TYPE Conceptual Analysis
PUBLISHED 03 September 2025
DOI 10.3389/frwa.2025.1620626

EDITED BY
Natalia Hoyos,
Universidad del Norte, Colombia

REVIEWED BY
Amy Quandt,
San Diego State University, United States
Muhammad Yousuf Jat Baloch,
Shandong University, China

*CORRESPONDENCE
Gopal Penny
✉ gpenny@edf.org

RECEIVED 29 April 2025
ACCEPTED 31 July 2025
PUBLISHED 03 September 2025

CITATION
Penny G, Rodríguez-Flores JM, Fernandez-Bou AS, Koebele EA, Schiller A, Solomon D, Carlson K, Classen-Rodriguez L, Daniels M, Grimm R, Hall M, Kiparsky M, Mercado S, Mudd K and Sanchez S (2025) Enhancing water security and landscape resilience through multibenefit land repurposing.
Front. Water 7:1620626.
doi: 10.3389/frwa.2025.1620626

Enhancing water security and landscape resilience through multibenefit land repurposing

Gopal Penny[1]*, José M. Rodríguez-Flores[1], Angel Santiago Fernandez-Bou[2], Elizabeth A. Koebele[3], Anna Schiller[1], Divya Solomon[4], Katie Carlson[5], Leticia Classen-Rodriguez[6], Molly Daniels[7], Robyn Grimm[8], Maurice Hall[1], Michael Kiparsky[9], Stephanie Mercado[10], Karina Mudd[11] and Sonia Sanchez[10]

[1]Environmental Defense Fund, San Francisco, CA, United States, [2]Union of Concerned Scientists, Western States Program, Berkeley, CA, United States, [3]Department of Political Science, University of Nevada-Reno, Reno, NV, United States, [4]Department of Applied Economics and Management, Cornell University, Ithaca, NY, United States, [5]Zanjero, Sacramento, CA, United States, [6]SocioEnvironmental and Education Network, Merced, CA, United States, [7]Environmental Incentives, San Diego, CA, United States, [8]California Water Data Consortium, Sacramento, CA, United States, [9]Center for Law, Energy and the Environment, University of California, Berkeley, Berkeley, CA, United States, [10]Self-Help Enterprises, Visalia, CA, United States, [11]Valley Eco, Merced, CA, United States

Achieving water sustainability in many water-scarce regions will require reducing consumptive water use by converting irrigated agricultural land to less water intensive uses. Conventional approaches to this challenge that emphasize water conservation as a singular objective often promote ad hoc practices that temporarily leave land idle while missing an opportunity to enhance landscape resilience and harness synergies of managing water and land together. Multibenefit land repurposing offers an alternative solution to this challenge by strategically transitioning irrigated agricultural land to other beneficial uses that consume less water and provide benefits for multiple constituencies. In practice, multibenefit land repurposing involves the process of collaboration among different groups (e.g., growers and community members) and the outcome of converting irrigated agriculture to other multibenefit uses (e.g., groundwater recharge basins with habitat and water quality benefits). It integrates into a single framework the joint objectives of conserving water, creating benefits for society and the environment, and stimulating the growth of participatory governance networks. But the pathways through which multibenefit land repurposing can achieve these objectives have yet to be demonstrated, either empirically or conceptually. To this end, we illustrate conceptually how multibenefit land repurposing can be designed to enhance water security and enable a transition to more resilient landscapes, building a theory of change around three key elements: (i) creating multibenefit outcomes, (ii) improving strategic regional coordination, and (iii) shifting underlying institutional conditions to promote innovation, adaptation, and cooperation. We draw from experience with the ongoing Multibenefit Land Repurposing Program (MLRP) in California, which has brought together over 100 different organizations in support of eight regional teams to work collectively on coordinated land transformation. We use examples from MLRP to illustrate key components and challenges of the theory of change, including how multibenefit land repurposing may be implemented in practice. Despite being a relatively new approach, we argue that multibenefit land repurposing offers a pathway to building resilient landscapes, including in regions with historically severe and inequitable depletion of water resources.

KEYWORDS

land repurposing, polycentric governance, groundwater sustainability, systems change, landscape resilience, social-ecological systems, water security

1 Introduction

In many water-scarce agricultural regions, increasing demand for water, coupled with the effects of climate change, have pushed social and environmental systems toward irreversible tipping points. These tipping points are evidenced by dry wells and rivers (Pauloo et al., 2020; Penny et al., 2020), abandoned farmland (Subedi et al., 2022), increasing distress migration (Solomon et al., 2024), and growing lists of endangered species (Mount et al., 2019). Given that agriculture accounts for the majority of global water withdrawals (United Nations, 2024), programs that focus on water sustainability often seek ways to reduce agricultural water demand through, for instance, increased irrigation efficiency or conversion to water-efficient crops (Wang et al., 2015). In some cases, however, achieving water sustainability will require removing agricultural land from production, posing a question of what happens to the land that was formerly in agriculture.

Here we focus on the goal of landscape resilience in regions where reducing the irrigated agricultural footprint is a necessary step toward water sustainability (Hanak et al., 2019). Such a water and land transition is often pursued by temporarily leaving cropland idle or permanently retiring cropland (Kelsey et al., 2018; Mooney and Hansen, 2024), both of which decrease water consumption by reducing evapotranspiration from crops. Although well-planned regenerative fallowing can have environmental benefits, a reduction in water access (i.e., through drought or through conservation programs) often leads to an ad hoc process in which fields are left unplanted and idle (Pancorbo et al., 2023). Idle fields, in which soil is exposed to erosion, can contribute to environmental externalities such as pests, weeds, and air pollution, and social externalities such as economic decline in rural communities, particularly when the reduction in agricultural production is extensive or permanent (Alston and Kent, 2004; Ayres et al., 2022a; Dilling et al., 2019; Sunding and Roland-Holst, 2020). In these cases, business-as-usual conservation approaches that prioritize water savings as a singular objective likely miss an opportunity to strategically manage water and land together to enhance landscape resilience and equity. Designing effective conservation tools that jointly address water and land management is therefore a critical policy concern (Foster et al., 2013; Varela-Ortega et al., 2011).

Land repurposing has been advanced as an approach to address this challenge through the conversion of agricultural land to other beneficial uses that consume less water (Bryant et al., 2020; Quandt et al., 2023). *Multibenefit* land repurposing moves beyond this definition to conceptualize land repurposing as the strategic coordination and implementation of projects or practices to create resilient landscapes by repurposing irrigated agricultural land and providing multiple benefits in support of diverse constituencies (e.g., agriculture, rural households, vulnerable communities) and ecosystems (DOC, 2025b; EDF, 2021). Multibenefit land repurposing embodies a paradigm in which agricultural landscapes can be reimagined to enhance water sustainability, support thriving ecosystems, maintain productive agriculture, and ensure water and food security (Fernandez-Bou et al., 2025). Yet as a strategic and collaborative approach to regional-scale water and land management, multibenefit land repurposing is a relatively new concept with limited real-world examples (Kelsey et al., 2018; Quandt et al., 2023). Furthermore, the coordination and implementation question of how multibenefit land repurposing can contribute to resilient landscapes has yet to be addressed.

In this paper, we theorize how multibenefit land repurposing can support resilient and equitable water and land management, drawing on empirical work from geophysical and agronomic studies as well as theories of human behavior, polycentric governance, and resilience of social-ecological systems. In building a theory of change, we argue that land repurposing creates an opportunity to find common ground among diverse parties including landowners, growers, rural communities, Indigenous Peoples, and environmental interests (Espinoza et al., 2023; Fernandez-Bou et al., 2023). As such, it offers potential to facilitate inclusive and adaptive governance that is more resilient to both expected environmental trends (e.g., climate change) and unexpected disturbances (e.g., economic shocks) (Chaffin et al., 2014). Unlike conservation programs that focus on primarily single-purpose benefits (e.g., water savings, flood risk reduction, or habitat restoration) with co-benefits added secondarily, multibenefit land repurposing strategically incorporates multiple benefits from the beginning as a basis for inclusive planning. As such, multibenefit land repurposing is conducive to holistic solutions rooted in transdisciplinary and coproduction of strategies with different actors representing different interests (Fernandez-Bou et al., 2025). While the land repurposing approach can be viewed as one of many tools to enable land and water conservation, we envision the approach as providing a foundation for a paradigm shift that will foster a culture of sustainability. Such ambitious goals are necessary when considering the daunting challenge of moving deeply rooted water and land management regimes toward greater resilience and equity, particularly as many agricultural regions are experiencing hotter conditions with less reliable precipitation.

Interest in land repurposing has grown in recent years in research and practice, particularly in California (Espinoza et al., 2023; Kelsey et al., 2018). For instance, recent geospatial analyses have helped to visualize where programmatic land repurposing may be most valuable in creating benenfits (Bryant et al., 2020; Nuñez-Bolaño et al., 2025). Multiple parties including water resource managers, conservation practitioners, and agricultural interests have expressed support for strategic land repurposing alongside appropriate incentives for growers (Quandt et al., 2023). Further economic analysis using input–output models has found that strategic land repurposing investments have the potential to offset costs and bring net economic benefits to local communities in California (Fernandez-Bou et al., 2023). Real-world examples are also emerging through intensive efforts under California's Multibenefit Land Repurposing Program (MLRP) (DOC, 2025b). Many of the authors of this manuscript (see Acknowledgements) are actively involved in implementing MLRP, and we draw conceptually from this program to illustrate potential ways that multibenefit land repurposing may work in practice. However, we lack empirical data from which to draw broad conclusions about the effects of the approach. As such, the current efforts under MLRP serve as an experiment through which to test multibenefit land repurposing concepts and solutions. We therefore focus on developing a theory of change to articulate how multibenefit land repurposing, and by extension MLRP, can be designed and implemented to achieve more resilient landscapes.

We begin by discussing how a business-as-usual approach to water conservation may produce undesirable results due to a resources challenge associated with insufficient, or poor quality, water and land (Section 2.1), a governance challenge associated with collaborative decision making (Section 2.2), and a structural challenge associated with limited financial and technical capacity, lack of experimentation, and entrenchment of the status quo (Section 2.3). We then introduce an example of the San Joaquin Valley in California and briefly review the guidelines and status of MLRP (Section 3). Subsequently, we theorize how multibenefit land repurposing can help address the aforementioned challenges by transforming physical landscapes, governance structures, and the underlying conditions necessary to create resilient landscapes (Section 4). To ground our theory of change, we include an example describing how MLRP is being implemented in Madera County, California (Section 4.4). We then step back to discuss how the broader policy and management context can be tailored to support effective multibenefit land repurposing programs (Section 5.1). We conclude by summarizing the potential benefits of multibenefit land repurposing, as we describe in this manuscript, in the context of challenges, uncertainties, and unanswered questions to motivate additional research (Section 5.2).

2 Key challenges in water and land management

Multibenefit land repurposing has the potential to catalyze a shift toward resilient landscapes by concurrently addressing key challenges that lie at the nexus of water and land management: (i) a resources challenge associated with water insecurity, environmental degradation, and environmental injustice, (ii) a governance challenge associated with lack of coordination and inequities in decision making, and (iii) a structural challenge having to do with limited capacity to explore new ideas and mental models that reinforce the status quo. Although these challenges are closely related, business-as-usual conservation programs that solely emphasize water sustainability are unlikely to address them holistically. In this section we describe the challenges broadly, with references to examples from around the world, noting that we explore the challenges in greater depth through the California case study (Section 3).

2.1 The resource challenge

Climate change, population growth, and economic development have strained our environmental systems, contributing to unreliable access to increasingly contaminated resources. We refer to the resource challenge as the issue of addressing insufficient, or poor quality, land, water, and air. In many cases (Chiarelli et al., 2022; Di Baldassarre et al., 2018; Micklin, 2007; Penny et al., 2016), the resource challenge grows as competition increases for scarce resources due to increasing demand or increasingly unreliable supply associated with climate change (Overpeck and Udall, 2020). For instance, water diversions and groundwater extraction can threaten ecological health by altering natural flows (Rahman et al., 2019) and concentrating contaminants (Iqbal et al., 2025; Meng et al., 2024). These issues also threaten water security of households (Srinivasan et al., 2025), farms (Deines et al., 2020), and cities (Calverley and Walther, 2022), and undermine the value of land and property (Henry, 2024; NASS, 2024; Shew et al., 2024). Manifestations of the resource challenge have occurred in regions around the world. Crystalizing this point, Porkka et al. (2024) found that 39% of global land area is associated with increasingly frequent low streamflow, largely due to reservoir construction and irrigation expansion. Notable examples of the resource challenge include, but are not limited to, Australia (Wei et al., 2011), China (Chen et al., 2003), Pakistan (Wescoat et al., 2018), and Spain (Vicente-Serrano et al., 2019).

