have reduced annual income (Bradfield et al., 2023; Harwood et al., 1999; Miller et al., 2004). Furthermore, this research provides more information on the time it would take for a farmer to achieve profits by viewing cumulative NPV, information which may support farmers' ability to make investment decisions.

While an annual budget between different crops can summarize economic strengths and weaknesses (such as higher revenue and lower profits during a 'normal' year), comparing different cropping sequences and their corresponding cash flows over time is necessary to understand how early year investment costs may affect overall profits. An annual sequence shows which years produce net returns or losses (Figure 3 A), but cumulative NPV over the different sequences of crops shows when they match or exceed profits for continuous rice. From the rotational sequence (Table 2), years 2 and 3 represent a year-one transition into rotational crops. These years have extra costs associated with opportunity costs for all crops and sub-surface drip irrigation investments for tomatoes (Figure 3 A). These years substantially influence profit outcomes rather than just accounting for each crop budget during an 'normal' year. Only RSTT became more profitable than RRR without benefits but both systems are more profitable with benefits after 9-12 years. With assumed fallowing years (RRF) RSBB-benefit actually matched RRF profits after 6 years, despite the reduced revenue stream from the safflower and opportunity costs associated in years 2 and 3. RSTT-benefit takes about 9 years to match RRF due to the higher investments (Figure 3 E).

RSTT was more profitable than RRR by year 12, without any assumed benefits, suggesting rotations with tomato and sunflower can be a viable rotation decision for farmers who have the ability to invest over that time frame. Although RSBB rotational crops have a much lower investment cost, RSBB reduced profits by $664 compared to RRR by year 15 (Figure 3 B). Therefore, high-revenue crops like tomato and sunflower are critical for increasing the profit potential of rice-based rotations under baseline scenarios. These estimates are conservative because we incorporated opportunity costs and assumed a lower average yield for rotation crops when grown in rice fields, thus farmers may still achieve profit with RSBB under different conditions.

Furthermore, the long-term analysis allowed us to model how rotational benefits, in the form of rice yield increases (by 10%) and input savings (50% reduction in herbicide costs), may affect profit outcomes (Feng et al., 2021). In our simulations, RSTT exceeds RRR by $65 and RRF by $280 in year 15, but RSTT-benefit exceeds RRR by $1019 and RFF by 1234 in year 15 (Figure 3 B and E). With these assumed benefits, rice farmers could double income over long term and decrease investment constraints by integrating tomato and sunflower into rotations. These assumptions should be further explored through on-arm research yet other studies provide evidence for these benefits. For example, White et al., 2020 found that rice farmers in Peru achieved higher yields and lower inputs, resulting in improved profits. Zhou et al., 2023 found that, crop rotation intensification practices increased rice yield by at most 4.6% while Feng et al., 2021 found crop rotations with rape seed increased rice yield by 20%. For the other rotation, RSBB-benefit exceeds RRR by $317 and RRF by $532 in year 15 but some profit is achieved by year 6 when fallowing occurs, due to the lower financial investments. While in the long term RSTT is more profitable, RSBB-benefit is a more feasible option and still presents as being substantially more profitable then RRR and RRF. Zabala et al., 2023 found that crop choice rather than crop diversification practice was more important for economic impact. Our results disagree with this finding and suggest that profit is more dependent on the agronomic benefits produced by diversification (Bowles et al., 2020; Davis et al., 2012; Lin, 2011; Upadhaya et al., 2022; Zhou et al., 2023).

By exploring the probability of profit, using the Monte Carlo approach, we have a better understanding of the risk management farmers are facing when deciding to rotate. Under the presumption that there are a couple of years of fallowing, RSTT-benefit and RSBB-benefit have a very high likelihood of being more profitable than rice (between 80-95%). However, without fallowing and without benefits, risk increases for rotations and RSTT is only a 55% or less chance of being as profitable as RRR, with RSBB showing only a 10% chance or less of being as profitable as RRR. These outcomes suggest that farmers are likely to succeed in profits when rotating over the long term, under the premise of rotational benefits and increasing water scarcity years. The risk is also dependent on the farmers ability to have reduced profits for anywhere between 6-12 years depending on the investment requirements and water scarcity events (Figure 3 E). The slow profit return is a disincentive for rotation, and it becomes understandable why continuous rice continues to be the dominant practice. These outcomes are similar to DeVincentis et al. (2020).

2.16 Implications for the California rice sector

Until now, we have had little data on the economic implications of crop rotations with rice in California, concerning changing climates and increased costs of production. An important finding of our research is that occasional fallowing does not substantially impact profit. Other research has concluded that fallowing can benefit rice crops by improving nitrogen availability (Olk et al., 2009), which was not modeled here. RRF presented with loss of about $200 in total over the full 15 years (Figure 3 D). Nonetheless, climate change modeling shows a 14% decrease in rice yields/ha by 2050 in California (Lee et al., 2011). A fraction of this loss may be recovered through rotating crops. Furthermore, irrigation for rice is from surface water that is dependent on seasonal snowfall. Predictions show a stark reduction in snowpack by 2060, suggesting that a 65% loss of the snowpack might occur by the end of the century in a high warming scenario (Pathak et al., 2018). Hrozencik & Aillery, (2021) acknowledge that measures that include continued shifts in area irrigated, increased irrigation efficiency through system upgrades, and changes in regional cropping patterns, are ways for increasing resilience under water supply scarcity.

Furthermore, rice currently has the greatest number of herbicide-resistant weeds than any other cropping system (UC Statewide IPM Program, 2023). Herbicide costs have gone from 135$/ac in 2015 to 205$/ac in 2021 (UCANR, 2023). The continuous cropping, with similar cultural management practices has led to an increase in the need for chemical herbicides. Crop rotations have been shown to reduce resistance and decrease weed density (Assefa et al., 2021; Altieri, M., 2009; UC Statewide IPM Program, 2023). Therefore, if inputs continue to increase cost of productions, this may drive rotations to become a realistic option for farmers in California to increase resilience (Muleke et al., 2023). Yet further questions arise with respect to the impact fallowing has on rice lands. Slavato et al (2024) shows that over last decade the amount of rice land in fallow has increased. If crop rotations do provide benefits to rice, then fallowing land may provide similar increases in rice yields and weed control. We did not account for this in our model, and the question should be posed, is better to leave this land fallow or try and grow another crop on it?

Conclusion

2.17 Research limitations and future directions

While our research shows certain profitability advantages with rotations compared to continuous rice in the long-term, there are other important factors that may be limiting the feasibility of crop rotations in rice environments. Beyond the economic barriers in the form of low revenues and investment costs, focus group findings from this study provided robust qualitative knowledge for socioeconomic factors affecting crop rotation adoption. Focus groups identified human resources, such as labor, time, and management requirements as key barriers, reinforcing findings from Rosenberg et. al (2022) and other research on rotations (Calo & Master, 2016; Carlisle et al., 2019, 2022; Esquivel et al., 2021). These factors could fall under the category of opportunity cost. Under our opportunity cost category, we accounted for time for learning the new system and finding markets. Further research may want to quantify other variables that fall under opportunity cost to expand on these factors. Furthermore, many of the crops considered have very limited markets and may require contracts and even if a farmer wanted to rotate, they may not be able to because of this limitation.

Despite the high probability for crop rotations to exceed rice profits over the long term with assumed benefits, a targeted approach for extension should be adopted to support farmers in a better position to rotate. While a targeted approach may not engage a large percentage of the rice sector of California it will be beneficial for niche communities which can have rippling effects for food system sustainability by building more resilient regional farms (Emery & Fey, 2006; Emery & Flora, 2006; McDaniel et al., 2021). Esquivel et al. (2021) found that factors that allow farms to choose diversification have more to do with secure land tenure, adequate access to capital and resources, and access to markets, factors found missing with continuous rice regions (Rosenberg et al. 2022). If crop rotations become a goal for the California rice sector to achieve resiliency, technical advisors should focus on increasing factors required for rotations to be successful in continuous rice regions.

This research acknowledges a few limitations and provides future research recommendations. Our research is meant to broadly estimate potential profit outcomes with rotations using secondary and qualitative evidence. Financial circumstances are different for every farmer and changes in important costs (irrigation), or revenue (crop yield or prices) would make rotations more or less feasible. A second limitation of this research is that we do not model all potential benefits rotations provide. In actuality, the input savings could reach beyond herbicides and also impact fertilizer and other input costs such as water, insecticides, and fungicides for both rice crops and non-flooded rotational crops (Bowles et al., 2020). In this case, the results presented here are on the conservative end of potential profit with rotations. Third, there are numerous crop sequences farmers could practice with respect to rotation, all of which could not be reproduced here. Our rotation models were concerned dominantly with rice production and less concerned with upland crops. Therefore, we developed rotations with longer years in rice (Rosenberg et al., 2022). Further research should look at other sequences that different crop mixtures as well as changing the number of years in rice and in rotational crops to see how this may affect profit. Also, while this research models yield as a component of revenue, we are limited in our understanding of yield gaps when introducing non-flooded crops in rice environments and further research should investigate these yield gaps. Finally, an important consideration for rotations with rice that are not accounted for in this study are the environmental consequences for crop rotations. The California rice industry highlights rice systems' other environmental services such as carbon sequestration and waterfowl habitat. Increased crop rotation will inevitably decrease waterfowl habitat and may decrease soil carbon stocks. Future research may want to assess how these ecosystem services are valued economically and factor this into our CBA model.

Figures

Figure 1. Profit, revenue and cost ranges and quartiles of individual crops. (n = 1000). Rotational crops include tomato, sunflower, beans, and safflower. A) Costs do not include extra costs to reconstruct rice fields when switching in and out of rice, opportunity costs of the rotational crops, or irrigation investments. B) Profit and cost changes when including extra costs to reconstruct rice fields when switching in and out of rice, opportunity costs of the rotational crops, or irrigation investments.

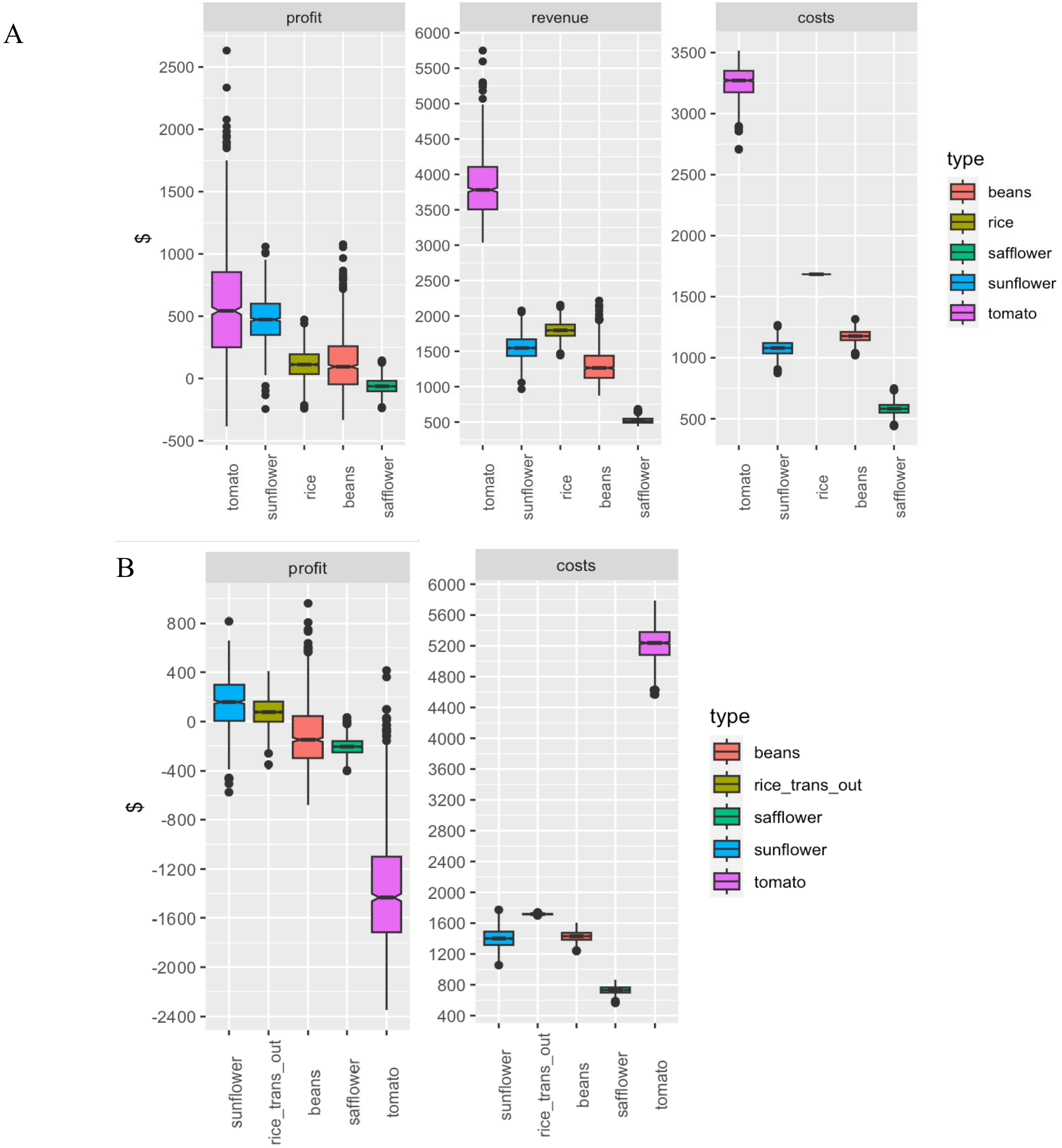


Figure 2. Breakdown of costs by each crop. Opportunity cost is only associated with year 1. Irrigation for tomato includes investment costs for drip, straw management costs include field work required to switch in and out of rice from the rotational crop. Seed for tomato includes greenhouse propagation cost, seedling cost, and transplant cost.