Conserving water by reducing agricultural demand may be necessary to address these challenges in many water-scarce agricultural regions. Business-as-usual conservation approaches often elevate temporary cropland fallowing, or simply leaving land idle, as a solution to water scarcity (DWR, 2025; Harris, 2023). Temporarily leaving land idle without careful management, however, may lead to undesirable externalities such as the proliferation of pests and weeds, erosion and soil degradation, and the mobilization of airborne pollutants from dry soil (Ayres et al., 2022b; Reicosky et al., 2023). Expansion of idle land may also reduce employment opportunities and weaken the regional economy. At the same time, there may be opportunity costs associated with unproductive idle land when it could be converted to alternative land uses, such as recovering lost habitat, creating new green spaces, or constructing renewable energy facilities.

Ad hoc approaches to conserve water also miss an opportunity to capture synergies of managing both water and land together (Mooney and Hansen, 2024; Plassin et al., 2021). Many of the drivers and consequences of the resource challenge are spatially related, and strategically conserving water and land resources can improve outcomes of conservation while mitigating negative environmental and social concerns (Kelsey et al., 2018).

2.2 The governance challenge

The resource challenge described above is often accompanied by a governance challenge, or specifically, a collective action problem wherein individual incentives impede the ability of the collective to agree upon or implement sustainable and equitable solutions (Gardner et al., 1990). We define governance as the set of social and political processes, rules, and norms that collectively determine how goals are defined and tradeoffs are resolved, thereby shaping specific decisions and actions that determine how resources are utilized (Biggs et al., 2012; Kiparsky et al., 2016). The governance challenge therefore has to do with overcoming conflicting incentives among actors to enhance coordination and equitably manage limited and potentially polluted water and land resources (Ostrom, 2005). The governance challenge commonly occurs in water-scarce agricultural regions ranging from Australia (Marshall and Alexandra, 2016), to Bangladesh (Ishtiaque et al., 2017), Mexico (Hoogesteger and Wester, 2017), and South Africa (Rawlins, 2019).

In water-scarce agricultural landscapes, growing demand for water often contributes to a competitive environment where individualistic decisions are prioritized (Gardner et al., 1997). This concern can be exacerbated by the need to maximize revenues to offset risks and increasing costs of seeds, fertilizer, and other agricultural inputs. Despite good intentions, business-as-usual agricultural water conservation programs may manifest in fragmented decision-making that undermines resilience amidst change (Mendez-Barrientos et al., 2019). For instance, top-down approaches to conservation (i.e., those that are designed and managed centrally by government agencies) are likely to be insufficient because they fail to match the needs of agricultural landowners and growers, who have discretion over how to manage the land (Koebele et al., 2022). Similarly, purely bottom-up approaches (i.e., those built on voluntary, individual decisions in response to external factors such as drought or incentive payments) may fall short by failing to maximize the multiple benefits of intentionally managing land and water together or considering landscape-scale processes, as these activities require coordination and technical capacity to design and evaluate projects across the landscape. Bottom-up approaches may also exclude underrepresented groups from the decision-making process, producing outcomes that disproportionately favor those with political influence (Dobbin and Lubell, 2021; Ostrom, 2005).

Addressing landscape inequities in polycentric land and water governance arrangements, where multiple actors hold different, yet often overlapping authorities over decision making (Carlisle and Gruby, 2019), requires approaches to cross-scale collaboration and coordination that not only promote equitable representation but also equitable influence over decisions and outcomes (Koebele et al., 2024). Achieving these goals may require overcoming financial or capacity restrictions on inclusive participation, setting clear rules for collaboration, and providing readily-accessible platforms for information sharing (Gerlak et al., 2012). Effective leadership may further support equitable participation (Pholsim and Inaba, 2022). However, even with these procedural elements in place, direct governmental oversight may be necessary to guide resources toward equitable outcomes (Ostrom, 2005), though this may also be challenged by fragmentation in governance authority over different aspects of the problem or across scales (Kim et al., 2015; You, 2024). Identifying institutional configurations that promote equitable outcomes in environmental transitions amidst these challenges is therefore critical for addressing the governance challenge at the land and water management nexus.

2.3 The structural challenge

The governance challenge described above is underpinned by a structural challenge in which systems becomes increasingly constrained by limited capacity to experiment with new ideas or adapt to changing circumstances (Holling, 2001). This issue of stagnation or path dependence is particularly concerning in the face of climate change, growing water scarcity, and increasing pollution (Marshall and Alexandra, 2016). The structural challenge is shaped by institutions (rules, norms, and strategies) and perceptions, or mental models, that reinforce existing behaviors and therefore maintain the status quo (Anderies et al., 2016; Monat and Gannon, 2015). The structural challenge is common to many social-ecological systems (Holling, 2001) including examples in India (Shah, 2010), Nigeria (Shanono et al., 2019), and the United States (Fernandez-Bou et al., 2021b).

To illustrate how this challenge may emerge and become increasingly intractable, consider the following dynamics that commonly occur in fertile, water-scarce regions. Historical land and water development patterns, coupled with modern economic incentives, often motivate the production of water-intensive crops to generate income and support livelihoods, even as the necessary land and water inputs become degraded in the process. Long-standing social and cultural values often favor existing practices, including conventional agriculture, over alternatives that may be more sustainable (Wreford et al., 2017). This process leads to systems that stagnate around existing behaviors, inhibiting opportunities to experiment with new solutions and learn how to address emerging threats (Holling, 2001). Collectively, these factors can produce a scenario in which landowners and growers face difficulties in preserving a livelihood strategy that is increasingly untenable in the face of larger market, environmental, and regulatory forces, and where they are increasingly disincentivized to act in the interest of the collective (Shah, 2010).

Consequently, there is a need to reshape key institutions that influence behavior across scales, from the farm to the region. This includes fostering an environment that encourages experimentation, rewards collaboration, and promotes sustainability (Holling, 2001). It includes cultivating the capacity to collaborate and innovate around new ideas (Cundill et al., 2015). If new behaviors are adopted and contribute to more desirable outcomes, perceptions of what is acceptable and possible are likely to shift and individuals across constituencies may learn to adopt new mental models about the system (Levy et al., 2018). This process may require new financial investment to catalyze these changes, including incentivizing new behavior and creating new institutions (Ranjan et al., 2019; Wreford et al., 2017). Such investments are likely necessary to catalyze a shift away from business-as-usual conditions to those that enable resilient landscapes.

3 Case study: the San Joaquin Valley

3.1 Land and water challenges

To provide a better sense of how these challenges create opportunities to improve water security and resilience, using a multibenefit land repurposing approach, we shift our focus to the example of the San Joaquin Valley in California. The San Joaquin Valley highlights how challenges associated with water and land management generate the need for creative approaches to water sustainability (Figure 1). The Valley also serves as an active testing ground to understand and explore multibenefit land repurposing, having received recent funding from the state government through MLRP.

Water and land challenges are intimately related in the San Joaquin Valley due to its fertile soils, arid climate, and economic reliance on agriculture. Demand for agricultural products and associated economic opportunities led to widespread conversion of habitat areas to agricultural land in the nineteenth century (Olmstead and Rhode, 2020; Stewart et al., 2019), including the removal of 95% of historical wetlands (Garone, 2020). Agriculture became the economic engine of the Valley, creating new demands for water and motivating the construction of extensive surface water infrastructure for storage and conveyance, and a parallel legal framework for managing and allocating water. Surface water rights in California are governed both by riparian rights, in which rights are associated with

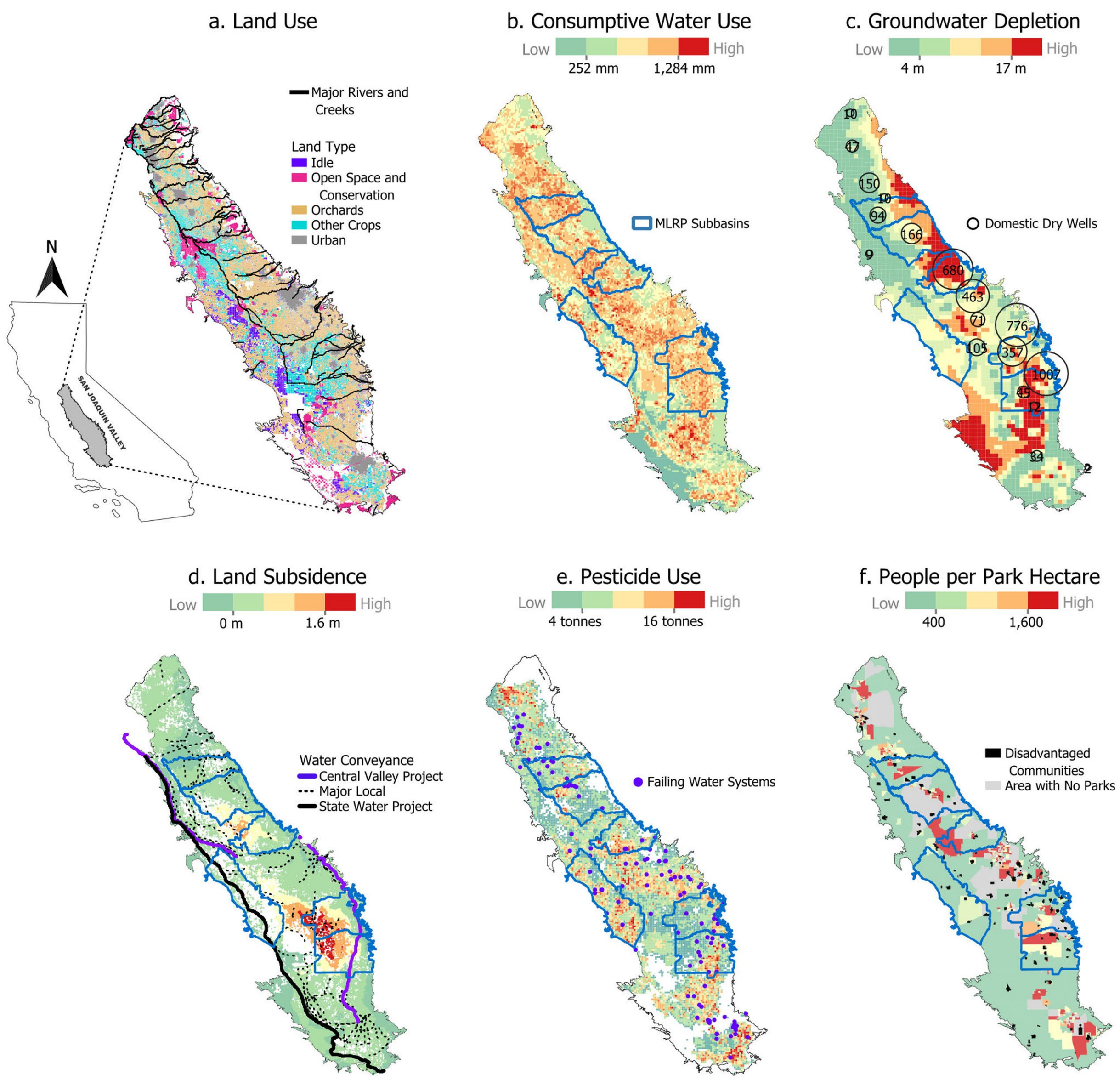

FIGURE 1
San Joaquin Valley drivers of change, undesirable outcomes, and MLRP subbasins. **(a)** Land use map including major crop categories (DWR, 2024a) and protected areas (GreenInfo Network, 2024). **(b)** Average annual consumptive water use (2014–2023) (Melton et al., 2022) **(c)** Groundwater depletion (1995–2020) (Levy et al., 2021) and counts of reported domestic dry wells (2014–2024) (DWR, 2024b) **(d)** Total land subsidence (2015–2024) (DWR, 2024c) and canal system. **(e)** Average annual pesticide use (2011–2022) (DPR, 2024) and failing water systems as defined by the California State Water Board (CSWRCB, 2024) **(f)** Population per park area (California State Parks, 2020) and disadvantaged communities (Fernandez-Bou et al., 2023).

land ownership along waterways, and appropriative rights, in which rights are allocated based on the time of first use (Börk, 2022). Appropriative water rights give priority to older claims that demonstrate continued beneficial use, meaning those with senior rights must continue to use water to maintain their right. Those with junior rights are first to lose access to surface water in times of drought. In contrast, groundwater rights were historically associated with the principle of correlative use, in which landowners may extract a reasonable amount according to the extent of their overlying land. Outside of court adjudications, this right was rarely enforced, allowing unregulated pumping in many parts of the state (Owen et al., 2019). Recent developments, however, are changing groundwater rights. In particular, the state passed the California Sustainable Groundwater Management Act (SGMA) in 2014, which will require groundwater subbasins across the state to achieve sustainability by 2040. We briefly describe SGMA and key implications, below.

As of 2023 in the San Joaquin Valley, there are over 1.7 million hectares of irrigated agriculture (Figure 1a), of which over 1 million hectares are water-intensive orchards (almonds account for 489 thousand ha) (DWR, 2024a). The landscape reflects the long-term evolution of agriculture in the Valley, shifting from primarily annual crops to orchards. For example, the region once supported extensive cotton cultivation, with more than 480 thousand hectares in the early 2000s, declining to just over 100 thousand hectares by 2019 (USDA NASS, 2022). This transition has been driven by economic profitability and largely enabled by advances in irrigation techniques such as drip and micro-sprinkler systems (Taylor and Zilberman, 2017). While these technologies allow for more efficient irrigation, they have also enabled the expansion of cropland, including in marginal lands and areas reliant solely on groundwater, contributing to an overall increase in water demand. This agricultural intensification has driven high levels of water consumption, as shown by evapotranspiration (ET) patterns across the region (Figure 1b).

The transition to water-intensive agriculture in the San Joaquin Valley was not without consequences. As surface water became increasingly scarce, groundwater extraction grew dramatically to 40% of the state water supply (Hanak et al., 2019). Groundwater pumping has led to aquifer depletion across the valley, resulting in over 3,800 domestic wells going dry in the past ten years (2014–2024) (DWR, 2024b) (Figure 1c). Subsidence in areas of extensive groundwater depletion damaged major canals (Figure 1d), decreasing delivery capacity and requiring costly repairs (DWR, 2023). The Friant-Kern Canal, the eastern artery of the Central Valley Project, has experienced a 60% reduction in capacity (Friant Water Authority, 2019), while the California Aqueduct, the main canal of the State Water Project, has lost 44% of its designed capacity (DWR, 2023). Recycling of groundwater for repeated irrigation has also led to concentration of salts and degraded soils, diminishing yields in places that lack the ability to flush salts from the soil (Levy et al., 2021; Pauloo et al., 2021; Scudiero et al., 2017). At the same time, demand for farm labor fueled the growth of vulnerable, lower-income communities entirely dependent on groundwater for water supply (Palerm, 2000).

The region also faces environmental justice challenges. Many community water systems throughout the valley have been designated as failing water systems by the California State Water Resources Control Board (CSWRCB, 2024). These water systems fail to meet drinking water standards, often due to high concentrations of nitrates or pesticides, or are unable to provide drinking water due to water shortages (Bennett et al., 2024; Larsen et al., 2017; Li et al., 2023) (Figure 1e). Research has shown that these issues disproportionately affect vulnerable communities (Balazs and Ray, 2014; London, 2021; Pace et al., 2022). Areas with limited park access exacerbate these environmental burdens, as underserved populations are deprived of essential recreational and green space amenities, which are critical for access to a healthy environment and overall well-being (Figure 1f). This lack of access contributes to the broader public health threats faced by vulnerable communities (O'Connell et al., 2023; Rowland-Shea et al., 2020). Many of these issues will be exacerbated by climate change, which will lead to higher temperatures, greater variability in total precipitation, greater likelihood of extreme events, and greater evaporative demand, along with less total snowpack storage and changes in the seasonality of snowmelt (Medellín-Azuara et al., 2024; Swain et al., 2018).

Concerns around groundwater in the San Joaquin Valley reached a tipping point in 2013–2014 when extreme drought resulted in water rationing across California and spurred the state legislature to pass SGMA (Leahy, 2015). SGMA requires subbasins across California to meet a variety of sustainable groundwater management criteria by 2040 (Leahy, 2015) and is reshaping the San Joaquin Valley in multiple ways. Although SGMA avoids the topic of land management, achieving groundwater sustainability under the law could require removing 500–900 thousand acres (approximately 200–400 thousand hectares) of irrigated farmland from production, amounting to nearly 20% of irrigated agriculture in the valley (Hanak et al., 2019; Hanak et al., 2023). Additional farmland may need to come out of production due to warming temperatures and changes in precipitation associated with climate change (Escriva-Bou et al., 2023). Such a dramatic shift in agriculture threatens the economic fabric of the valley. Farm production and economic revenues will fall and many growers may be forced out of agriculture, especially in areas without surface water rights. Land values in areas with reduced water access have already plummeted by up to 50% (Henry, 2024; Shew et al., 2024). The livelihoods of households that depend on economic activities associated with agriculture will be also threatened (Quandt et al., 2023). Expansion of idle land and loss of active vegetation will increase temperature, dust pollution, and the likelihood of dust storms, posing further environmental hazards for the region (Adebiyi et al., 2025).

SGMA is also reshaping groundwater governance in the Valley. Under SGMA, authority is shared across multiple decision-making centers, both in terms of delegating responsibility for groundwater sustainability to local agencies and in terms of facilitating communication and decision making across scales. SGMA requires the formation of local Groundwater Sustainability Agencies (GSAs) that oversee local groundwater management, including the development and implementation of Groundwater Sustainability Plans (GSPs). GSPs are regulatory documents that outline strategies to achieve groundwater sustainability within each groundwater subbasin. Increased collaboration can be viewed as an objective of the law (Lubell et al., 2020) which supports connectivity across governance structures at multiple levels (Milman and Kiparsky, 2020). The formation of GSAs and creation of GSPs have contributed to greater participation in groundwater management (Quandt et al., 2023).

Despite these features, implementation of SGMA has reflected aspects of the business-as-usual conservation approach described above. For instance, without further intervention, water conservation under SGMA may occur through an uncoordinated, ad hoc process that expands idle land, introduces pests, worsens air quality, and exacerbates inequalities (Quandt et al., 2023). Local decision making and coordination structures under SGMA have often emerged from existing institutions, thereby continuing to marginalize historically underrepresented and underserved parties, including low-income rural communities (Dobbin and Lubell, 2021), small and socially disadvantaged farmers (Mendez-Barrientos et al., 2019), and growers outside irrigation districts (Mendez-Barrientos et al., 2019). Conflicting interests and lack of trust among diverse parties are among the most frequently cited obstacles to inclusive planning in SGMA implementation (Leach et al., 2021). Additionally, the high transaction costs associated with participating in SGMA's groundwater governance approach preclude many actors from the social and political interactions that create an opportunity for representation and policy influence (Koebele et al., 2024). In other words, a business-as-usual approach under SGMA could address a water problem while exacerbating other social and environmental issues.

3.2 The Multibenefit Land Repurposing Program (MLRP)

Concerns about groundwater pumping limitations, declining agricultural land values, historical loss of habitat, and increasing environmental health risks have generated intense focus on how to minimize the ramifications of such a dramatic transition in California (Kiparsky, 2016; Niles and Hammond Wagner, 2018). Growing interest in land repurposing in the San Joaquin Valley contributed to the state legislature funding the Multibenefit Land Repurposing

Program as a large-scale experiment to test innovative approaches to manage landscapes under increasing water scarcity (EDF, 2021). Note that we refer to this specific program using the acronym MLRP, while avoiding using a similar acronym (i.e., MLR) when discussing multibenefit land repurposing generally.

MLRP is administered by the California Department of Conservation (DOC) and has leveraged nearly US$100 million in state funding to bring together over 100 organizations to contribute to this process (Self-Help Enterprises, Environmental Defense Fund, and Environmental Incentives, 2024). State budget bills passed in 2021 (SB170, Ch 240, Stat. of 2021) and 2022 (AB 211, Ch. 574, Stat. of 2022) funded the program with the goal of repurposing irrigated agricultural lands to improve groundwater sustainability, enhance wildlife habitat, and provide benefits to vulnerable communities [i.e., disadvantaged communities as defined by California state agencies (CalEPA, 2022)]. DOC solicited block grant applications of up to $10 million from GSA-led or GSA-affiliated teams to implement regional multibenefit land repurposing efforts in high-priority or critically overdrafted subbasins (DOC, 2025b, 2025a). DOC awarded eight block grants from 2022 to 2023, including six in the San Joaquin Valley (see Figure 1b), prioritizing proposals that (i) aligned with program goals, (ii) demonstrated the ability to build strong partnerships, (iii) focused on creating benefits for disadvantaged communities, and (iv) were led by teams with strong capacity and expertise (DOC, 2025b). Block grantees (i.e., the teams awarded block grants within each subbasin) focus on a range of activities such as outreach, coordination, planning, project implementation, and monitoring (Self-Help Enterprises, Environmental Defense Fund, and Environmental Incentives, 2024). Every block grantee must also prepare a multibenefit agricultural land repurposing plan that describes strategies and opportunities for multibenefit land repurposing within the subbasin area [for complete requirements, see DOC, 2025b]. Because participation in MLRP is voluntary, grantees can also create financial incentives to motivate growers to enroll their land in MLRP. In this manuscript, we use the term "growers" to broadly refer to land-owning or land-operating individuals with the authority to make long-term decisions about agricultural land management. Growers therefore may comprise agricultural landowners, tenant and small farmers, and socially disadvantaged growers (DOC, 2025b). In addition to the block grant funding, DOC created a separate Statewide Support Entity (SSE) to facilitate collaboration across subbasins, build capacity, and oversee program-wide monitoring efforts (DOC, 2025b). The program-wide monitoring approach developed by the SSE focuses on high-level indicators that capture elements of engagement, collaboration, project costs, and project outcomes consistently across the program (Self-Help Enterprises, Environmental Defense Fund, and Environmental Incentives, 2025). DOC further requires each block grantee to develop monitoring plans for individual projects (DOC, 2025b).

In practice, block grantees coordinate program implementation within each subbasin while meeting regularly with DOC and, separately, with all MLRP organizations through SSE-organized meetings. DOC works with block grant teams to ensure progress toward regional goals. While block grantees have considerable discretion over how to approach land repurposing in their subbasins, they must work closely with DOC to ensure that all program costs are eligible for reimbursement. DOC approves individual project funding only after ensuring that projects meet program guidelines, which require that projects enhance groundwater sustainability and provide at least one additional benefit for society or the environment (DOC, 2025b). DOC also requires that each subbasin collectively advances projects that contribute to connectivity of resources such as habitat or energy, are conducted on lands least viable for irrigated agriculture, and provide meaningful benefits for disadvantaged communities (DOC, 2025b). Regarding the latter requirement, MLRP guidelines outline four criteria that must be met for DOC to determine that a project provides meaningful community benefits. To meet these criteria, projects must (i) intentionally create direct, measurable benefits that (ii) enhance community resources and (iii) meet an expressed need of the community while (iv) protecting against harms to the community and community resources. Full details on these requirements are available through the MLRP guidelines for Round 1 (DOC, 2025a) and Round 2 (DOC, 2025b) solicitations. Beyond the state general funds that support the current block grant awards, California voters recently approved a general obligation bond which includes an additional $200 M public investment in MLRP, ensuring the program remains funded in California in coming years (California Proposition 4 of 2024).

In the sections below, we describe a theory of change for multibenefit land repurposing, building our analysis on existing literature and informed by progress within MLRP. While we use the example of MLRP the San Joaquin Valley as an empirical illustration of how multibenefit land repurposing can be designed and implemented, we note that the Valley reflects many of the challenges faced by water-scarce agricultural landscapes in other regions. For instance, agriculture is the primary water user in many basins around the world, and ecological health has suffered due to reduced habitat area and connectivity (Bond et al., 2019; Hoang et al., 2023). Rural communities in these basins commonly depend on groundwater for domestic water supply and face increasing risks due to groundwater depletion and contamination (Levy et al., 2021; Pauloo et al., 2020). Likewise, many regions exist in which economic and institutional inertia complicate efforts to improve water and land sustainability (Nath et al., 2023). As such, we anticipate the research presented in this article will inform land and water management approaches in regions beyond the San Joaquin Valley.