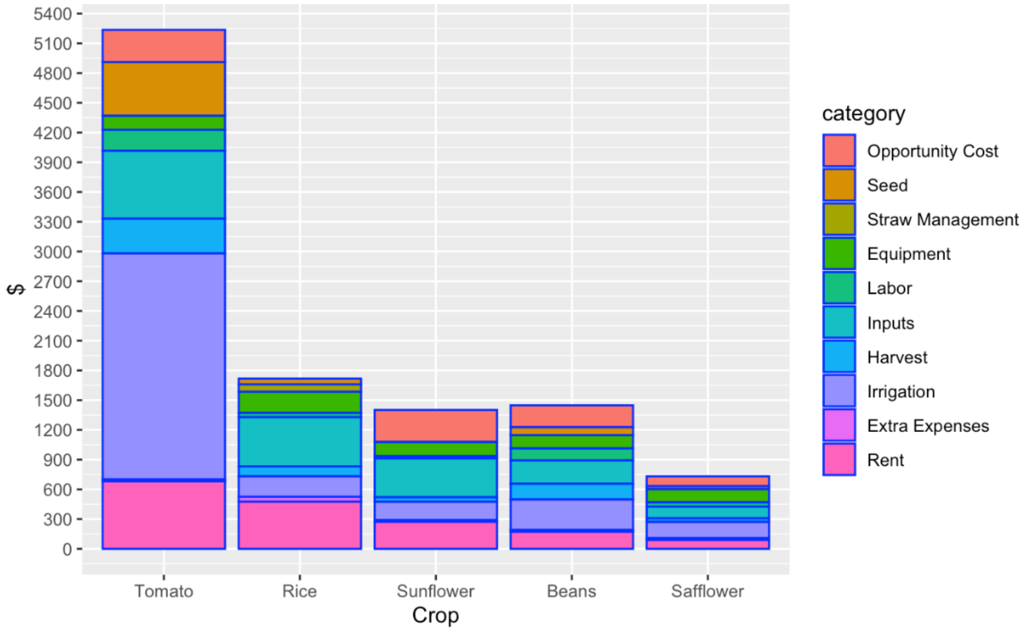


Figure 3. Average NPV over 15 years for six long term crop rotation scenarios. A) Annual NPV comparing three baseline models (RRR, RSBB, RSTT). B) Cumulative NPV comparing three baseline models. C) Cumulative NPV comparing Baseline rotations RSTT and RSBB to rice with fallow (RRF). D) Cumulative NPV comparing baseline continuous rice (RRR) to rotation scenarios with benefits (RSTT-benefit, RSBB- benefit). E) Cumulative NPV comparing rotations with benefit and rice with fallowing (RRF, RSTT-benefit, RSBB-benefit).

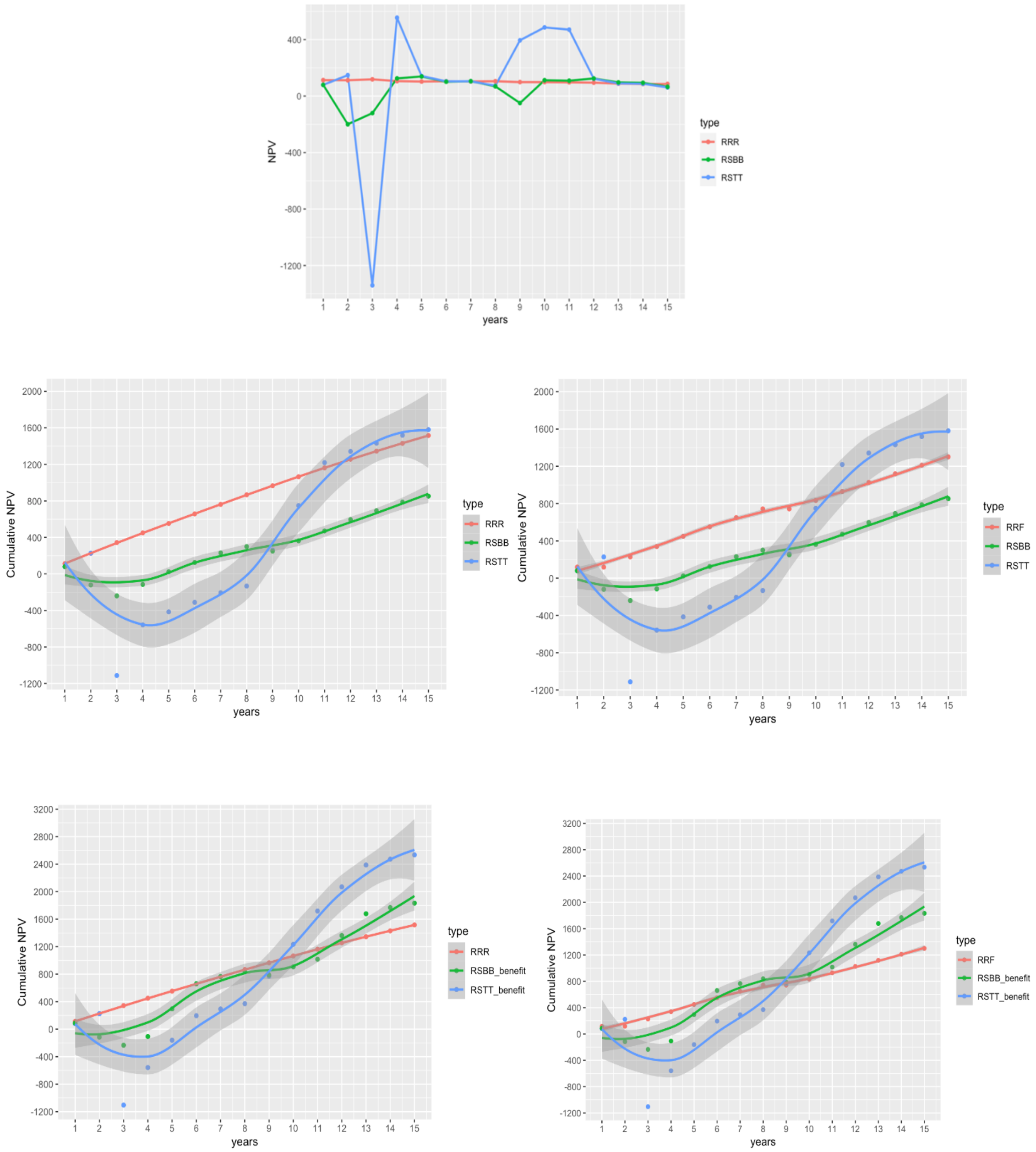
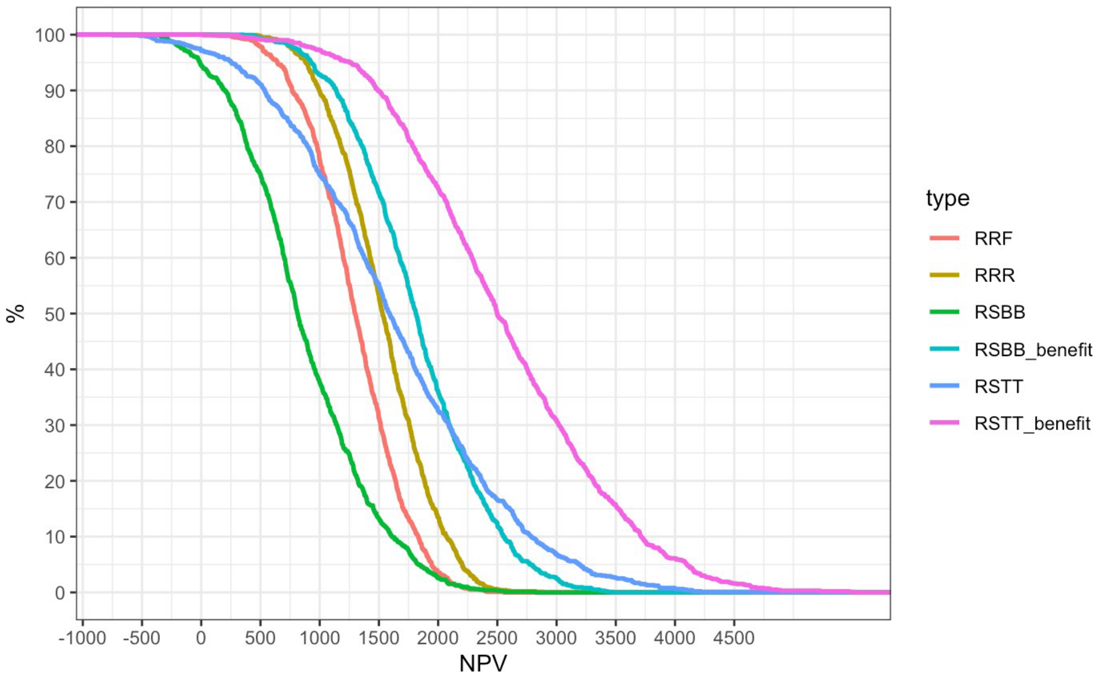


Figure 4. Probability of achieving above certain NPV of six crop rotation scenarios at the end of the 15-year period. NPV of RRF and RRR at 50 % considered points of comparison to assess profitability risk.



Tables

Table 1. Summarization of important results from focus group on tomato

Focus group findings	Topic
Tomatoes and sometimes sunflower are grown with drip irrigation, and this can be a large investment. Drip irrigation needs to be used for multiple years to get profit from it. Drip, filters, mainlines, pump-\$1500-2000/acre for installation/materials. \$144/acre for labor.	Irrigation requirements
Despite the investment, it's becoming easier to do tomatoes since canneries are looking for more farmers and there are no geographical limitations for growing tomatoes. So, finding markets is not difficult. The learning curve for rice farmers will be using the irrigation.	Opportunity cost
The equipment for tomato is completely different than rice, and the labor time overlaps with rice. Most of the work is contracted out to canneries. They will even put in the drip for you. Pay contracting company for the labor and seed (\$900-1000/acre). Hoeing crew \$125 per acre.	Labor and equipment
In general, the risk factor is much higher in tomato then in rice because there will be a lot of variability in tomatoes. Large swings and large investments. \$400-500/acre profit maybe more on average.	Yield variability profitability
When rotating back into rice from tomato herbicide investment are less. You can expect a 10-15% increase in rice yields. \$100/acre savings in herbicide cost.	Rotational benefits and input savings,
Landowners want as much money every year as possible; you are forced into what the landowner can do to maximize profit. Percentage (crop share): 10-15% range, 12% standard.	Land leasing
Rice-legume-wheat-tomato-corn-vineseed (cover crops in between). Rice-tomato-sunflower-rice-tomato (tomatoes every 4th year) Fusarium wilt issues. Rice-sunflower (good due to low N use in sunflower).	Rotation sequences and other

Table 2. Description of systems evaluated over 15-year period and corresponding abbreviation. Abr = Abbreviation. RSTT (Rice Sunflower Tomato, Tomato), RSBB (Rice Sunflower, Beans, Beans), RRR (Rice, Rice, 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). Trans = transition years- in or out of rice.