4 Multibenefit land repurposing as a promising solution

The challenges described above reveal how business-as-usual water conservation approaches may produce undesirable, inequitable outcomes stemming from lack of strategic planning and persistence of entrenched institutions. At the same time, the opportunity that emerges through conservation brings the potential to create landscapes that support a mosaic of productive agriculture, healthy communities, and thriving habitat, if designed and implemented intentionally. We argue that multibenefit land repurposing can help catalyze this shift by providing a template for regional coordination and landscape transformation (Figure 2). In what follows, we present a theory of change for multibenefit land repurposing, building our argument on scholarly literature and examples from MLRP in the San Joaquin Valley. Because MLRP is a work-in-progress and the outcomes of the program have not yet been realized, we focus our analysis on how multibenefit land repurposing can be designed to promote resilient landscapes while highlighting specific challenges that may arise and complicate land repurposing efforts. The theory of change therefore serves multiple purposes. On the one hand, it articulates a vision for how multibenefit land repurposing can contribute to equitable, adaptive, and productive landscapes. On the other hand, it can be considered a set of hypotheses that serve as a framework for future critical analyses of multibenefit land repurposing programs such as MLRP.

In the context of irrigated agricultural land needing to come out of production (Figure 2-i), multibenefit land repurposing targets multiple aspects of the existing system to advance a transformation toward resilient landscapes. It can be designed to reshape business-as-usual enabling conditions (Figure 2-ii) through new incentives, opportunities, and resources to enable collaborative mindsets, increased financial and social capital, and new adaptive strategies. It can be structured to strengthen collaborative and adaptive governance networks through regional coordination and planning (Figure 2-iii). And if executed well, it can add social and environmental value to the landscape through multibenefit projects (Figure 2-iv). In the following subsections, we theorize how these transformations can occur and identify obstacles that may impede such transformation, using MLRP as a basis for analysis. In particular, we focus on the potential for multibenefit land repurposing to address the resource challenge through multibenefit projects (Section 4.1), the governance challenge through regional coordination (Section 4.2) and the structural challenge through a shift in the enabling conditions for water and land management (Section 4.3). We conclude by grounding our analysis in the Madera County MLRP block grant, one of the eight regional grantees implementing MLRP (Section 4.4).

4.1 Creating value through multibenefit projects

Multibenefit land repurposing can be used to mitigate the challenge of inadequate land, water, and air (addressing the Resource Challenge defined in Section 2.1) through the implementation of multibenefit projects that reduce the strain on resources and create social and ecological value. Within MLRP, block grantees determine what outcomes are most valuable and therefore how to properly incentivize projects that achieve these outcomes. Potential projects and benefits being explored within MLRP include habitat restoration to improve ecosystem health and connectivity, green spaces to provide recreation for communities, and renewable energy facilities to reduce greenhouse gas emissions (Self-Help Enterprises, Environmental Defense Fund, and Environmental Incentives, 2025). Projects can be designed to meet the needs of local communities through, for instance, job retraining or the creation of other economic benefits. Growers can benefit from projects through incentive payments or other design features such as enhanced subsurface water storage, soil

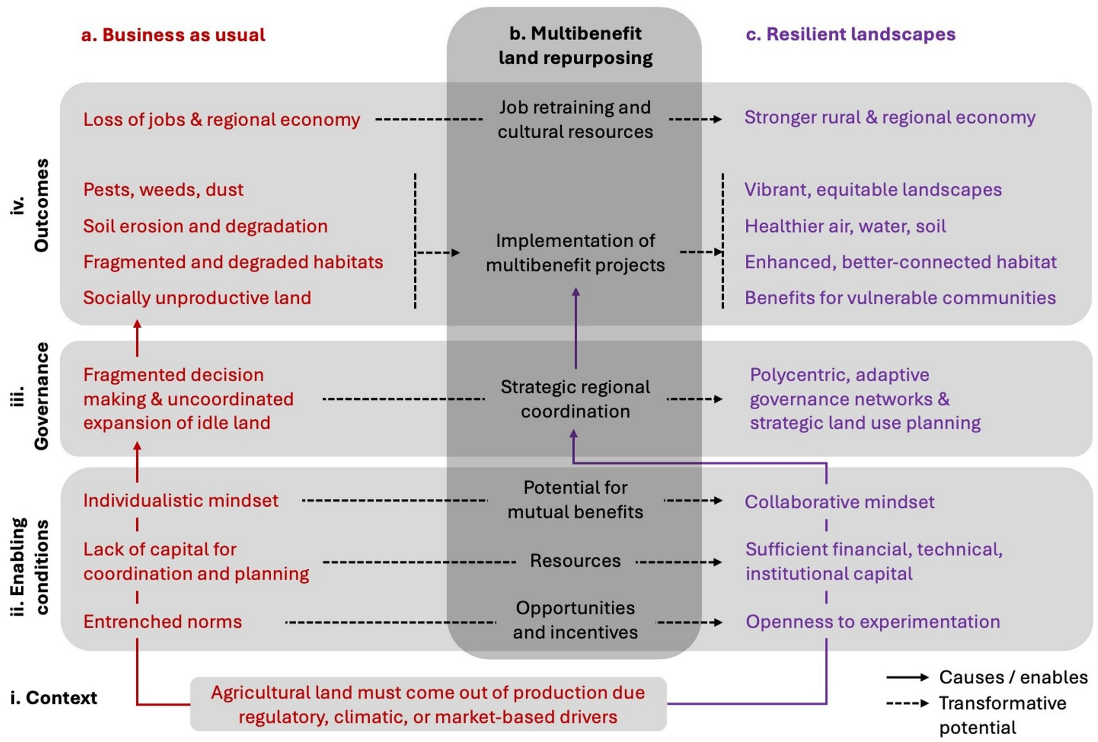

FIGURE 2
Transformative goals of multibenefit land repurposing in situations where agricultural land must come out of production. **(a)** Business-as-usual water conservation, with enabling conditions (**ii**, see Section 2.3) and fragmented decision making (**iii**, Section 2.2) that lead to an uncoordinated process that leaves land idle and socially unproductive (**iv**, Section 2.1). **(b)** Multibenefit land repurposing seeks to establish new institutions and incentives, motivate collaboration, and implement multibenefit projects. **(c)** Resilient landscapes, the ultimate goal of multibenefit land repurposing, can be characterized by a spirit of adaptation, collaborative and adaptive governance, and sustainable, productive, and more equitable landscapes. The potential for multibenefit land repurposing to transform landscapes is dealt with in the remainder of Section 4 for Outcomes (**iv**, Section 4.1), Governance (**iii**, Section 4.2), and Enabling conditions (**ii**, Section 4.3).

TABLE 1 Potential benefits from land repurposing projects synthesized from literature.

Solutions	Benefits
Transitioning from water-intensive crops (e.g., orchards) to water-efficient crops or non-agricultural uses.	• Reduced water consumption and drought resilience (Escriva-Bou et al., 2023; Medellín-Azuara et al., 2024; Richter et al., 2017) • Reduced air and water pollution from fertilizer and pesticide use (Larsen et al., 2023; Nicholson and Williams, 2021; Rudnick et al., 2021) • Multiple socio-economic and public health benefits, especially near communities (Ayres et al., 2022a; Espinoza et al., 2023; Fernandez-Bou et al., 2023; Gunier et al., 2017) • Reduced vulnerability in regions prone to subsidence and/or with high domestic well density (Levy et al., 2020; Pauloo et al., 2020; Rodríguez-Flores et al., 2023) • Diversified sources of income and job training (Hoffacker et al., 2017) • Adoption of climate-resilient crops to ensure farmers' productivity (Pathak et al., 2018; Rising and Devineni, 2020)
Transitioning to regenerative agriculture	• Preservation and sequestration of soil carbon (Mitchell et al., 2017; Tully and Ryals, 2017; Vendig et al., 2023) • Increased soil water holding capacity (Borum et al., 2024; DeVincentis et al., 2022; Mitchell et al., 2012) • Enhanced pollinator habitat and above- and below-ground biodiversity (Altieri and Nicholls, 2018; Guzman et al., 2019, 2021; Heisey et al., 2022) • Increased agricultural resilience to climate change (Kaye and Quemada, 2017; Morris and Bucini, 2016) • Reduced agrochemical inputs (Benbrook et al., 2021; Larsen et al., 2024; Larsen and Noack, 2021) • Socio-economic and public health benefits (Bezner Kerr et al., 2022; Larsen et al., 2017; Rasmussen et al., 2024; van der Ploeg et al., 2019)
Managed aquifer recharge (MAR)	• Greater water availability through replenished groundwater (Alam et al. 2020) • Reduced flood risks (Kocis and Dahlke 2017; Huang and Swain 2022) • Enhanced groundwater levels and quality (Bijay-Singh and Craswell, 2021; Ulibarri et al., 2021) • Incentives for farmers to adopt water conservation practices (Bruce et al., 2023) • Improved protection of drinking water supply wells (Castaldo et al., 2021; Marwaha et al., 2021)
Habitat and floodplain restoration	• Support for threatened and endangered species (Bourque et al., 2019; Keeley et al., 2018; Richmond et al., 2017; Stewart et al., 2019) • Enhanced upland and riparian habitats (Bryant et al., 2020; Lortie et al., 2018; Serra-Llobet et al., 2022) • Enhanced habitat connectivity (Cameron et al., 2022; Keeley et al., 2018; McComb et al., 2022) • Improved baseflow and protected groundwater-dependent ecosystems (Hall et al., 2018; Howard et al., 2023; Rohde et al., 2018)
Solar photovoltaic projects	• Contribution to regional clean energy transition goals (Ayres et al., 2022b; Biggs et al., 2022; Kalra et al., 2024) • Diversification of farm-scale economic revenue through agrivoltaic systems (Fernández-Bou et al., 2024; Cuppari et al., 2021; Warmann et al., 2024) • Affordable and reliable energy source for communities (Lukanov and Krieger, 2019; Miraee-Ashtiani et al., 2023; Murphy et al., 2024) • Enhanced revenue from marginal agricultural lands with minimal ecological impact (Hoffacker et al., 2017; Wu et al., 2023) • Enhanced ecosystem functions and conservation outcomes in ecovoltaic systems (Ashraf et al., 2024; Moore-O'Leary et al., 2017; Nordberg et al., 2021) • Greater retention of soil carbon and soil moisture (Hernandez et al., 2019; Krasner et al., 2025)
Projects led or co-led by communities and/or Tribes	• Protected and/or enhanced community assets (Pastor et al., 2024; Wang et al., 2023) • Improved access to green spaces and recreational areas, promoting physical and mental health benefits (Ekkel and de Vries, 2017; Flegal et al., 2013; O'Connell et al., 2023; Rowland-Shea et al., 2020; Sister et al., 2010) • Enhanced food access and well-being through community gardens (Algert et al., 2016; Ferris et al., 2001; Lin and Egerer, 2020; Twiss et al., 2003) • Greater climate resilience and mitigation of exposure to climate impacts (Benevolenza and DeRigne, 2019; Hankins, 2024; Jerrett et al., 2024; Pfefferbaum et al., 2013) • Opportunities to foster education, leadership, stewardship, and engagement (Bennett et al., 2018; Fernandez-Bou et al., 2021a; Hibbett et al., 2020; Merenlender et al., 2016) • Support for tribal practices, co-management, stewardship, and return of land to Tribes (Anderson, 2005; Baldy, 2013; Long et al., 2022; Long and Lake, 2018; Ross et al., 2008; Stevens, 2020)

conservation, or water savings. The types of benefits that can be created are varied (see Table 1) and may be combined in creative ways.