Abr	Year under rotation														
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
RSTT	rice trans	sunflower yr. 1	tomato yr. 1	tomato	rice trans	rice	rice	rice trans	sunflower	tomato	tomato	rice trans	rice	rice	rice trans
RSBB	rice, trans	safflower yr. 1	beans yr. 1	beans	rice trans	rice	rice	rice trans	safflower	beans	beans	rice trans	rice	rice	rice trans
RRR	rice	rice	rice	rice	rice	rice	rice	rice	rice	rice	rice	rice	rice	rice	rice
RRF	rice	fallow	rice	rice	rice	rice	rice	rice	rice	rice	rice	rice	rice	rice	fallow
RSTT-Benefit	rice trans	sunflower yr. 1	tomato yr. 1	tomato	rice trans w/ ben	rice w/ ben	rice	rice trans	sunflower	tomato	tomato	rice trans w/ben	rice w/ben	rice	rice trans
RSBB-Benefit	rice trans	safflower yr. 1	beans yr. 1	beans	rice trans w/ ben	rice w/ ben	rice	rice trans	safflower	beans	beans	rice trans w/ ben	rice w/ ben	rice	rice trans

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Chapter 3 Benefits and Tradeoffs of Diversifying Rice-based Cropping Systems: Soil Health, Productivity, and Multifunctionality

3.1 Abstract

In California, crop rotations have been proposed as a practice to tackle challenges related to water scarcity and herbicide resistance. While diversified crop rotations have been shown to increase soil health and yields while providing broader ecosystem services, outcomes are uncertain in flooded rice systems. Including aerobic crops in rotation with rice may alter soil carbon and nitrogen dynamics as well as weed pressure, reducing herbicide use, but long-term effects in growers' fields remain unclear in California. Our objectives are to investigate the benefits and trade-offs of summer-based crop rotations with rice systems (both organic and conventional). Across 46 rice fields, we evaluated soil health, yields, weed abundance, and herbicide inputs. We further evaluated outcomes using an adapted multifunctional framework to discern overall system multifunctionality and ecosystem service (ES) tradeoffs across 4 ES categories: Regulating, Supporting, Provisioning, and Conserving. Soil health metrics showed that crop rotations reduced active carbon, ACE protein and total carbon (TC) with accumulation of minor elements compared to continuous rice fields. Rotated conventional fields had increased yields (13%) and lower weed abundance. While rotated conventional fields had higher rice agronomic efficiencies (weeds, water, yields and nutrient availability) with lower regulating ES (C sequestration, N retention, Microbial energy), conventional continuous rice showed broader ES which contribute to landscapes (bird habitat, C sequestration). As a result of tradeoffs occurring within each system, no differences in total multifunctionality were observed. Overall, this research suggests multiple benefits for crop rotations with rice systems but does not suggest

win-win scenarios for all ES.

3.2 Introduction

Crop diversification is a key principle for achieving environmentally and economically sustainable and resilient agricultural systems (Beillouin et al., 2021; Gurr et al., 2016). In crops grown under aerobic conditions, multiple studies have shown how complex crop rotations support soil health and agronomic performance (Tamburini et al., 2020). Specifically, these practices can increase carbon sequestration, N cycling, N retention and soil physical, chemical and biological properties; reduce insect weed and disease outbreaks, and increase (Adeux et al., 2019; King & Blesh, 2018; Li et al., 2023; McDaniel et al., 2014; Renwick et al., 2019; Snapp et al., 2019). Due to the biogeochemical processes occurring under a flooded environment, diversification impacts are less certain when applied to seasonally flooded rice systems. Flooded rice conditions supply similar benefits of diversification on their own, such as increase carbon and organic nitrogen storage, and improved nutrient availability (Chivenge et al., 2020; Zhou et al. 2014), which may be disrupted when rotating out of rice. However, climate change and global pressures are forcing historically continuous rice systems around the world to change (C. Chen et al., 2020, Saud et al., 2022, Siagian et al., 2019, Zou et al 2014).

Soil health is defined as the continued capacity for soil to function as a vital living ecosystem that sustains plant, animals, and humans by providing nutrients, storing carbon, reducing greenhouse gas emission, supporting microbial activity and diversity, and cycling and storing water (NRCS, 2023, Drinkwater & Snapp, 2022). Soil health assessments provide a comprehensive framework for measuring a suite of indicators across biological, chemical, and physical properties (Moebius-Clune, 2016). Rice-based crop rotations are complex agroecosystems due to the back and forth between a flooded and non-flooded environment which has major effects on a range of soil functions (Zhou et al. 2014). A 10-year study assessed soil health under different rice rotations in subtropical regions of China and found soil structure, pH, and total N (TN) to be improved under certain rotation types (S. Chen et al., 2012). Other research has shown long term improvements with soil structure and soil fertility in the form of available nutrients (He et al., 2021a, Zhou et al. 2014). In contrast, other studies suggest that the replacement of flooded rice with aerobic crops for multiple years would have negative effects on soil N reserves (Eagle et al., 2000, Yang et al., 2022), due to the increase in soil organic matter mineralization rates, elimination of rice straw input, and the transformation of NH^{4+} to NO^{3}_{-}, which is more susceptible to loss (Witt et al., 2000; Yang et al., 2022). Finally, rice soils are known for their ability to store carbon- a backbone for soil health functions-over the long term due to high C inputs and anaerobic soil conditions (Espe et al., 2015; Liu et al., 2021; Motschenbacher et al., 2013, W. Zhou et al., 2014). Chen et al. (2021) found that flooded rice soils are between 39–127% more efficient in SOC sequestration than aerobic cropping systems, but C pools are more labile, and easily depleted under aerobic conditions, like in a crop rotation scenario. Chen et al. (2021) focused on land use change of rice fields that were permanently converted to upland systems, unlike rotation scenarios. Based on contrary findings and the complexity of replacing rice with non-flooded crops on soil C and N cycling, further research is required to understand soil health differences between summer-based rice crop rotations and continuous rice systems.

From an agronomic perspective, crop rotations with rice can improve rice yields and decrease weed pressure (Adeux et al., 2019; Pardo et al., 2021). Zhou et al. (2023) found that crop rotation increased rice yields by 4.6% while Feng et al. (2021) found crop rotations with rape seed increased rice yields by 20%. In Brazil and the Southern US, a rice-soybean rotation has been adopted by farmers to successfully control weeds (Scherner et al., 2018). Evidence also suggests that rotations can reduce herbicide inputs through better weed control and reduced resistance (MacLaren et al., 2019, Pardo et al., 2021). While crop rotation impacts on weeds have been studied in southern states (Pardo et al., 2021), differences in weeds, inputs, and yields among rotated and continuous rice systems remain poorly understood. Due to challenges in documenting on-farm weed occurrence and density, limited studies have identified the effects of diversification on weed outcomes across larger regions (*Brim-DeForest et al.*, 2023; MacLaren, et al. 2019). As an alternative, farmer perceptions and experiences have been widely used to examine the extent of weed problems and the use of different control practices (Calha et al., 2023; Jussaume Jr. et al., 2022; Loux & Berry, 1991). In particular, Jabbour et al. (2014) found that farmer knowledge and perceptions were predictive of seed density and species richness and abundance. Therefore, a multitude of cropping system performance indicators can be assessed across a wide geographical region by utilizing farmer surveys to appraise weed abundance and herbicide use.

For California's Sacramento Valley, which produces 20% of total US rice (NASS USDA 2023), increased herbicide resistance and water scarcity events continue to impact farmers' ability to maintain profitability and productivity over time. In response, fallowing has increased in the region, with recent trends of up to 50% of annual cropland being fallowed during drought years (

2023, California Rice Commission, 2022, NASS USDA 2023). Diversifying the number of species grown through crop rotation has been proposed as a strategy to address some of these agronomic challenges (UC IPM, 2023). In previous work, farmers reported multiple benefits of crop rotation related to soil health, yields, weeds, and reduced herbicide and fertilizer inputs (Rosenberg et al., 2022), yet limited data exists to support these claims.

Furthermore, California holds some of the highest organic production in the US, with a national goal to expand support for organic production (CCOF, 2023; CDFA, 2023). Diversification often becomes inherent in organic systems due to the lack of synthetic inputs such as pesticides, herbicides, and fertilizers. Therefore, farmers tend to rely on cover crops for nitrogen and crop rotations for weed and pest control. These practices combined may support the retention of carbon and nitrogen pools that may be reduced in conventional crop rotations, although crop rotations effect on weed pressure in organic systems is less clear (Singh et al., 2020). Nath et al. (2022) showed that weed species diversity and weed dominance increased in multiple organic systems, with the number of consecutive cropping seasons of rice, while Gao et al. (2022) showed that Rice–chickpea rotation with organic amendments increased weed seed density over time, compared to conventional rotation and monocrop systems with chemical fertilizers. In order to provide better recommendations for all farmers, investigating the changes in agronomic and soil health effects across both organic and conventional systems is important for determining how and for whom diversification may be more suitable, while identifying specific tradeoffs.

Ideally, agricultural systems should provide for multiple goals, balancing ecological, agronomic, and socioeconomic sustainability outcomes. Multifunctionality frameworks can be used to assess these goals through the measurement of indicators that support ecosystem services (ES) including provisioning (such as food production), regulating (such as soil and water functions that support cycling, pest suppression), and supporting services such as those that improve other services (nutrient availability, soil structure) (Hölting et al., 2019; Wittwer et al., 2021). Generally, systems that show higher multifunctionality are more resilient and can be linked to higher profitability and increase human livelihoods (Blahna et al., 2017; Drinkwater & Snapp, 2022). Conversely, research suggests that maintaining very high functionality of any one service is likely to conflict with other services, and therefore tradeoffs are required to increase the number of functions within a system (Blahna et al., 2017; Garba et al., 2024). Apart from provisioning services, flooded rice systems in California provide a variety of ES in different categories such as waterfowl habitat during the winter (Calrice, 2023) and carbon sequestration (Chen et al., 2021). However, crops often used in rotation with rice use less water, contributing to water conservation (Bijanzadeh et al., 2022). Thus, understanding how crop rotations affect multifunctionality (the averaging of all ES) across different categories is important for stakeholders and farmers to make adaptive decisions based on their goals and to estimate systems performance.

Limited research has explored the benefits and tradeoffs of diversified crop rotations compared to continuous rice systems under both conventional and organic management. Working across 46 fields in California, our objectives were to determine how crop rotations affect 1) chemical, physical, and biological indicators of soil health, and 2) weeds, herbicide use, and 3) yields compared to continuous rice systems. We further 3) evaluate how these different management systems affect multifunctionality through an adapted ES framework. We hypothesized that 1) In both conventional and organic systems, rotations will increase soil health, but soil carbon and nitrogen pools will decrease in rotated conventional fields. Second, we hypothesize that rotated systems will increase yields and reduce weeds, but tradeoffs will lead to lower multifunctionality in conventional rotated systems than continuous rice or organic fields.

Methods

3.3 Region of study

California produces rice on approximately 212,000 ha annually (USDA, 2023). The majority of California rice, roughly 95%, is grown in Sacramento Valley (Geisseler & Horwath, 2016) (Figure 1). The region has a Mediterranean climate characterized by the mild winters and hot, dry summers; therefore, irrigation is required for summer crops. In general, rice in the Sacramento Valley is grown continuously and only about 10% of rice acreage is under some form of crop rotation. Crops in rotation with rice are diverse and range from tomato, sunflower, beans, tomato, triticale, corn, vine seed and wheat (Rosenberg et al., 2022). Organic rice systems in California will often fallow between rice crops rather than incorporating alternative crops and may integrate winter cover crops. Therefore, rotated rice systems can be described in varying degrees in this region.

3.4 Sampling and data collection

Following previous on-farm field studies, we collected soils and management data from rice fields across the Sacramento Valley rice growing region where farmers had been practicing crop rotations for more than 10 years (Andrews et al., 2002; Crookston et al., 2022; Mann et al., 2019; Williams et al., 2020). The control was fields which had been continuously cropped with rice for 7 years or more. Rotated fields were coming into rice after some form of rotation at the time of soil sampling (Supplementary Table 8). Rotations ranged in the types of summer rotations and number of years in rotation (between 1-5 years). In total we sampled from 46 fields. 12 of which were organic, and 34 were conventional. For organic fields, 8 were under some form of rotation and 4 considered continuous rice (Table 1). For the conventional fields, 18 were continuous rice and 16 were rotated (Table 1). For 3 of the organic fields (4) rotations include fallowing land for one or more years commonly between rice crops (Supplementary Table 8). One conventional rotated field includes a winter cover crop while 7 fields under organic production included winter cover crops (Supplementary Table 8).

3.5 Soil health indicators

Soil samples were collected at the field-scale based on the methods described in the Comprehensive Assessment of Soil Health Manual (Moebius-Clune et al., 2016). Samples were taken in early spring each year before any inputs but after the first or second tillage operation was performed. Samples were randomly collected at 10–25 points per field, depending on field size, to ensure sufficient field coverage (Mann et al., 2019). A core was taken roughly 15 cm deep to the tillage line using a shovel and then surface debris was removed (Warren J et al., 2019). Samples were mixed thoroughly in a large bucket, and 1.5–3 kg of soil were bagged and placed in a cooler on ice. Bulk soil samples were stored at 4 °C until soil samples were sent to

Cornell for soil health analysis (Moebius-Clune et al., 2016).

Soil analysis included soil texture, available water holding capacity (AWC), ACE soil protein, soil respiration, active C, total C (TC), Total N (TN), Aggregate stability, and standard nutrient analysis: Extractable phosphorus (P), extractable potassium (K), minor elements (Mg, Mn, Fe, and Zn), and pH according to procedures outlined in Cornell's Standard Operating Procedures (Cornell Soil Health Laboratory, 2023) Soil texture was determined using the methods by (Kettler et al. (2001). Micro and macro nutrients were measured on a modified Morgan's extractant, using a rapid-flow analyzer and an ICP Spectrometer (Haney et al., 2010). Minor elemental ratings combined Mg, Fe, Mn and Zn for a total summary based on their distribution with 100 being the optimal range for all elements (Moebius-Clune et al., 2016). Soil pH is measured with an electrode in a 1:1 soil to water suspension (Haney et al., 2010). AWC was measured by applying different levels of air pressure to water held by the soil sample between field capacity and wilting point, presented in grams of water per gram of soil (Reynolds, W. D., & Topp, G. C. 2008). Aggregate Stability was measured based on how well soil aggregates hold together under a simulated rainfall event and measured by the fraction of dried aggregates that disintegrate to < .25mm (Moebius-Clune et al., 2016). Soil Proteins were measured by an extraction with a citrate buffer under high temperature and pressure, expressed in Mg/g^{-1} of soil (Keen & Legrand, 1980; Walker, 1994; Wright & Upadhyaya, 1996). Soil Respiration was measured by capturing and quantifying carbon dioxide (CO_2) expressed as total CO_2 released in Mg/g^{-1} of soil over a 4-day incubation period (Haney & Haney, 2010). Active carbon was measured by potassium permanganate oxidation, presented in Mg/Kg of soil (Burt, 2014; Wade et al., 2020; Weil, R,R, et al. 2009). The TC analysis measured all of the carbon in a sample using complete oxidation of carbon to CO_2 using high temperature combustion (1100°C) and is presented as a percent

3.6 Agronomic and environmental indicators

Farmers provided management information such as water management, fertilizer application, rice variety, seeding technique, seeding date, seeding rate, and winter flood management. They also provided information on yield, weed abundance, cropping history, and herbicide programs (Supplementary Tables 6-8). Weed abundance scores were based on farmer assessment of the fields during the year sampled. Farmers provided a rating between 1 and 5, with 5 being exceptionally high in abundance and 1 being very low in abundance. (Colbach et al., 2020; Hanzlik & Gerowitt, 2016; Loux & Berry, 1991; Shaw et al., 2009)They provided a separate rating for each weed species they encountered that year (Supplementary Table 7). Weed abundance scores were then averaged together (total abundance / # of weed species encountered). For conventional fields a weed abundance rating was provided for pre-herbicide application. For herbicide inputs, farmers provided the number of applications for each product used and a total number of applications was used for the herbicide indicator.

3.7 Multifunctionality assessment

For our multifunctional assessment we added three extra metrics to expand into other ES provided by these cropping systems, including cropping diversity, water use, and bird habitat (Supplementary Material Table 8). In addition to yield, diversity is an important indicator as it relates to more diversified diets and markets for regional agriculture systems – which have been linked to overall socioeconomic well-being (Adeux et al., 2022; Mastura et al., 2023; Yang et al., 2024). We therefore counted the number of crops planted over the 7-year cropping history provided by farmers. Fields that used cover crops in the winter received a point as well since it is considered a "crop" and can have benefits to soil biology (Gao et al., 2022; Ouverson et al., 2022; Tosi et al., 2022). Flooded rice fields in this region are known for providing important waterfowl habitat, especially during the winter months (Brouder & Hill, 1995). Therefore, bird habitat was included as an ES based on the number of years farmers winter flooded, which correspond directly to the number of years in rice. A contrary concern for California is water consumption as this region is prone to drought and water scarcity. Rice consumes a relatively high amount of water during summer months, whereas other crops in rotation often use less water (Cooley, 2015). Therefore, we determined the average water consumption of each crop using regional and state sources and then calculated average water use over 7 years based on cropping history (Supplementary Table 8) (Cooley, 2015; Johnson and Cody, 2015 ; Matios & Burney, 2017; UCANR 2023).

3.8 Data analysis

All statistical analysis was performed in R (R development Core Team, version 2023). Unless otherwise noted, data are reported as mean values and their standard errors. Due to variation among farms and uneven numbers of the different management systems, we explored the effects of rotation through multiple statistical approaches. To confirm we were choosing the correct model for analysis, multiple models were developed and compared, and the best fitting model was selected based on lower Akaike Information Criterion (AIC) scores (*AIC*, 2023; Fenster et al., 2021a). Data was visually inspected for normality. If it appeared skewed, we transformed the data to achieve normality. All data is reported as non-transformed values for interpretability.

First, each indicator was analyzed separately. A Generalized Additive Model (GAM) was used to analyze the soil health indicators using the REML method in the MGCV package to prevent overfitting (Hastie & Tibshirani, 1987). GAM are flexible models designed for non-parametric data used to analyze complex relationships, and can handle nonlinear patterns by combining multiple smoothing functions of predictor variables (Basheer, 2023). GAM is particularly valuable when trying to model relationships which are affected by geographical differences (Damalas et al., 2007) Rice soils are known for their high clay content with the northern rice regions having 2:1 shrink swell clays (Hill et al., 2006, USDA, 2023). Furthermore, rotations in Sacramento valley tend to occur in the southern regions (Rosenberg et al., 2022). We controlled for these variables by including % clay (representing soil texture) and latitude and longitude as covariant factors in our statistical models. For soil health metrics, Treatment and Treatment * System was considered fixed effects and smoothing splines were inputted for latitude and longitude with an interaction for percent clay content. All GAM models used Gaussian family except Respiration which used Tweed family to compare treatment effects. Tweed family can be appropriate If your response variable is continuous but strictly positive and right skewed (e.g., concentrations, durations, reaction times) (Tweedie M.C.K., 1984; Wood, S., 2016).

When exploring agronomic differences concerning yield, conventional and organic system were analyzed separately. We used a linear model for all agronomic variables because there was no significant geographical or soil texture influence. For the yield model, a liner mixed model using Lme4 package (Bates et al., 2015) was used. For conventional fields, treatment (rotated vs continuous), seeding date, seeding rate and total N and variety were fixed effects with year sampled as random effects. The same approach was followed for the yield model with organic systems, except for total N applied because these numbers were not reported by farmers due to the combination of cover crops and chicken manure providing organic N inputs (Table 1).

For weed abundance models, we used Treatment and an interaction with System, winter flood, and water management type as fixed effects. Finally, for herbicide inputs we used a general linear model using Poisson for statistical family because data was given as counts rater then continuous variables (Sinharay S., 2010). Treatment, winter flooding and water management as fixed effects (Table 1, Supplementary Table 3).

We removed the 4 organic continuous rice fields from the second half of our study because their high clay content was a confounding factor that was driving some soil health differences (Table 1). A Spearman's correlation analysis showed strong relationships between soil health indicators and soil clay content (Supplementary Figure 1), thus the management effects of rotation in organic systems could not be separated from soil type. Therefore, after our initial univariant analysis, we compared conventional continuous rice to two types of rotation: conventional rotation and organic rotation.

A PCA reduced dimensionality between variables to assess relationships and differences between the three cropping systems and explore relationships among variables to support our interpretations of our results. The package ggpubr (Kassambara, 2023)was used to visualize the biplot and check assumptions (Fachada et al., 2017), in order to reduce all significantly distinguished dependent variables into individual principal components. The package ggbiplot (Wickham H., 2016) was used to visualize the PCA based on different management categories and look at the relationship between all variables. Each measured variable was normalized to scale from 0 to 1 by scaling its maximum and minimum values using scale function in R to all have a standard deviation of 1. The packages Corr (Wei & Simko, 2017) and Corrplot (Wei & Simko, 2021) were used to run a spearman's rank correlation to evaluate the association between diversification (treatment) and system with the first two components of the ordination and the degree of association among the soil health an agronomic metric.

Multifunctionality

Scholars use multiple approaches in measuring multifunctionality (Garba et al., 2024; Hölting et al., 2019; Manning et al., 2018; Wittwer et al., 2021). However, all approaches aim to gain an understanding of how agroecosystems impact multiple sustainability factors and summarize those impacts into a simplified score (Wittwer et al., 2021). To estimate multifunctionality, an "averaging" method was used for normalized values in each broader ES category, weighting all indicators equally (Hölting et al., 2019). This approach has been extensively used in literature (Hölting et al., 2019; Wittwer et al., 2021). In this study, we define our ES by the measure of the indicator that directly or indirectly influences it, and then we categorize them under a larger service category (Wittwer et al., 2021) (Supplementary Table 2): Regulating, Supporting, and Provisioning. We added a Conserving category to include bird habitat and water savings (Supplementary Table 2). Weed abundance was multiplied by -1 to indicate weed abundance as a dis service. For conventional growers, an average of weed abundance scores before herbicide application and after herbicide application was used, in order to capture weed abundance more accurately for conventional fields. The number of herbicide applications was used for an herbicide use score. Then each field's herbicide use score was subtracted from the average value of continuous rice herbicide use to transform it to a measure of input savings. Despite the positive effect herbicides have on controlling weeds, which was captured in our weed abundance score, herbicide use can negatively affect the environment as well which is why we account for input savings as a service. Therefore, organic fields have an inherently higher input savings score then conventional fields. Water use values were subtracted from continuous rice average water use (0.617 ha/m) to provide a water savings value. We averaged minor elements rating with P and K standardized values to estimate overall nutrient availability. The package Multfunc (Byrnes, 2015) was used to average all indicators and provide an overall multifunctionality score. A Tuckey pairwise analysis was used to determine significant differences among rotation groups.

Results

3.9 Soil health and Agronomic differences

Farms ranged from Southern Yolo County to Northern Butte and Glenn County and West spanning to Colusa County, and East into Yuba and Sacramento County (Figure 1). Soil texture ranged from 44.3% clay ± 2.7, 11% sand ± 2, and 44% silt ± 1.6 for continuous rice fields (when averaging both organic and conventional). Rotated fields (both organic and conventional) have a mean soil composition of 42% clay, 9% sand, and 48.6% silt (Table 1). Organic rice only fields had the highest average clay content compared to the others (56.6) (Table 1). Most farmers used relatively similar nutrient management regimes (placement, and source). Although TN, planting dates, and seeding rates were different for farmers based on variety, region, and climate (Supplementary Table 6). Water management regimes also varied depending on herbicide programs (Supplementary Table 7)

The GAM analysis shows continuous rice fields having higher rates of TC, active carbon, and ACE soil protein (Figure 2) compared to rotated fields (Table 2). Continuous rice fields had 15.8 % more TC, 17.6 % more active carbon, and 37.6 % more ACE soil protein compared to rotated fields. There was also an interaction between System and Rotation that effected differences in active carbon ($P = .003$), with organic rotated fields having less active carbon than organic continuous fields. Rotated fields had 19.8% higher minor elemental ratings compared to continuous rice fields and 205.9% higher total phosphorous, with a significant System effect for organic fields ($P = 0.03$). Rotated fields had slightly higher respiration compared to continuous rice fields (6.9 %) ($P = 0.09$) (Table 2). Predicted water holding capacity, aggregate stability, total N, pH and total K showed no significant difference by Treatment or System effect (Supplementary Table 1).

For the agronomic indicators, early weed abundance ratings for conventional continuous rice were higher than conventional rotated fields (Table 3). Farmers with conventional rotated fields reported on average a weed abundance of 2.48 while farmers with continuous conventional fields reported and average abundance of 4.21. There was a minimal significant difference between organic fields for weed abundance (P = 0.064). Farmers with organic rotated fields reported an average weed score of 3.12 while organic continuous rice growers reported an average score of 3.37 (Table 3). Yield for rotated conventional fields was 13% higher than conventional continuous rice, while organic fields showed no significant differences between yields. (Table 4). There was no significant difference by treatment for herbicide applications (Table 5).

3.10 PCA and Spearman's correlation

PC1 represents 36.5 % and PC2 represents 20.1% of total variation explained across all principal components. Organic rotated fields overlap more with conventional continuous rice on both PC1 and PC2, suggesting similarities between these groups (Figure 3). Conventional rotated fields show a wider separation between conventional continuous rice fields along PC1, however overlap with organic rotated fields along PC1, suggesting there are distinct differences between conventional rotated and conventional continuous fields but similarities with organic rotated fields. When viewing the PCA vectors, ace protein and weed abundance are positively associated with organic rice fields and conventional continuous rice fields, while minor element rating and yield are positively associated with conventional rotated fields (Figure 3). Phosphorous is positively associated with organic rotated fields (Figure 3). Yield is positively associated with PC2 and PC1 which reflects the higher yields with conventional rotated systems compared to organic fields or conventional continuous fields. Active carbon is negatively correlated with PC1 and slightly positively correlated with PC2 suggesting stronger correlation with conventional continuous fields. Weed abundance and ace protein are negatively to both PC1 and PC2 suggesting a stronger correlation between organic rotated and continuous rice fields. Weed abundance and ace protein are also positively correlated to each other, as are active carbon and total carbon. Minor elements and P have a positive relationship with each other, though less distinct. There are no vectors correlating to yield, suggesting less interpretability for this variable.