Each subbasin in MLRP has approached this challenge differently based on local needs and preferences. In the planning stages, some regions have emphasized strategies such as cover crops (Borum et al., 2024), multibenefit groundwater recharge basins that include habitat restoration (EDF, 2020a), agrivoltaic solar energy projects (Fernandez-Bou et al., 2024), and buffer zones around communities to reduce environmental health concerns (Fernandez-Bou et al., 2023). The first set of MLRP-funded projects was approved by the California Department of Conservation in 2024 (Self-Help

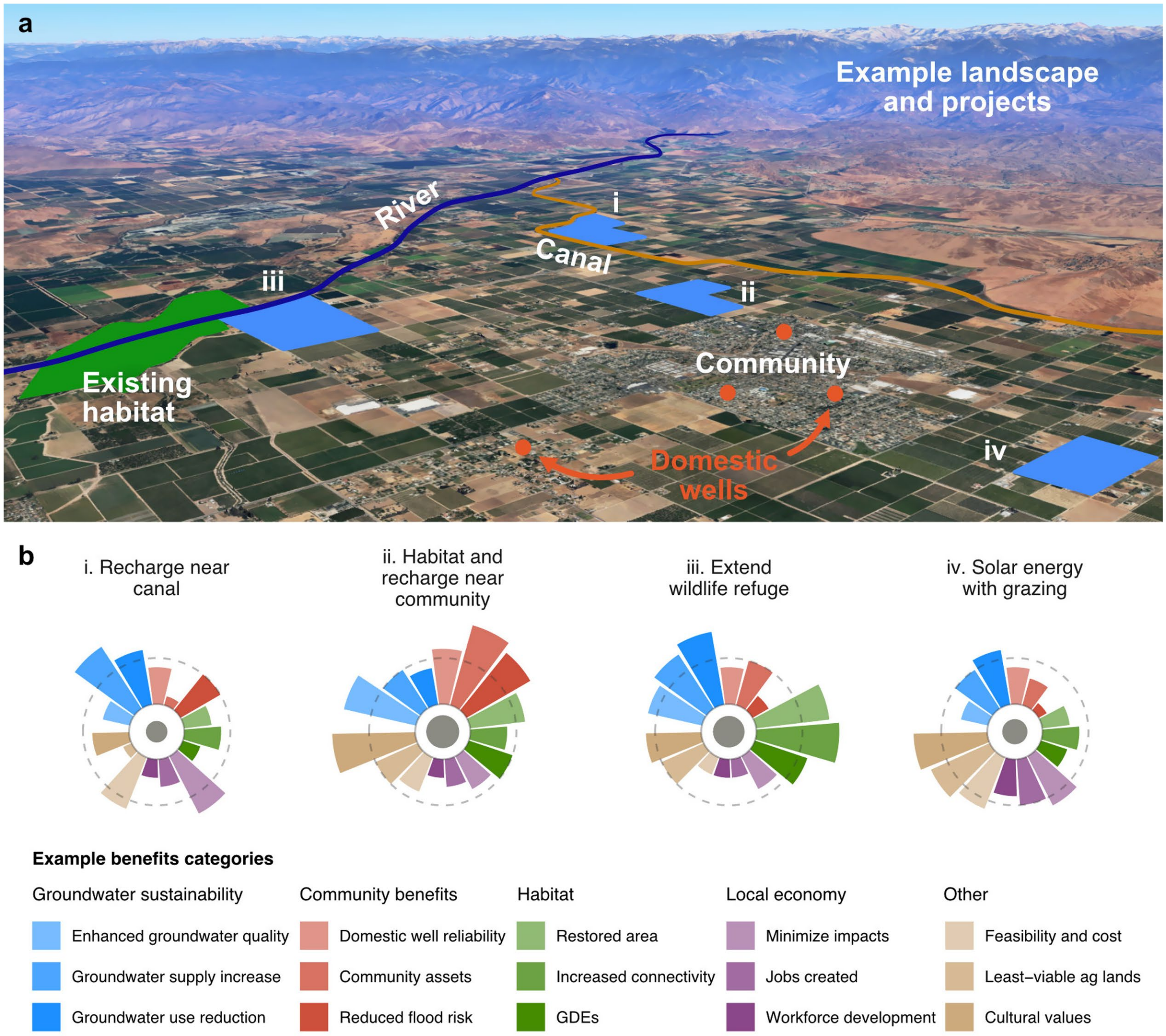

FIGURE 3
Illustrative example of land repurposing options, benefits, and tradeoffs. **(a)** The hypothetical land repurposing projects presented in the figure include **(i)** an aquifer recharge project near a canal, (ii) creation of green space and aquifer recharge near a disadvantaged community, **(iii)** extension of wildlife reserve via riparian habitat restoration, and **(iv)** conversion to solar energy with grazing. **(b)** Benefits and tradeoffs for the four example projects across five categories (water, community, habitat, economy, other). The values for each benefit were chosen to be representative of what could be anticipated from each project, while noting that various actors might score and weigh the value of each benefit differently. Quantifying benefits under each category may require multiple indicators (e.g., water sustainability could include increased supply, reduced consumption, and enhanced water quality). Equitably identifying and navigating these tradeoffs represents a key component of the governance challenge.

Enterprises, Environmental Defense Fund, and Environmental Incentives, 2025). One project involves restoring upland habitat on a former dairy farm, reducing water consumption and restoring soil health, and improving ecosystem connectivity. Another project will convert orchards to pollinator habitat while creating a hedgerow barrier between farming activities and a neighboring community. Other projects will implement multibenefit recharge basins that restore riparian habitat while providing infrastructure for managed aquifer recharge that replenishes aquifers and alleviates groundwater contamination.

The variety of possible land repurposing options allows considerable flexibility in determining which projects may be implemented in any particular region or parcel of land. Strategically locating projects can increase their value and provide additional benefits, as illustrated through the hypothetical examples in Figure 3. But each project design may present benefits more desirable to some actors than others, creating a need to evaluate tradeoffs and prioritize among potential projects (e.g., Figure 3b).

MLRP block grantees can face various challenges in designing and implementing suitable multibenefit projects. For instance, some landowners lack the resources to plan and design projects, meaning technical assistance could be a necessary element in developing project proposals. Multibenefit projects can present novel design hurdles and require careful coordination among ecologists, engineers, designers, water managers, and project proponents. Project permitting can also present significant hurdles, particularly when working under the short multiyear timeframe of MLRP block grants. Innovative projects could require considerable outreach and planning, meaning that projects that are shovel-ready are more likely to be implemented with MLRP funds. Shovel-ready projects are likely to come from growers that already have

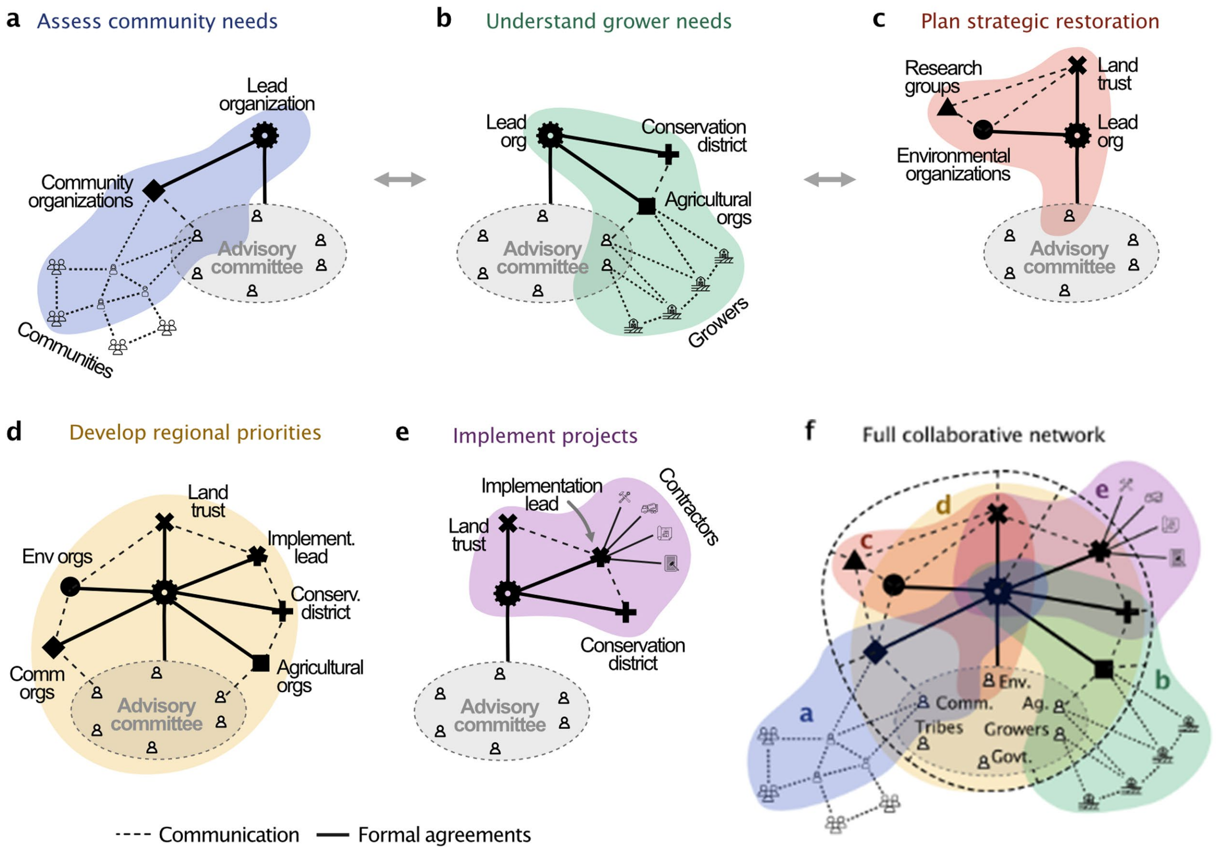

FIGURE 4
Key implementation activities and resulting polycentric networks. Regional activities include joint projects to **(a)** assess community needs, **(b)** understand grower needs, **(c)** plan strategic restoration, **(d)** develop regional priorities, and **(e)** implement projects. **(f)** A regional polycentric governance network resulting from the combination of activities and relationships. Note that the engagement activities often occur in parallel for different groups **(a–c)**. Each node (or shape) represents an individual, organization, or community. The dashed and solid lines represent relationships characterized by communication and formal agreements, respectively, across actors. The shaded background colors indicate joint projects that advance multibenefit land repurposing goals and reinforce collaboration across groups of actors. This visual style for representing polycentric networks follows Galaz et al. (2012).

resources to conceptualize and plan projects, meaning small growers without such resources may face greater obstacles to participation in MLRP.

For projects in which land remains private, landowners may have preferences for certain project types and designs, thereby limiting the space of feasible projects. Maintenance and monitoring represent additional challenges, especially for project types and benefits that represent a divergence from business-as-usual approaches. For instance, monitoring for community groundwater benefits represents a challenge when changes in groundwater levels and groundwater quality are attributable to many factors, not just nearby MLRP projects. In subsequent sections, we note additional opportunities and challenges associated with regional coordination, decision making, land enrollment, and project costs.

4.2 Enabling effective polycentric governance

Multibenefit land repurposing can be structured to achieve more collaborative and equitable decision making (addressing the governance challenge in Section 2.2) through coordinated, inclusive planning. MLRP is designed to catalyze this shift by building decision-making networks around collaborative activities that ensure participation from diverse constituencies (Figure 4). Each MLRP block grantee has considerable discretion in how to approach these joint activities. As such, the manner in which these activities are pursued can differ across block grantees and many of the activities may occur in parallel (Self-Help Enterprises, Environmental Defense Fund, and Environmental Incentives, 2024). As part of this inclusive decision making process, different actors often play different roles, as described below.

Regional land repurposing initiatives within each subbasin are often coordinated by a lead organization, such as the lead applicant on block grant proposals or a consulting firm, that has coordination capacity and technical knowledge but not necessarily the ability to execute all aspects of the program required by DOC. The lead organization therefore builds a constellation of partners and advisors to execute regional land repurposing programs through joint activities. The following examples, represented visually in Figure 4, are representative of how various block grantees have approached this task within the San Joaquin Valley.

In order to provide benefits to various constituencies, block grantees must understand and incorporate their needs and priorities into the land repurposing process. To guide this process, multiple subbasins in MLRP have established advisory committees comprised of representatives of interested parties such as agriculture, small growers, indigenous peoples, local communities, local government, and environmental interests. To bring communities into the fold (Figure 4a), the lead organization may contract with a community-focused organization with expertise and experience engaging with communities. The latter organization then engages with local communities through activities such as outreach to local leaders, community events, and focus group discussions. As noted above (Section 3.2), each MLRP block grantee must implement projects that collectively create meaningful benefits for communities, including benefits that address an expressed need of the community. This requirement creates a process in which block grantees must identify landowners in the vicinity of communities, with the potential to provide benefits to communities, and the opportunity for communities to influence projects to meet their needs. Continued engagement with communities beyond the project planning process is also important to ensure benefits are delivered and adequately monitored.

Growers, and in particular landowners, have the authority to make decisions over their own land management, including voluntary enrollment in MLRP. Grower engagement is therefore critical, both to identify growers that may be amenable to enrolling their land and to design projects and incentives that align with their needs (Figure 4b). Financial incentives for land enrolled can play an important role in motivating growers to participate in MLRP, not just in terms of enrolling land but also engaging in the inclusive planning and project development process. Because land repurposing represents a new and unfamiliar approach for most growers, early engagement with this group is important to understand landowner decision making and give them the confidence and desire to enroll and participate in MLRP. This is especially true for cases in which the land enrolled remains in private ownership. Every subbasin within MLRP works with a combination of agricultural organizations, conservation districts, and agricultural representatives to cultivate grower interest and design projects (Self-Help Enterprises, Environmental Defense Fund, and Environmental Incentives, 2024).

Through a similarly cooperative approach, some block grantees have pursued strategic planning for habitat restoration by initiating collaborations with environmental organizations, research partners, and land trusts (Figure 4c). In order to design feasible projects that create multiple benefits and are aligned with various constituencies, ongoing engagement with growers, communities, and environmental organizations must occur in parallel (Figures 4a–c).

The potential for different types of land repurposing projects to create different types of benefits leads to tradeoffs in terms of how different projects benefit different constituencies. Within MLRP, the guidelines require that each block grantee mitigate conflicting priorities by developing a multibenefit agricultural land repurposing plan that describes a strategic roadmap to equitably addresses the needs of diverse constituencies (DOC, 2025b). Block grantees have approached this task by relying on the network of advisors and partners established through the engagement process (Figure 4d). Some subbasins have sought to build consensus across diverse constituents by creating project selection criteria and scoring rubrics through a collaborative process, including review and input from their advisory committee (Madera County, 2024). Block grantees then submit project proposals to DOC for review. Once projects are approved by DOC, additional partners can be brought in, as needed, to coordinate and execute project implementation (Figure 4e).

The activities described above have brought together organizations with historically siloed interests to work collectively on landscape transformation (Self-Help Enterprises, Environmental Defense Fund, and Environmental Incentives, 2025). The combination of joint activities has the potential to create a highly collaborative governance network capable of understanding needs and challenges across a diverse range of constituencies and scales (Figure 4f). When conducted in an open and forthright manner, this process can contribute to familiarity, trust, and reciprocity, and reduce the potential for conflict to obstruct potential solutions (Lubell, 2007).

Various challenges may arise in the implementation and integration of these activities within each subbasin. Difficulties in reconciling objectives across organizations, for instance, may hamper the process of building trust or the ability to accommodate community needs in project planning. Following a recently-developed best practices framework for multibenefit land repurposing (Fernandez-Bou et al., 2025) can alleviate these concerns but nevertheless requires that multiple parties accept the premise of inclusive planning and shared benefits. Within MLRP, the engagement must occur within the timebound requirements of program funding, creating challenges in moving projects from conceptualization to implementation in just a few years.

Determining and communicating realistic expectations can also be challenging. For instance, extensive community engagement around project ideas that never materialize can undermine trust and the likelihood of future participation. Additionally, small and disadvantaged growers may be more vulnerable to potential financial risks of enrolling land in MLRP. Thoughtful and transparent communication is therefore important when communicating with and enrolling this group of growers in the program. Throughout this process, DOC and the SSE play an important role to support regional block grantees in following best practices for land repurposing. In some cases, DOC may need to step in as an oversight body to ensure program guidelines are followed. The extent to which these activities promote trust and collaboration will shape not only MLRP projects but also the perceived success of MLRP within each subbasin.

4.3 Systemic change in water and land management

The paradigm of multibenefit land repurposing can also motivate a shift in the underlying conditions that shape behavior and actions throughout the water and land system (addressing the structural challenge in Section 2.3). We focus on three structural dimensions in which multibenefit land repurposing, including MLRP itself, has the potential to serve as a vehicle to promote this shift (see Figure 2-ii, enabling conditions). These dimensions include (i) a shift toward collaborative mindsets, (ii) increased financial resources to enable greater capacity and system flexibility, and (iii) a greater openness to experimentation with novel land practices. We argue that each of these changes can be catalyzed through a paradigm shift that occurs through a learning process as actors deliberate challenges and solutions associated with water and land management in the context of opportunities provided by land repurposing (Pahl-Wostl, 2009). We define learning as an iterative process in which actors evaluate decisions, assumptions, and beliefs in the context of new information or deeper reflection (Tosey et al., 2012). Lower levels represent more common modes of learning and result in changes in actions to improve outcomes under an existing paradigm or goal. A paradigm shift may occur as actors engage in higher levels of learning, which involves reflecting on the assumptions or context in which decisions are made at lower levels (Flood and Romm, 1996). The process of higher-level learning has been theorized to enhance resilience of social-ecological systems (Figure 5a) (Cundill et al., 2015). The examples below, from the San Joaquin Valley, help illustrate how multibenefit land repurposing has the potential to contribute to higher-level learning and contribute to a paradigm shift across each of the three structural dimensions noted above.

The concept of multibenefit land repurposing began to emerge in California alongside evidence that extensive agricultural areas may be left idle in response to water conservation requirements of SGMA (Hanak et al., 2019). In particular, some environmentally focused nonprofits viewed the possibility of idle land as an opportunity to support specific goals such as habitat restoration (Butterfield et al., 2020; EDF, 2021) (Figure 5b, loop 1). Habitat restoration as a sole objective, however, lacked broad support among other constituencies in the Valley, underlining the need to identify approaches and design outcomes for the agricultural transition in a way that creates benefits not only for the environment but also for vulnerable communities, Tribes, and growers (EDF, 2021) (Figure 5b, loop 2). A legislative proposal to create a dedicated state funding program to address and repurpose land idled under SGMA built momentum and buy-in, partly due to a broad list of eligible projects types including those that directly benefit communities, growers, and the environment (EDF, 2021; Gardiner, 2021). Once the program was established and funded via legislation and the concept of multibenefit land repurposing was institutionalized (DOC, 2025a), coalitions of organizations representing diverse constituencies recognized the need for greater collaboration in order to secure MLRP block grants from DOC (Self-Help Enterprises, Environmental Defense Fund, and Environmental Incentives, 2024). The requirements of the program, application scoring criteria (DOC, 2025b), and a competitive application pool further selected for applications that build on or establish collaborative, equitable governance networks to execute MLRP activities (see Section 4.2) and fulfill the objectives of the program (see Section 3.2) (Figure 5b, loop 3). Beyond the application process, MLRP has motivated collaboration in a variety of ways. MLRP guidelines require that each subbasin prepare multibenefit agricultural land repurposing plans that are "developed in coordination with the applicable groundwater sustainability agency, farmers and ranchers, local/state/federal agencies, local disadvantaged communities, tribes, non-governmental organizations, and environmental justice organizations" (DOC, 2025b). The guidelines also require that these plans "identify a clear process for engaging disadvantaged communities in project development and implementation" (DOC, 2025b). Some block grantees and individual projects have further initiated community science to measure project benefits, including installing and donating air quality monitors near land repurposed sites and tracking nitrate presence in tap water near aquifer recharge projects. Such activities within MLRP (Section 4.2) have the potential to reinforce broader collaboration in water and land management, including SGMA implementation,

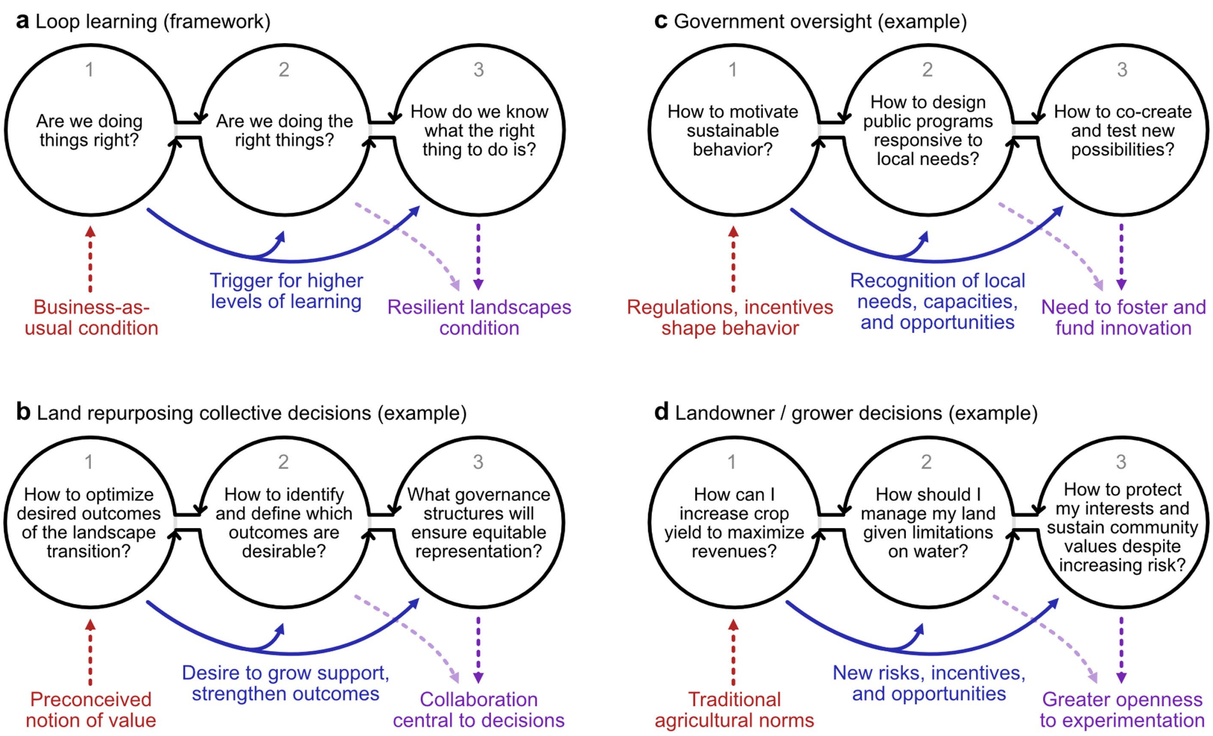

FIGURE 5
The paradigm shift that multibenefit land repurposing seeks to enable. This may occur through **(a)** learning processes that involve reflection on business-as-usual approaches and lead to new perspectives more conducive to resilient landscapes. Examples (i.e., hypotheses) of these learning processes for **(b)** collective decision-making in land repurposing programs, **(c)** government oversight of unsustainable behavior, and **(d)** grower decisions about how best to manage land. Each loop represents a learning process. Higher-level loops reflect on the assumptions of lower-level loops. Business-as-usual conditions (red) favor the status quo and therefore tend to focus on lower levels of learning. Multibenefit land repurposing can catalyze (blue) higher levels of learning and contribute to the conditions necessary for resilient landscapes (purple). See text for details.

especially if shared goals and increased familiarity contribute to improved trust and enduring relationships (Lubell, 2007).

Even with the above shift toward greater collaboration, multibenefit land repurposing requires funding to support the transaction costs of collaboration, planning and implementation efforts, and incentive payments. Public funding may be the most likely vehicle through which to generate these financial resources but conventional government paradigms are not always aligned with the needs of multibenefit land repurposing. For instance, state agencies have tended to shape behavior through penalties, incentives, and pre-defined goals (Figure 5c, loop 1). SGMA motivates behavior change by penalizing regions that fail to bring their groundwater subbasins into sustainability (Leahy, 2015), providing funding for SGMA implementation projects (Senate Bill 170, Section 80, 2021), and establishing land fallowing programs that conserve water (DOC, 2025b). With that said, top-down enforcement faced resistance among water and agricultural organizations across California when groundwater regulations were proposed (Leahy, 2015). As SGMA statutes were being designed, numerous organizations, agencies, and interests made clear that local regions have local needs when it comes to water and land management, motivating the state legislature to design SGMA in a way that allowed for local discretion and control in meeting general SGMA requirements (Leahy, 2015) (Figure 5c, loop 2). Multibenefit programs require considerable flexibility, yet public implementation funds have generally supported single-purpose projects rather than mulibenefit projects (Grimm et al., 2025). MLRP was funded after a group of environmental non-profits, community-based organizations, and agricultural groups developed an example program concept and encouraged the state legislature to adopt and fund a program to incentivize and support local organizations and agencies to co-create and test new ideas for multibenefit projects (EDF, 2021). When the state took this critical step, of funding and codifying MLRP, it acknowledged the need to foster and fund innovation to support multbenefit projects (Figure 5c, loop 3).