Spearman's correlation analysis reinforces these results by providing correlation and significance values. Diversity is positively correlated to PC1 (0.68) and System is negatively correlated to PC2 (-0.54) (Table 6). All dependent variables show a significant correlation with PC1 and diversification ($P < 0.05$) (Table 6). In relation to PC1, active carbon, ace protein, and total carbon are negatively correlated with PC1, and minor elements and total phosphorus are positively correlated to PC1. Yields are positively correlated with PC1 and PC2. The PCA distinguishes a stronger correlation between system with yield then Diversity. Weed abundance is negatively correlated with PC1. All dependent variables are significantly associated with PC2 except for total phosphorus. In relation to PC2 all variables are positively correlated except weed abundance which is negatively corelated.

3.11 Multifunctionality

When viewing all of indicators by their designated ES, we can see how each system has different benefits and tradeoffs. The higher the score within each ES category indicates a higher strength of service (Supplementary Table 1, Figure 4). Reviewing mean values for conserving ES, which include water savings, and bird habitat, we see a clear tradeoff between rotated and continuous rice fields. Rotated fields saved 0.395 ha/m of water per year compared to 0.617 ha/m

(Supplementary Table 2, 8). Rotational fields had 3.25 years of which were providing bird habitat while continuous rice fields had close to 7, except for few fields that did not have winter flood due to water scarcity in the drought year of 2022. Rotated conventional fields show significantly higher provisioning services due to the combined higher rice yields and addition of more diversified food production (Figure 4 and 5a). Rotated fields had on average a crop diversity score of 3.2 while continuous rice had an average of 1.05 (Supplementary Table 2C). Organic rotated systems show overall the most evenness for multifunctionality across all services and categories (Figure 4 and 5a), with only bird habitat and weed abundance (described here as a disservice) showing large deficits, and inputs savings being high by default because organic systems do not use herbicides (Figure 4). However, fewer of those services reach a strength of 0.5 or higher. Alternatively, we see higher extremes between ES categories with conventional continuous rice fields (Figure 4). While conventional continuous rice shows a greater number of high functioning services compared to either rotated system (services that are 0.5 or higher), conventional rotated systems show a decrease across all regulating services compared to the other two systems (Figure 4).

When categorizing services as regulating, provisioning, supporting, and conserving, organic rotated fields regulating services were significantly higher compared to the other two systems, Organic rotated> conventional continuous rice> conventional rotated (.53 ± 0.039, 0.40 ± .026, .27 ± .028,) (Figure 5a). Furthermore, provisioning services were significantly higher in conventional rotated fields (.65 +- 0.06) compared to conventional continuous (.39 +- 0.08) and organic rotated (0.34 +- 0.44) fields. Supporting services were significantly higher in conventional rotated fields due to the reduction in weed abundance (interpreted as a dis-service), and the increase in nutrient availability (Figure 4). There was no significant difference in conserving scores. While rotated fields have much higher water savings, continuous rice fields offer more years of waterfowl habitat (Figure 4).

When comparing total multifunctionality between the three systems, there was no significant difference. Total multifunctionality scores were .48 ± .03 for rotated organic fields, .448 ± .02 for conventional rotated fields, and .441 ± .02 for continuous conventional fields (Figure 5b). Therefore, despite trade-offs within and between service categories, rotated fields provide similar multifunctionality and remain as productive as continuous rice systems due to increases in selected supporting services and all provisioning services (Figure 5b).

Discussion

3.12 Soil health changes

This is the first study to assess multiple indicators related to soil health and agronomic differences in diversified and continuous rice systems in California. We observed specific trade-offs related to carbon, organic nitrogen pools, and nutrient availability (minor elements and phosphorous) when comparing continuous rice to rotated fields. Our results suggest that diversifying rice systems is not necessarily important for soil health, as it is for other aerobic cropping systems and broadly align with other literature on the effect of land use change on flooded rice environments (X. Chen et al., 2021; W. Zhou et al., 2014). There were significantly higher rates of active carbon and ace soil protein in continuous rice fields, as well as higher total carbon (Table 2, Supplementary Table 4). Our results suggest that nutrient retention becomes compromised, and mineralization becomes primary in rotated fields. Ace protein is understood as an indicator for a readily available organic nitrogen for microbes and is closely linked to active carbon and organic matter. The slow decomposition of rice straw residue continuously replenishing the soil organic matter complex can be linked to both ace protein and active carbon (Moebius-Clune et al., 2016). Witt et al. (2012) showed in a two-year study that replacing rice with maize caused a reduction in soil carbon and nitrogen due to a 33–41% increase in mineralized C and less N input. The reduced active C and ace protein in rotated fields found in our research supports the outcome of increased mineralized C and N which is preserved in continuous rice fields.

However, total carbon was less significantly different then active carbon between rotated and continuous fields (P = 0.04 compared to 0.00 consecutively) (table 2, Figure 1). Furthermore, geography and soil texture were better predictors for determining carbon differences (Supplementary table 3). These results show that while carbon differences exist between rotated and continuous rice systems, the loss of total carbon may be less then active carbon. Chen et al (2021) found higher rates of minerally associated carbon in aerobic croplands compared to flooded rice lands. Therefore, our results suggest that the proportion of recalcitrant carbon to labile carbon may be changing in rotated and continuous fields.

Furthermore, while retention of active C and organic N is compromised in conventional rotated fields, our research suggests higher nutrient availability in rotated systems. While ace protein was lower in rotated fields, there was no difference in TN, suggesting that rotations do not lose nitrogen, but rather change N state through increased mineralization. Furthermore, rotated fields saw an increase in minor elements and phosphorous. These results agree with Zhou et al 2014 who found a synergy between the SOM accumulation during rice years and SOM mineralization during upland crops which improved soil fertility. We did see slightly higher respiration rates on rotated fields to add further validity to this interpretation, thought these differences were not statistically significant (P= 0.09) (Table 2). However, at the time of sampling our respiration rates between continuous rice and rotated fields were not significantly different. Our findings may be further interpreted if we had a microbial N indicator, and further research should assess microbial biomass and diversity differences as well as carbon fraction differences between these systems.

Finding management practices that balances both retention and mineralization is important for long term sustainability and maintaining high yields. There is evidence that a certain amount of these organic pools would be returned to the soil at the time rice comes back in rotation and maintained for three years or more. Zani et al. (2023) showed higher soil C stocks under diversified organic rotation with an introduced grass-clover treatment and G. Zhou et al., 2020 found cover crops and straw incorporation enhanced soil organic C and total N, both studied over a period of only three years. Furthermore, organic rotated fields did not show as stark of a difference with regards to soil health indicators compared to conventional rotated fields (Figure 3 and Supplementary Figure 2). Therefore, other management practices such as compost and cover crops may increase retention rates for conventionally rotated fields while still providing the increase in yields and weed management (Drinkwater & Snapp, 2022; Fenster et al., 2021b). Tang et al. (2022) found that organic matter increased by 1.54 and 3.01% under rice straw with manure treatments compared to no rice straw incorporation alone with double cropped rice systems. Suggesting a common practice by organic growers to utilize chicken manure may promote SOM accumulation in rotated systems. Particularly, ace protein was on average less than 1 mg/g-1 below conventional continuous rice while active carbon only showed a 47.59 mg/kg difference, compared to a 122.39 mg/g-1 difference between continuous rice and conventionally rotated fields (Supplementary Figure 2 and Supplementary Table 4).

3.13 Yields

Rosenberg et al (2022) interviews found that rice growers experienced an increase in rice yields between 10-15%. We found an increase of 14% for conventional systems. Interviews with rice farmers in Sacramento Valley also stated that as farmers maintain rice after rotation this "bump" in yields could decline (Rosenberg et al., 2022). While organic systems showed no significant difference. Due to the limited number of organic fields, we recommend further research to assess these differences for organic systems. While this research suggests crop rotations can increase rice yields, the PCA did not reveal correlations with this variable. We expected to see closer relations among our PCA variables to support our interpretations. Increased mineralization rates could be responsible for improved nutrient management and increased nutrient uptake by rice crops (Zhang et al., 2023). At the same time, because weed abundance in the early season is significantly less in rotated fields this could support a better emergence and stand. Scherner et al. (2018) cites a yield reduction from weeds in rice production is estimated to be 10-15% (Baltazar & Roy J. Smith, 1994; Moody, 1993), and the introduction of rice soy-bean rotations has reduced this loss in Brazil (Scherner et al., 2018). Our research found conventional fields to have higher yield differences than Q. Zhou et al. (2023) and lower yield differences than Feng et al. (2021), suggesting management and environment effects on yield is contingent on regional context. Covariant factors such as variety differences along with seeding rate explained a high percentage of the variation (Supplementary Table 3), which suggests that rotating alone is not enough to support higher yields, but a combination of recommended best management practices and appropriate varieties are important as well.

3.14 Weeds and inputs

Our research shows a substantial difference in weed abundance between rotated and continuous rice fields. However, we saw only a negligible significant difference in weed abundance in organic rice fields ($p = 0.064$), suggesting that herbicide programs and other cultural management techniques are more important than rotations alone for suppressing weeds.

Overall weed control is a complex topic, with many factors affecting outcomes. In aerobic systems, diversification can reduce weed species abundance through increasing species diversity (MacLaren et al., 2020). However, the selection process can be different in rice-based rotated systems as maintaining a flooded environment during years in rice will naturally select for aquatic and semi aquatic weed species. Research shows rotations are particularly effective on Barnyard grass (Echinochloa spp.) (Pardo et al., 2021; Scherner et al., 2018) by decreasing seed banks as they can be controlled in both upland and flooded systems, both by using alternative modes of action for herbicide use or alternative cultural control such as tillage (UC IPM, 2023). Therefore, rotations may be reducing the abundance of specific weed species that can occur in both dryland and flooded environments (semi aquatic).

Furthermore, organic rotation systems did not have a significant effect on weeds (Figure 2, 3, Table 3), suggesting that rotations for weed control are more effective for conventional fields. Organic farmers may not be seeing significant weed control with rotation due to the lack of herbicide use and therefore limited late season control, causing weed seed banks to continue to repopulate each rice season. Furthermore, the PCA showed that weed abundance ratings were more closely associated with ace protein (Figure 3), suggesting an influence by organic nitrogen pools on weed abundance. Wickramasinghe et al. (2023) found that alternating upland and low-land crop rotation can influence nutrient dynamics which either can favor, or disfavor weeds. Wickramasinghe et al. (2023b), also found that after two rotations, the total weed biomass in organic systems increased with increasing crop diversification.

Surprisingly, our research did not find any difference in herbicide input use for conventional fields. Nicholson and Williams (2021) found a reduction in pesticide use in both frequency and intensity in more diversified landscapes and therefore we also expected to see a reduction in the number of applications due to the issues farmers experience with herbicide resistance however this was not the case. This could be because the population of farmers we sampled from were not experiencing herbicide resistance, or the numbers provided were under-reported. Further research may be needed to experiment with herbicide requirements under diversified fields, as most trials are done in controlled continuous rice conditions.

3.15 Multifunctionality and over all sustainability goals

We hypothesized that extended crop rotations (i.e. longer periods out of rice) would decrease overall multifunctionality, but this was not the case (Figure 5b). All systems resulted in similar multifunctionality after accounting for trade-offs, but each performed different functions within ES categories. Therefore, increasing agricultural diversity can influence multifunctionality. Rotated conventional fields are seen providing higher provisioning services- crop diversity and higher rice yields- but also an increase in certain supporting services such as reduced weeds and increased nutrient availability. This suggests higher agronomic efficiencies with conventionally rotated systems, which is the direct benefit farmers would experience. Yet these agronomic efficiencies are seen at the cost of regulating services (nitrogen retention, microbial energy, C sequestration) (Figure 4 and 5a), which are highest in continuous rice and rotated organic fields (Figure 4 and 5a). Our results disagree with X. He et al. (2023) findings that diversification can provide a win-win scenario for ecosystem services. Overall, their research had limited observations for crop diversity and they showed few benefits (X. He et al., 2023). Our results agree with Wittwer et al. (2021), who also found that organic fields seem to be providing a greater diversity of functions at more moderate levels, while conventional systems (especially continuous rice) seem to be providing a larger number of functions at high levels and low or negative levels (Corn et al., 2021 and Finney & Kaye, 2017). While this research suggests crop rotations may not achieve win-win scenarios with all ES we accounted for, other ES were not measured in this study and should be considered when looking at systems performance. Gurr et al., (2016) and He et al. (2023) shows crop rotations significantly reduced pests and insecticide applications and delivered economic advantages. Insect ecology and other input savings was not accounted for in this research.