Project implementation in MLRP requires finding growers willing to enroll land in the program, ideally where multibenefit outcomes can be maximized (e.g., near disadvantaged communities or critical habitat). This represents a critical challenge for MLRP, which is designed to create social and ecological benefits but not necessarily enhance revenue. Enrollment in MLRP can pose a financial risk in terms of program longevity, upfront costs and opportunity costs, and returns on investment (e.g., from low water use crops), especially for smaller growers. Growers are continually evaluating the risks of various approaches to farm management, and are generally more accustomed to the familiar approach of maximizing crop yield to sustain revenues (Figure 5d, loop 1). For some growers, however, a perceived increased risk to farming (such as a reduction in water access) may motivate them to adapt their farming practices, such as through planting different crops or other water saving approaches (Figure 5d, loop 2). Conservation behavior among growers depends on a variety of factors including economic considerations, on- and off-farm benefits, community values, and trust in government agencies (Ranjan et al., 2019). While the most critical factors are often specific to the location or farm, research has demonstrated that alignment with pre-existing grower motivations (e.g., the perceived social value of land stewardship) is more likely to lead to conservation behavior (Prokopy et al., 2019). Block grantees therefore face the task of engaging with growers to help them understand the climate and regulatory context of their land management decisions and providing sufficient technical support and incentives to open the possibility for land repurposing to serve as a viable alternative. If the increased risks of drought (e.g., due to climate change) or regulatory compliance (e.g., due to SGMA) are accompanied by new opportunities and incentives (as may be provided through land repurposing), growers may begin to evaluate approaches that would have been previously unacceptable provided these approaches align with their interests and community values (Figure 5d, loop 3). In other words, consideration of these risks and opportunities may create a greater openness to experimentation and willingness to embrace new forms of adaptation as useful strategies for protecting their livelihoods while preserving their individual and community values. This perspective might also allow them to consider land repurposing as a viable option, particularly if incentive payments are properly designed such that the economic value of land repurposing is commensurate with the opportunity costs of other land management strategies. MLRP has proven successful in bringing some growers into the program, with ten projects having been approved by the Department of Conservation in 2024 (Self-Help Enterprises, Environmental Defense Fund, and Environmental Incentives, 2025). As some growers begin to enroll in land repurposing programs, social barriers to land repurposing may dissipate such that participation can expand beyond the realm of innovators and strategic early adopters into the realm of behavioral norm (Dearing, 2009; Rogers, 2003).

While these paradigm shifts may be accelerated by MLRP, such a progression should not be taken for granted. Systems change will require consistent, persistent, and inclusive efforts. Inequitable planning and exclusion of certain viewpoints could disrupt momentum, lead to the dissolution of coalitions, and a reversion to entrenched, siloed interests. A similar regression could occur if program outcomes do not lead to balanced, measurable, and perceivable benefits among interested parties. The long-term success of multibenefit land repurposing will also depend on adequate and reliable support from public or private funders, which will be contingent on the perceived return on investment. If program costs are too high or the benefits too low, the long-term viability of multibenefit land repurposing may be tenuous, especially if the harm associated with alternative pathways are tolerable or insufficiently understood. Finally, the ability to scale multibenefit land repurposing to larger areas will depend on demonstratively successful examples, so that growers gain trust and confidence in land repurposing strategies and embrace the program in larger numbers.

Structural factors outside MLRP are also likely to play a role in these dynamics. For instance, some GSAs in the San Joaquin Valley have designed allocation systems that incorporate a groundwater budget to align with SGMA requirements and apportion groundwater rights to landowners accordingly (Babbitt et al., 2018). Pumping restrictions required by allocation systems may shift grower perceptions and generate openness to programs such as MLRP.

4.4 MLRP implementation in the Madera subbasin

In order to provide greater insights into how MLRP may function at the local level, we use this section to provide an overview of the Madera subbasin MLRP block grant, while noting that the specific governance structure, organizational roles, and project development and selection process look different in each MLRP subbasin.

Madera County sits on the eastern side of the San Joaquin valley and most of the county coincides with the Madera groundwater subbasin. Agriculture in the county generates nearly $2 billion per year in gross value (Madera County Department of Agriculture, 2024). In order to stabilize groundwater levels under SGMA, Madera County has created a groundwater allocation system that will require considerable reductions in groundwater pumping for many farms that lack surface water rights, in turn curtailing agricultural production (Madera County, 2021). Reduced agricultural revenue will affect not only growers but farm laboring communities and associated food production and distribution industries. Madera County applied for and secured MLRP funding as one of the eight MLRP block grants awarded by DOC (Self-Help Enterprises, Environmental Defense Fund, and Environmental Incentives, 2024). We refer to the local multibenefit land repurposing program in Madera County as the Madera MLRP. Madera MLRP seeks to translate the statewide program into opportunities and benefits for local landowners and communities in the Madera subbasin (Madera County Water, 2025).

Collaboration within Madera MLRP is similar but not identical to the framework outlined above (Section 4.2). The block grantee team includes Madera County as the lead applicant along with a Partner Group comprising organizations predominantly associated with agriculture (Table 2, left column). Madera County hired Zanjero, a water resources management consulting firm, to coordinate implementation of Madera MLRP, who in turn hired two sub-consultants to provide additional support (Table 2, center column). The Madera MLRP administrative team, led by Madera County and supported by Zanjero, jointly coordinated land repurposing activities. As noted previously, DOC requires that each block grantee develop a multibenefit agricultural land repurposing plan (or MALRP, an acronym we use in this section). Madera MLRP used the process of developing the MALRP as a fulcrum around which to conduct engagement, develop priorities, and solicit projects. As of July 2025, Madera MLRP has produced an administrative draft MALRP (see Madera County Water, 2024).

The Madera administrative team developed the Madera MALRP with input from the Partner Group and a variety of interested parties within the subbasin, including organizations representing community and environmental interests (Table 2, right column). Madera MLRP engaged local constituencies by distributing information via flyers and email broadcasts, attending community events and grower resources fairs, and holding workshops. In total, Madera MLRP organized or participated in 39 public outreach activities and events (Self-Help Enterprises, Environmental Defense Fund, and Environmental Incentives, 2025). The administrative team coordinated engagement activities and Linguistica translated program materials into Spanish and provided live translations to enable bilingual participation at workshops. Various organizations conducted outreach to growers, including the Madera Ag Water Association (MAWA), Madera County Farm Bureau, the Madera/Chowchilla Resource Conservation District (RCD), and the Punjabi Agricultural Growers Group (PAGG). Outreach was conducted both in the development of the MALRP and after the administrative draft was released. In addition to public events, the administrative team directly engaged with key stakeholder entities representing environmental interests, such as River Partners and Sustainable Conservation, and entities representing community needs, such as Self-Help Enterprises, Leadership Council for Justice and Accountability, Fairmead Community and Friends, and the Madera Coalition for Community Justice (MCCJ). Lessons from the engagement process were collected by the administrative team and incorporated into the MALRP, ensuring the process of defining priorities reflected diverse perspectives within the subbasin. The resulting document defines objectives, strategies, and guidance for MLRP implementation in Madera County (Madera County, 2024).

The Madera MALRP describes the process through which projects were proposed and selected (Madera County, 2024). Eligible projects included a variety of land use types that have potential to accommodate multiple benefits (Table 3, left column), similar to those described above (Section 4.1). Project proposals followed a multi-step application process, including (i) submission of pre-applications to determine eligibility and identify primary project type, (ii) completion of project proposals, with optional support provided by a technical assistance team organized by Madera MLRP, and (iii) competitive review of project proposals following scoring criteria defined in the MALRP (Table 3, middle column). The project scoring process assigned higher scores for aligning with Madera MLRP objectives and demonstrating feasibility. The objectives included reducing water use and providing various environmental benefits or social benefits, including benefits for disadvantaged communities (Table 3). The feasibility component included providing a reasonable budget and robust monitoring plan. Detailed scoring criteria for each category is further described in the draft MALRP (Madera County Water, 2024).

Madera MLRP received 72 pre-applications and 28 complete project proposals (Madera County, 2025b). In June 2025, based on the outcomes of project scoring, Madera MLRP published summaries of six projects as part of a public comment period, after which proposals will be finalized and submitted to DOC to allow state-level oversight and review (Madera County, 2025b). The six projects include (a) multibenefit stormwater management, (b) tribal / cultural space, (c) combined recharge and flood management, (d) low-water use agave crop, (e) buffer area adjacent to a disadvantaged community, and (f) groundwater recharge with native habitat restoration (Madera County, 2025b). The range of selected projects in Madera reinforces the need

TABLE 2 Madera MLRP partners [adapted from Madera County, 2024].

Madera MLRP Partner Group	Consulting team	Organizations engaged in MALRP process
• Madera County • Madera/Chowchilla Resource Conservation District • Madera County Farm Bureau • Madera Ag Water Association (MAWA) • California Farmland Trust • Linguistica Interpreting and Translation	• Zanjero • ERA Economics • Davids Engineering	• Leadership Council for Justice and Accountability • Self-Help Enterprises • Fairmead Community and Friends • River Partners • Union of Concerned Scientists • Madera Coalition for Community Justice (MCCJ) • Sustainable Conservation • University of California Cooperative Extension (UCCE) Madera County • Punjabi American Growers Group (PAGG)

TABLE 3 Eligible projects and scoring documented in the administrative draft MALRP.

Eligible project types	Project scoring	Other co-benefits
• Community recreational area or cultural space	Key goals and outcomes	• Air-quality improvement
• Dryland farming	• Achieve net water savings (2 pts)	• Employment opportunities
• Floodplain habitat	• Support community and domestic wells (4)	• Tribal or cultural benefit
• Less water-intensive crop	• Buffer water way areas (4)	• Soil quality enhancement
• Rangeland	• Support disadvantaged communities (4)	• Water quality enhancement
• Pollinator habitat	• Provide other co-benefits (right column of this table) (4)	• Renewable energy
• Recharge basin or facilities	Proposal quality and feasibility	• Habitat creation
• Rotational strip cropping	• Overall plan (4 pts)	• Recreation or community space
• Solar energy production, storage, transmission	• Budget (8)	• Flood risk mitigation
• Wildlife habitat	• Schedule (4)	
	• Monitoring plan (4)	

for MLRP to equitably assess and navigate tradeoffs, given that some projects may provide greater water savings while other projects provide more environmental or community benefits.

In addition to projects that were identified through the application and scoring process, one pilot project has already been approved by DOC and initiated by Madera MLRP. The project repurposes five acres of an almond and walnut orchard to pollinator habitat adjacent to La Viña, a small community in Madera County dependent entirely on groundwater for water supply and designated as a disadvantaged community by the state (Self-Help Enterprises, Environmental Defense Fund, and Environmental Incentives, 2025). The project creates a 100 ft. buffer between the community and the orchard, with the goal of saving water and reducing pesticide spray in the vicinity of the community, thereby improving soil and air quality for community residents (Self-Help Enterprises, Environmental Defense Fund, and Environmental Incentives, 2025). Outcomes will be assessed according to the monitoring plan, which includes a baseline assessment of the habitat installation and biannual visits to assess site conditions, check for maintenance needs, build a photo log of the project, and ensure pollinator habitat is being maintained (Madera County, 2025a).

Madera MLRP has also worked toward long-term systems change in multiple ways analogous to the themes identified above (Section 4.3). For instance, greater collaboration has occurred through the development of the MALRP, the project design process, and project implementation. Another central goal of Madera MLRP is to "increase grower interest and participation in MLRP and land repurposing strategies and programs" through education and outreach activities (Madera County, 2024). Madera MLRP seeks to cultivate interest by providing resources and technical assistance to growers and will promote success stories once projects are implemented. Madera MLRP has also sought to ensure long-term regional capacity for land repurposing in the subbasin and intends to seek a $1 million implementation grant that would extend beyond the time period of MLRP and allow for ongoing capacity to implement and coordinate land repurposing in the county (Madera County, 2024). Such systemic changes have potential to continue to shape water and land management in Madera County moving forward.