Continuous rice is often known as ‘the environmental’ crop due to the support of overall wetland landscapes in California – in terms of wildlife, which contribute to broader ecosystem multifunctionality at the landscape level. There is a current focus on reestablishing historic wetlands where crop production has expanded, like in the Sacramento Valley region (Hambäck et al., 2023). Therefore, rice environments offer an opportunity to measure multifunctionality of wetland agroecosystems that may not have been captured in this study. Currently, management with these agroecosystems suggest an inability to attain both wetland conservation and water conservation, two regional and state goals (Figure 4). Further research should consider opportunities to provide wetland habitat in winter months while still reducing summer irrigation needs which crop rotations offer.

Depending on stakeholder goals, these weighting may change. Policies need to balance environmental goals (i.e. climate and biodiversity goals) and farmers goals (i.e., livelihood, and agronomic performance). Oftentimes these goals can be mutually achieved through increasing diversification (Drinkwater et al., 2017; Finney & Kaye, 2017; D.-C. He et al., 2021; Jarchow & Liebman, 2011; Mastura et al., 2023). However, due to the unique environmental conditions of rice, our research shows this is not always the case. At the same time, when understanding sustainability for rice systems we need to consider the net outcome between carbon sequestration and greenhouse gas emissions. While the reduction of C inputs through crop rotation and increased soil aeration have been shown to decrease SOC stocks, other research also suggests this can lower CH_4 emissions (Brye et al., 2017). Zhang et al. (2023) P. 1, argues that future research needs to consider “cross-component effects to optimize net system emissions, specifically the “stacking” of best management practices for mitigation related to field GHG emissions or SOC change in long-term experiments”. While labile carbon stocks will likely decrease in crop rotations over time, TC may not be as affected and therefore net carbon may be positive, depending on how CH_4 emissions differ between systems.

3.16 Future research

We recommend further research to investigate our claims for organic systems, due to the smaller sample size and distinguishable soil texture differences with our organic continuous rice fields. A second limitation of our research is that it did not capture how soil health related indicators may change over time. Further research should investigate if there is a “balancing effect” with a certain number of years in and out of rice or if soil differences in rotated fields remain constant over time. At the same time, we recommend further soil microbial studies to investigate the N cycling events and microbial population differences. Furthermore, while this research demonstrated higher yields in rotated systems, we remain uncertain about the cause of these yield increases being related to better weed control or higher nutrient availability and further research should investigate these links. Concerning our weed analysis, while this research found abundance to be less in fields under conventional rotation, we did not capture any diversity changes which should be further explored to better understand the mechanisms for weed control. Further research may also be needed to assess input differences with different ways of measuring input use, as our methods may have been oversimplified. Nicholson and Williams (2021) reported inputs as a weighted amount of active ingredient for herbicides, which may be a more robust indicator. Concerning our multifunctionality findings, we have a better understanding of each system's strengths and weaknesses, and further research should look at reducing the tradeoffs and increasing gains across systems. We need to look more closely at water use differences between rotated fields and continuous rice fields, at the landscape scale. Evidence suggests that much of the 5 ft is run-off from rice and is used downstream unlike rotation crops (LaHue & Linquist, 2021), which was not accounted for in this study. Finally, our study did not account for greenhouse gasses which is an important sustainability factor with rice systems. Therefore, further research should assess net gains with carbon sequestration comparing both methane and carbon capture.

Conclusion

Summer rice-based crop rotations in California's Sacramento Valley are unique due to the temporal fluctuations between aerobic and anaerobic environments combined with the diversity of crops in rotation. These changes affect many chemical biological and physical parameters of soil functions, while also having impacts of agronomic outcomes related to weeds inputs and yield of the cropping systems. This research explored the benefits and tradeoffs with crop rotations in rice systems in both organic and conventional systems. Evidence from 46 rice fields suggests that rotated fields have lower soil carbon and nitrogen reserves, particularly with the active and organic pools of carbon and nitrogen, while there was a positive impact of rotation on rice yields and weed control. However, these tradeoffs were less in organic rotated fields, likely due to the additional amendments and cover crops supporting C and N pools. Furthermore, we explored overall multifunctionality by recategorizing these indicators into ES and their broader service categories (regulating, supporting, and provisioning), adding conservation factors including water-saving, bird habitat and crop diversity. Overall, there was no difference in average multifunctionality between the three cropping systems. This research confirms multiple benefits for crop rotations with rice systems however this research suggests rotations can compromise carbon and nitrogen retention and may compromise wildlife habitat at the landscape scale. Further research should investigate mitigating these tradeoffs.

Figures

Figure 1: Map of Sacramento Valley rice growing region showing field sampling locations. Green shading is rice area, blue triangles are conventional continuous rice fields, red triangles are organic continuous rice fields, purple circles are conventional rotated rice fields, and orange circles are rotated organic rice fields.

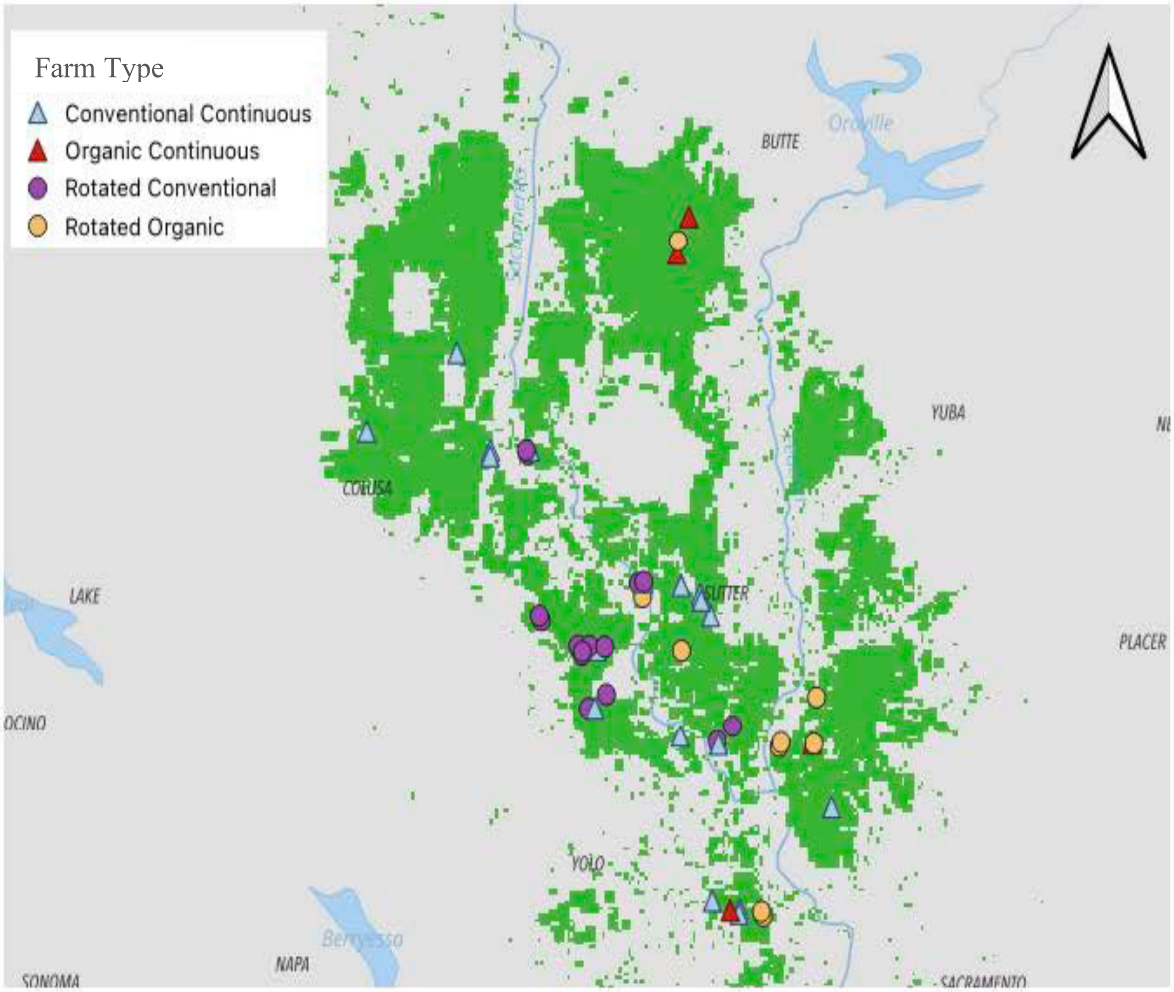


Figure 2: Effects of crop rotation on all A) soil health and B) agronomic indicators compared to continuous rice fields. Values are scaled between 0 and 1 for relative comparison. Soil health variables combine both conventional and organic systems and compare between rotated (blue) and continuous (red) rice systems. Agronomic indicators distinguish each treatment by organic and conventional. Management systems compared include Conventional Continuous N= 18 (red), Organic continuous rice, N = 4 (green), Conventional rotated, N= 16 (blue), and organic rotted, N= 8 (purple). Early weed abundance = Pre herbicide application for conventional fields. The corresponding statistical values ($P < 0.005$, R^2, SE) and mean values, are reported in Table 2-4. Boxplots display the median (horizontal line), the 25th and 75th percentiles (box) and minimum and maximum (whiskers) and outliers (points)

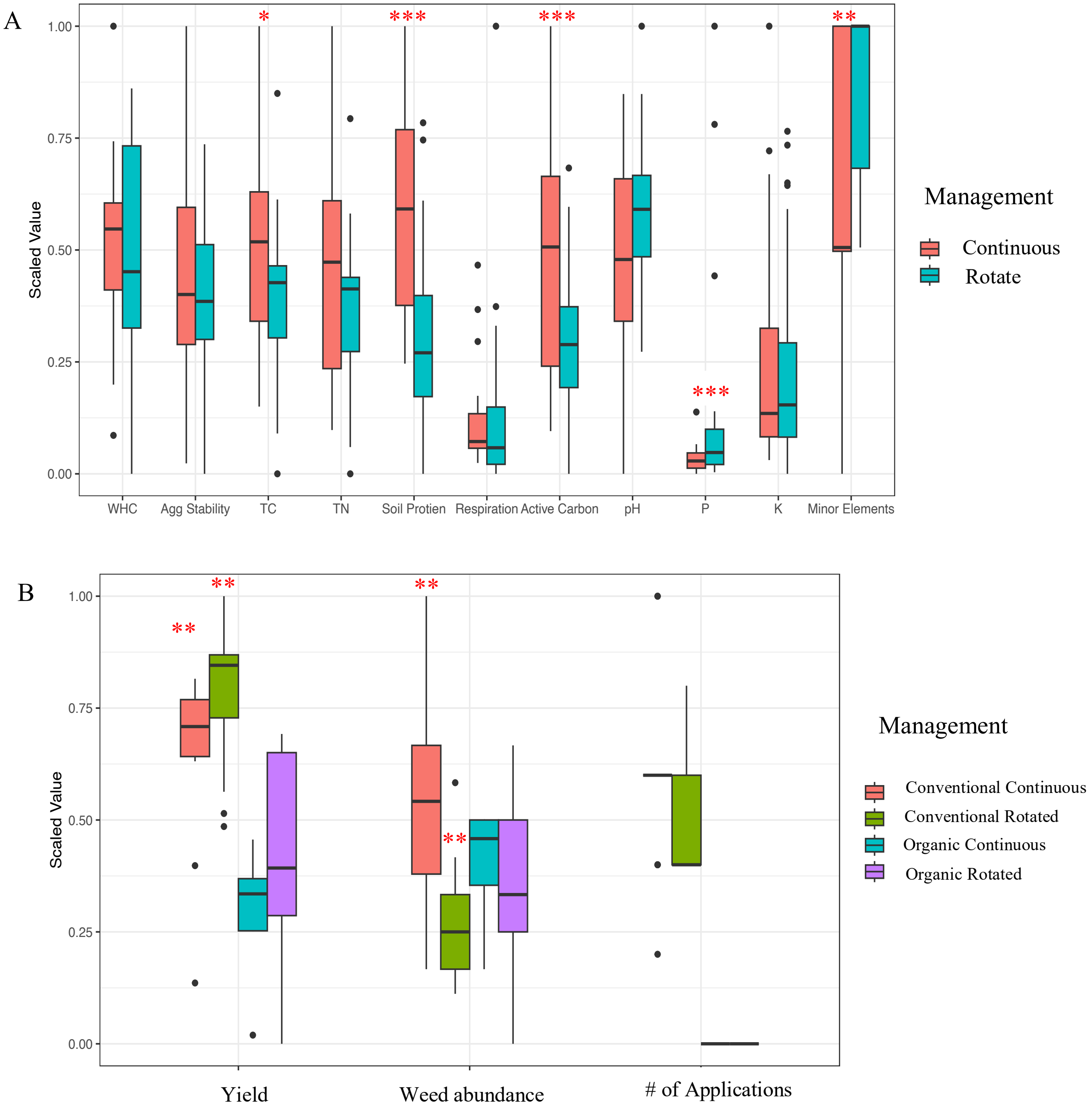


Figure 3: Principal component analysis of first and second component showing significant explanatory variables. Circle colors indicate management and size of bubble corresponds to crop diversity score. Bubbles in red circle are fields under conventional continuous rice, bubbles within the green circle are fields under conventional rotated management, and bubbles in the blue circle are fields under organic rotated management. Soil variables include total carbon, active carbon, ace protein, aggregate stability, and minor elemental rating. Agronomic indicators include early weed abundance and yield.

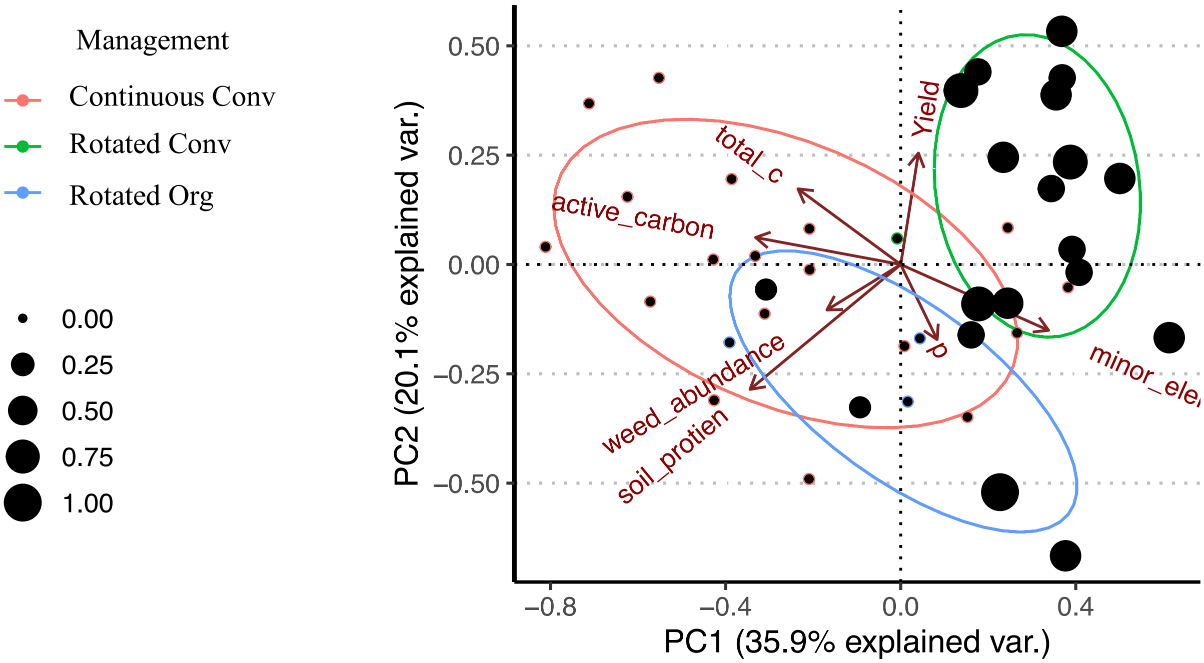


Figure 4: Standardized agroecosystem functions organized by service category for Continuous conventional, rotated conventional, and rotated organic rice systems. Error bars represent Standard Error. Categories are Supporting (purple), Regulating (blue), Provisioning (green), and Conserving (red) categories. The higher the bar indicates the stronger the service, except for abundance which is represented as a diss service.

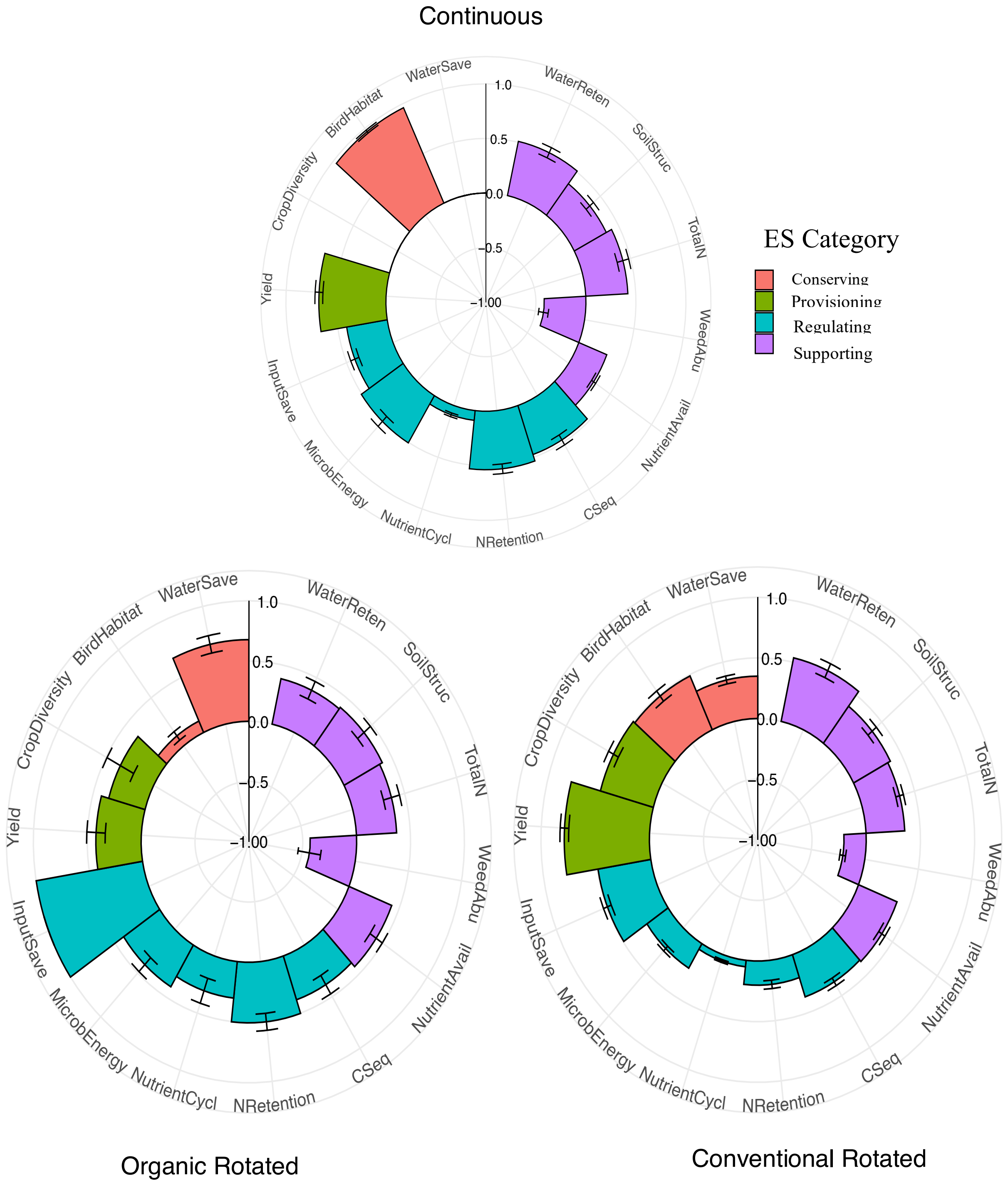
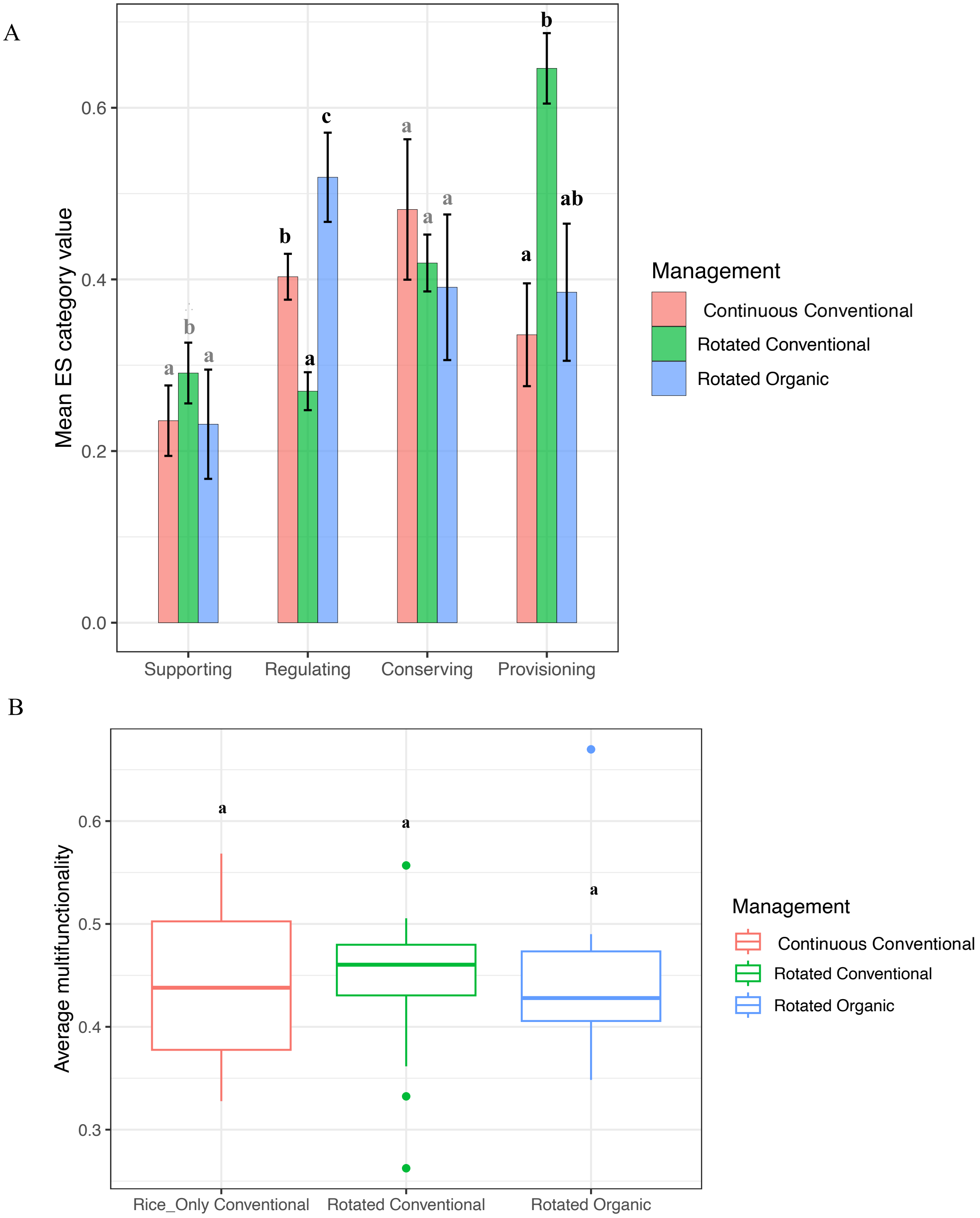


Figure 5: Overall ecosystem multifunctionality between Continuous conventional, conventional rotated, and organic rotated management systems. A) Average ecosystem function categories Supporting, Regulating, Conserving, Provisioning. Different letters indicate significant differences between the three cropping systems for each category. B) Average of all functions between cropping systems -pairwise comparison (n = 45). Boxplots display the median (horizontal line), the 25th and 75th percentiles (box) and minimum and maximum (whiskers) and outliers (points). All values scaled between 0-1.



Tables

Table 1: Summary of fields: Soil texture percent, seeding date, year sampled, Variety, Seeding rate, Total N, Winter flood, Water management by treatment and system.

Treatment	**Continuous rice**	**Continuous rice**	**Rotated**	**Rotated**
System	**Conventional**	**Organic**	**Conventional**	**Organic**
N	18	4	16	8
Sand % **SE**	13.21 2.33	6.23 1.78	7.51 2.71	12.83 4.05
Silt % **SE**	45.23 1.7	37.21 1.33	48.92 2.87	48.13 2.8
Clay % **SE**	41.55 2.94	56.55 2.91	43.47 4.01	39.03 3.25
Seeding date (month/day)-%	(5/3-5/14)-50, (5/20-5/29)-28, (4/20-4/26)-18, (6/5) -5	(5/10) -50, (5/1)-25, (5/15)- 25	(4/18-4/30) –31 (5/3 -5/6)-19, (5/10 -5/11)-31, (5/15-5/21) -19	(5/10-5/11) - 50, (5/15-5/28) - 38, (5/3) - 13
Year sampled (year) - %	(2021) – 44, (2022) -28, (2023)- 28	(2022) - 50, (2021) -50	(2021)- 44, (2022) -25, (2023) -31	(2021) - 63, (2022) -38
Variety -%	M209- 33, M206 -28, Other-39	S102-50, Other -50	M209- 38, M206 - 19, M211 -19, Other - 25	S102 - 63, Other, 35
Seeding rate (lbs./ac) **SE**	172.05 3.77	255 10	152.31 12.02	207.5 11.03
Total n (kg/ac) SE **Amendment -%**	165.5, 52.77	Chicken manure -75, Cover crop- 25	165.3, 18.9	cover crop – 50, Chicken manure -25, Chicken manure + cover crop -25
Winter flood Yes/no -%	Yes-78, No- 22	Yes- 50, No -50	No-100	Yes-38, No-63
Water management %	Continuous – 95, other -5	continuous flood - 100	Continuous – 38, Other – 62	Continuous flood - 100

Table 2: Mean values and statistical summary for soil health indicators between rotated and continuous rice fields. Soil health summaries include organic and conventional fields together. For values differentiated between organic and conventional systems see Supplementary Material Table 4. SE = Standard error, Treatment = Rotated vs Continuous rice, (P Significance <.005). System = Rotated vs Conventional.

Soil health indicator								
Indicator	Rotation	SE	Continuous rice	SE	Treatment p- value	R^2	System * Treatment p-value	System p-value
Total C %	1.95	0.09	2.26	0.11	0.04	0.78	NS	0.07
Minor element rating	85.50	3.83	70.09	5.76	<0.001	0.40	0.05	NS
Active C mg/kg	535.50	16.30	630.00	25.20	<0.001	0.58	0.00	0.01
Aggregate stability % soil > 25mm	41.60	3.55	47.08	5.01	0.13	0.91	NS	0.06
Ace Soil Protein mg/g $^{-1}$	3.03	0.17	4.17	0.19	<0.001	0.84	NS	NS
Total phosphorus (ppm)	3.12	1.05	1.02	0.13	0.008	.49	NS	0.03
Respiration	0.62	0.14	0.58	0.08	0.09	0.74	0.58	NS

Table 3: Mean values and statistical summary for weeds. Linear model accounted for Treatment *System as fixed effect. Treatment = Rotated vs Continuous rice, System = Organic vs Conventional (P Significance <.005). Mean values presented for organic and conventional systems separately for weed abundance. SE = Standard error, Conventional continuous fields n = 18, conventional rotated fields N = 16, organic continuous fields N = 4, Organic rotated fields N = 8.

Weeds								
Indicator	Rotation	SE	Continuous rice	SE	Treatment p-value	R^2	System * Treatment p-value	System p-value
Average abundance Conv	2.48	0.25	4.21	0.29	<0.001	0.34	NS	0.064
Average abundance Org	3.12	0.43	3.37	0.47				

Table 4: Mean values and statistical summary for yields. Summaries show mean values for organic and conventional systems separately. SE = Standard error, Treatment = Rotated vs Continuous rice, (P Significance < .005). Conventional continuous fields n = 18, conventional rotated fields N = 16, organic continuous fields N = 4, Organic rotated fields N = 8

Yield					
Indicator	Rotation	SE	Continuous rice	SE	Treatment p-value
Yield conv kg/ha	11296	451.62	9,985.98	451.62	0.001
Yield org kg/ha	7,082.42	986.16	5547.14	1075.81	0.171

Table 5: Mean values and statistical summary for inputs. Summaries show mean values for conventional systems only. SE = Standard error, Treatment = Rotated vs Continuous rice, (P Significance < .005). Conventional continuous fields n = 18, conventional rotated fields N = 16.

Inputs						
Indicator	Rotation	SE	Continuous rice	SE	Treatment p-value	R^2
Number of applications	2.37	0.23	2.94	0.22	0.898	0.26

Table 6: Spearman’s correlation coefficients and associated p-values comparing PC1 and PC2 to Management (System and Diversification) and PCA variables (Soil health and Agronomic).

Indicator	PC1	p-value	PC2	p-value
Dependent var – Soil Health				
Active carbon	-0.71	0.00	0.10	0.53
Ace soil protein index	-0.68	0.00	-0.60	0.00
Total c	-0.52	0.00	0.46	0.00
minor element rating	0.72	0.00	-0.29	0.06
Total phosphorus	35	0.03	-0.21	0.19
Dependent var – Agronomic				
Yield	0.18	0.05	0.70	0.00
Weed abundance	-0.49	0.00	-0.35	-0.02
Independent Var				
System	-0.02	0.89	-0.54	0.00
Diversity	0.68	0.00	0.20	0.21

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Conclusion

This research holistically investigates the implications of crop rotations with California rice systems by answering questions about the feasibility of rotations, its economic considerations, and the effects on agronomic, soil health, and environmental factors. To investigate these aims I use a mixture of methods including semi structured interviews and focus groups to encourage participatory approaches, as well as on farm field research, and economic modeling techniques. This research provides evidence that crop rotations can benefit rice growers in a number of ways, while describing the challenges growers face when implementing rotations as well as the tradeoffs that can be expected. These findings can guide stakeholders such as growers, farm advisors, and policy makers when considering the adoption of crop rotations with rice. I would like to conclude this research with a summation of these findings, and their implications for future work while describing some personal discoveries I made through this intellectual journey.

In chapter one, I evaluate the major barriers for adopting crop rotations, describe the benefits growers experienced with rotations, and discern the requirements for crop rotations to be successfully implemented. Investigating growers' perspectives are crucial for understanding region specific questions. I discovered that multiple factors limit farmers ability to rotate which include a combination of environmental, economic, recourse limitations and cultural limitations. A common assumption in the region is that heavy clay soils often associated with rice fields limit growers' ability to rotate, and while this chapter confirms soil texture and environmental factors are dominant concern, I show that the combination of the need for different equipment and different irrigation infrastructure, requirements to access to new markets, and secure more labor were all major concerns and challenges for rice growers. There was also a cultural component which limited growers' desires to rotate. Rice growers often come from a lineage of rice farming family's and identify as that. Therefore, motivations for crop rotations would often be to support the rice crop rather than to diversify more broadly and growers needed more information on how crop rotations effect the rice crop. Furthermore, findings suggested that while having loamier, deeper soils will support a more successful rotation crop, other requirements are just as important, such as social networks with other diversified grower communities, access to markets, access to contract labor for those who do not have specific equipment and knowledge of rotational crops, and ownership of land or flexible leasing agreements. My hope is that farm advisors can utilize this information to develop extension-based resources and programs to encourage rotations for whom it makes sense. Help farmers find access to markets and use farmer to farmer networking tactics. I also found this research to be the most fulfilling because it was the building blocks for the other two chapters, not just though the knowledge I gained from the interviews, but also through the relationships built with the growers and the farm advisors.

Findings from the baseline assessment showed farmers who rotate perceive rotations to be more profitable than continuous rice while those who did not see economics as a major barrier. Therefore, I focused an entire chapter to investigate these opposing views. The second chapter summarized overall economic components (costs, revenue, and profits) of four commonly rotated crops with rice and then looks at how profit changes over time. This chapter adds to the body of literature that shows why diversification is difficult for large scale systems. Oversimplification of agricultural systems have achieved the goal of maximizing profit through mechanization, yet these systems can be less resilient and adaptive (Abson et al., 2013; Isbell et al., 2017; Mortensen & Smith, 2020; Rodriguez et al., 2009). Chapter two highlights how economics acts as a barrier and determines under what circumstances rotations are more profitable than continuous rice. Generally continuous rice is considered a profitable crop and therefore farmers may not have a high incentive to switch out of rice. If they did rotate, this research found that there is a high risk when rotating into beans and safflower due to probable lower revenue outcomes, compared to sunflower and tomatoes. However, opportunity costs such as learning the cropping system and finding new markets as well as high investments in irrigation infrastructure make rotating into crops like tomato and sunflower less profitable in the short term and it could take as much as 11 years before growers see profit. When looking at scenarios where rotations have benefits to the rice crop and water scarcity events increase, the investment period reduces substantially, and both rotation types become more profitable than continuous rice. This research suggests that rotations can increase economic resilience under these scenarios.

The economic assessment has provided the California rice sector new data, which growers and other stakeholders can use to inform their decision making. For those farmers that are losing yield and profit to ever growing weed issues and are in water districts that continue to restrict water usages, rotations show a promising outcome for supporting them financially. Furthermore, this work quantifies the prominent investment period growers would experience, which is a substantial barrier and programs to support growers in overcoming this barrier may be necessary to support further adoption. The data collected for my second chapter remains foundational and further studies are necessary to investigate how crop rotations impact rice growers’ finances.

While this chapter demonstrates that rotations can be more profitable, the opportunity costs of staying in rice compared to switching to rotations should be further explored. I accounted for the time to learn the new cropping system and the time to find new markets, which did not present over all exceptionally high costs, especially under assumptions that custom hiring was an option for growers. However, there are other management considerations that may not have been considered, such as overall labor and field management. One of the most challenging aspects of this study was developing the Monte Carlo model and the associated online decision support tool framework. Both are flexible tools that can be used in other cropping systems, in other regions, and I hope researchers and stakeholders interested in cropping system economics will find them useful.

The premise of my research stems from the pervading views that sustainable systems must be diverse (Tamburini et al., 2020) and yet as I learned more about rice systems, the more I questioned if crop rotations were in fact more sustainable from an environmental standpoint. In my third chapter I compared a number of soil health indicators as well as agronomic indicators between rotated and continuous rice systems. This research shows that crop rotations can provide a number of agronomic benefits and support agricultural intensification, however on its own it cannot provide win-win for both agronomic and broader environmental services. Overall, through my last two chapters, I show that rotations can provide benefits in the form of reduced weed pressure, increased yields, and increased nutrient availability as well as long term economic resilience, and reduced water use, all of which agrees with current literature (He et al., 2023, Gurr et al, 2016, How et al, 2018). However retention of carbon and nitrogen will be compromised, which has ramifications for climate mitigation and nutrient retention. At the same time, at the landscape scale, bird habitat can be compromised if crop rotations expand.

My third chapter brought up more questions regarding the effect crop rotations have on environmental ecosystem services, and the mechanisms behind them. Although the outcomes of the third chapter showed a carbon tradeoff in rotated fields, future research should further explore how carbon changes and transforms between the two systems, while evaluating the net losses or gains when considering CH^4. Furthermore, I suspect that there is a temporal fluctuation with the organic and nitrogen pools that are not being captured in my third chapter and future research should assess cycling changes over time as well as look further into microbial structure and abundance differences for a better understanding of the mechanisms behind these changes. Similarly, further research should expand the lens of crop rotations with rice to include how rotations impact the aerobic crops. I think by only focusing on how rotations impact rice, we miss a big piece of the story regarding how rice rotations may also affect upland crops.

Multiple stakeholder goals including productivity, wildlife conservation, water conservation, and carbon sequestration need to be considered when making decisions for rotation. We now have data to support our understanding of how crop rotations effect multiple factors of an agroecosystem and hopefully this can be used to help guide these conversations and help us integrate rotations more successfully. I recall from the focus groups one grower said, “if rotations do show benefits, we need to be careful who we push them on, and where, because it may not before everyone.” While my research shows there are many benefits to rotating with rice, I whole heartedly agree with their statement and would like to remind my audience that rotations should be viewed as another option for growers rather than a solution for the entire region. As we have seen, continuous rice provides a number of benefits on its own which my research shows can be compromised when upland crops are grown in place of rice.

This work compliments the broader body of literature on the nuances of switching between an aerobic to an anerobic environment while offering further insight into multifunctional agriculture and tradeoffs. Identifying management practices for agriculture to mitigate tradeoffs are important in order to achieve robust multifunctional systems. Other research shows that stacking management practices can achieve higher multifunctional goals with fewer tradeoff's (Fenster et al., 2021 a and b), and therefore integration other management regimes on top of crop rotations, such as compost, cover crops, and animal integrations may help retain carbon and nitrogen pool better, while still providing agronomic benefits. As our focus on agroecological practices become more of a focus in our scientific communities, the integration of multiple management practices will become more pervasive.

Furthermore, our tasks for agronomy are moving away from achieving singular gains such as yield and are more focused on systems level thinking and synergies to achieve multifunctional agriculture. One thing I loved about this research was thinking through all the synergies, while also being confronted with the incompatibilities. Thinking critically about how to achieve a sustainable food system can be overwhelming and often times dogmatic views can get in the way of scientific discoveries. As we set ourselves up for future generations, we are tasked with thinking through multiple sustainability goals to not only increase production for a growing population, but also conserve natural resources and reduce environmental impact, while building socially equitable and economically viable systems. Agroecological frameworks that look towards multifunctional agriculture, ecological enhancement (Kremen, 2020), and regenerative practices are more crucial than ever. If this research has taught me anything, it is that every system comes with tradeoffs. Trying to mitigate these tradeoffs is difficult and only through a multi-stakeholder perspectives and interdisciplinary thinking are we going to achieve and re-create agricultural systems to meet our future sustainability goals.

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