Progress toward these goals in Madera has faced challenges similar to those mentioned above (Sections 4.1–4.3). Achieving meaningful impact at the scale necessary to meet the need and demand for multibenefit land repurposing projects could require funding and timeframes that extend far beyond the current MLRP grant program. The complexity of multibenefit projects, which must navigate dynamic agricultural economics, environmental regulations, community engagement, and long-term maintenance, demands extended planning and implementation periods that often exceed typical funding cycles. Long-term funding will also be critical to maintain and expand grower interest and participation in land repurposing more broadly. The current version of MLRP therefore represents an important step toward a more resilient future, but will not independently resolve water and land challenges in Madera County.

5 Discussion

5.1 Tailoring policy and regulations for land repurposing

Multiple policy considerations are important for shaping the institutional environment in which multibenefit land repurposing occurs. MLRP, for instance, exists within the broader land and water management apparatus of California, and therefore depends on additional financial, regulatory, and administrative considerations. In this section we focus on aspects of the broader governing and regulatory environment in which multibenefit land repurposing programs operate. While these lessons draw largely from the California context, they are relevant when considering the potential applicability of multibenefit land repurposing to other geographies.

Long-term funding is important to build and sustain the technical capacity required to strategically design and implement projects. Stable funding creates certainty among interested actors, helps foster collaboration and partnerships, and mitigates the risk of actors who decide to invest in and align their efforts with land repurposing programs. The costs associated with MLRP projects are significant and many projects have sought matching or supplementary funds from federal grants and local levies, such as through pumping fees. Despite the significant investment of $300 million from the state, the challenge of sustainable long-term funding remains open in California. Some projects, such as agrivoltaic projects or low-water use crops, may be economically viable in that they generate revenue to cover long-term costs. Other projects, such as habitat restoration or recreational space, may provide social, economic, or environmental benefits (Fernandez-Bou et al., 2025) that are difficult to monetize. In such instances, alternative funding models could include biodiversity credits (EDF, 2020b; Wunder et al., 2025) or financial contributions from beneficiaries of more reliable water supplies or other avoided costs (e.g., infrastructure damage from subsidence, drying wells that require mitigation, pest and weed abatement, air quality impacts). But whenever these funds cannot cover the costs of implementation, public and private investment will be needed. The inclination of public or private investors to pursue this avenue, and at what scale, will depend on the costs, benefits, and perceived value of land repurposing relative to alternatives.

From a state regulatory perspective, cross-agency coordination can help overcome fragmentation in governance and align future policies, funding, and technical support across agencies (Pecharroman et al., 2021). This approach can drive more effective progress toward sustainability and climate adaptation goals. Within MLRP, the Department of Conservation coordinates with other state agencies (e.g., the Department of Water Resources, the California Department of Fish and Wildlife) to minimize staffing redundancies, foster synergies, and encourage multibenefit outcomes. These collaborations have led to revisions in MLRP guidelines that clarify how projects account for water savings. By working together in this way, agencies can cultivate a unified strategy that accelerates progress and maximizes the potential benefits of land repurposing.

State and federal permitting also plays an important role in land repurposing, serving as either an enabler or a barrier depending on its design and implementation. When streamlined, flexible and transparent permitting processes has the potential to facilitate clearer pathways for implementers for efficient environmental assessments and accelerating project timeline. In some cases, projects that demonstrate net positive ecosystem benefits may qualify for exemptions that provide legal assurances that projects and growers will not be subject to future regulatory penalties if they fail specific environmental criteria. At the same time, local systems of land and water tenure (e.g., property taxes, and zoning rules), that have been in place for many years may serve as barriers to some of the proposed land repurposing actions. Rigid permitting requirements can create significant obstacles, leading to long timelines and increased costs, thus discouraging innovative, multibenefit land repurposing solutions. California has sought to reduce permitting burdens by streamlining the process for projects that provide environmental benefits, such as the Cutting the Green Tape initiative (CDFW, 2024), though much work remains to be done in this space. Programmatic permits are sometimes possible through federal and state agencies if projects features can be sufficiently defined in advance. But striking the right balance in permitting policies remains an important challenge to foster land repurposing initiatives while protecting environmental resources.

In addition to cross-agency coordination, cross-jurisdictional coordination can facilitate integrating multibenefit land repurposing into planning, programs and funding across local, regional, and state levels. In the San Joaquin Valley, such efforts have included aligning multibenefit land repurposing efforts with the economic initiatives, such as California Sierra San Joaquin Jobs (S2J2) (CVC, 2025), which consolidates city and county regional economic development strategies, climate action, and adaptation planning across the Valley. These initiatives are particularly important in the context of SGMA regulations, which will lead to major economic disruptions through reduced agricultural production and associated loss of revenue and jobs (Escriva-Bou et al., 2023). This land transition will adversely impact local economies, particularly vulnerable rural communities reliant on this sector. Mitigating the economic disruptions of SGMA requires proactive strategies, including workforce development, job creation and training programs.

Finally, having an oversight or administrative agency with the capacity and willingness to adapt its programs to emerging challenges is essential for effective implementation. Within MLRP, DOC meets individually with each subbasin every month and joins monthly meetings for all participating organizations to maintain open channels of communications. DOC has also adapted revisions to MLRP guidelines in response to feedback from organizations across MLRP subbasins. A flexible and responsive agency can streamline processes, ensure that funding reaches the right initiatives, and overcome obstacles related to shifting priorities, ultimately enhancing the effectiveness of these programs.

5.2 Concluding remarks

In many water-scarce regions of the world, irrigated agricultural land will have to come out of production to slow or reverse the degradation of environmental and water resources. The social and economic ramifications of reducing agricultural production has the potential to reshape the fabric of the landscapes with potentially dramatic consequences for growers and rural households due to lost revenue and jobs. Land use and land cover will also be transformed by reducing the footprint of irrigated agriculture. If the landscape transition follows business-as-usual conservation approaches, ad hoc approaches that leave cropland idle may contribute to social and environmental problems.

Multibenefit land repurposing presents an opportunity to manage the transition toward water sustainability strategically and equitably while enhancing water security and landscape resilience. It does so by targeting a resource challenge having to do with inadequate land and water, a governance challenge related to lack of coordination and inequitable decision making, and a structural challenge associated with lack of resources and innovation alongside entrenched beliefs and norms. Strategically identifying and selecting projects that alleviate groundwater depletion and pollution can enhance water security for communities, while also improving air quality by reducing the potential for pesticides to drift into homes and recreational spaces. Extending habitat areas can reduce threats to endangered species and improve ecosystem resilience. Enhancing collaboration and developing a shared vision for land repurposing can reduce barriers to cooperation and increase adaptive capacity. Additionally, shifting existing paradigms to allow for experimentation can create more flexibility in planning and enhance general resilience of the landscape to adapt to stressors and disturbances.

Although MLRP in California is in its early stages, it has already catalyzed progress in these areas by translating significant state investments into action on the ground. At the time of writing, these investments have stimulated active regional multibenefit land repurposing efforts in eight subbasins that have brought together over 100 organizations working together on this challenge.

The extent to which multibenefit land repurposing programs can catalyze a shift toward to resilient landscapes will depend on the many factors related to regulation, economics, and culture. Many components of multibenefit land repurposing can be expensive, including transactions costs of collaboration, planning costs associated with project design, and implementation costs such as moving earth and native seeds for habitat restoration. Additionally, the cost of incentive payments to motivate growers to repurpose their land may be high in areas with productive agriculture. These conditions will be heavily influenced by regulatory and market forces that shape the agricultural landscape. Permitting can also pose considerable challenges and translate to substantial costs before projects break ground. Whether public or private investors are willing to foot the bill, and at what scale, will depend on the costs and benefits of such programs. In the San Joaquin Valley, for instance, the confluence of pumping limitations, declining agricultural land values, and local and state investments in groundwater conservation help create the enabling conditions to allow for grower interest and voluntary participation in land repurposing projects. Finally, funding for long-term monitoring and research, beyond program timelines, will be important to enable retrospective analyses to understand program outcomes.

Another critical challenge has to do with the ability of land repurposing programs to meaningfully engage diverse constituencies in a way that enables representation, influence over decisions, and equitable outcomes. Aligning goals across diverse participants, organizations, and cultures can be a slow and daunting process requiring effective leadership and an openness to participate among individuals from diverse constituencies. This point is particularly relevant given the timebound nature of funding through MLRP. Additionally, community members may be taking risks in participation by donating their time when the benefits of projects for their community may be unclear or uncertain. Growers may be taking considerable financial risks by enrolling their land in a new and untested program. Overcoming these hurdles requires establishing trust through transparent communication, integrity, and recurring engagement. Building this trust also depends on demonstrating tangible success through storytelling and communications that make project benefits visible and relatable to potential participants, helping to reduce perceived risks and encourage broader adoption.

MLRP provides an example of how individual programs can take steps in the right direction in terms of strengthening collaborative partnerships and identifying multibenefit projects. As a pilot program, MLRP has potential to demonstrate the effectiveness of this approach and inform future investments about the best way to manage water and land in regions with diminishing water resources. At the same time, further research will be needed to help assess and advance progress toward these goals, including how to design multibenefit land repurposing programs to ensure equitable processes and outcomes. Interdisciplinary assessments will be essential to understand the complex dynamics that shape water and land decisions and associated outcomes. Future research should additionally consider the need and applicability of land repurposing to geographies outside of California. Such research could include the potential for land repurposing to mitigate concerns associated with excess water and flooding in addition to water scarcity. Solutions that push us toward resilient water and land management are urgently needed. As an approach to this challenge, multibenefit land repurposing offers potential and merits further consideration within academic, policy, and management communities.

Author contributions

GP: Conceptualization, Writing – original draft, Visualization, Writing – review & editing. JR-F: Conceptualization, Writing – original draft, Visualization, Writing – review & editing. AF-B: Writing – review & editing, Writing – original draft. EK: Writing – original draft. AS: Writing – review & editing, Conceptualization. DS: Writing – original draft. KC: Writing – review & editing. LC-R: Writing – review & editing. MD: Writing – review & editing. RG: Writing – review & editing. MH: Writing – review & editing. MK: Writing – review & editing. SM: Writing – review & editing. KM: Writing – review & editing. SS: Writing – review & editing.

Funding

The author(s) declare that financial support was received for the research and/or publication of this article. This research was supported through a gift to the Environmental Defense Fund from the Laural Foundation. KM acknowledges support from MLRP block grants in the Kaweah and Merced subbasins. MK acknowledges support from the Agriculture and Food Research Initiative, Project Award No. 2023-69012-35916, from the U.S. Department of Agriculture's National Institute of Food and Agriculture. This publication has not been formally reviewed by USDA. Any opinions, findings, conclusions, or recommendations expressed in this publication are solely those of the authors and should not be construed to reflect those of USDA or to represent any official U.S. Government determination or policy. USDA does not endorse any products or commercial services mentioned in this publication.

Acknowledgments

The authors thank those who have contributed to this work through review and discussions including Noa Bruhis, Dave McGlaughlin, Reyn Akiona, and Amanda Fencl. We also thank participants in MLRP, including those involved with regional block grant implementation and state agencies, in particular, the California Department of Conservation. We note that mulitiple authors are actively involved in implementing MLRP through the SSE (GP, JR-F, AS, MD, SM, SS) and multiple MLRP block grants (AF-B, LC, KM), including in Madera subbasin (KC).

Conflict of interest

KC was employed by Zanjero. MD was employed by Environmental Incentives. KM was employed by Valley Eco.

The remaining authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Generative AI statement

The author(s) declare that no Gen AI was used in the creation of this manuscript.

Publisher's note

References

Adebiyi, A. A., Kibria, M. M., Abatzoglou, J. T., Ginoux, P., Pandey, S., Heaney, A., et al. (2025). Fallowed agricultural lands dominate anthropogenic dust sources in California. *Communications Earth Environment* 6, 1–14. doi: 10.1038/s43247-025-02306-0

Alam, S., Gebremichael, M., Li, R., Dozier, J., and Lettenmaier, D. P. (2020). Can Managed Aquifer Recharge Mitigate the Groundwater Overdraft in California's Central Valley? *Water Resources Research*, 56:e2020WR027244. doi: 10.1029/2020WR027244

Algert, S., Diekmann, L., Renvall, M., and Gray, L. (2016). Community and home gardens increase vegetable intake and food security of residents in San Jose, California. *Calif. Agric.* 70, 77–82. doi: 10.3733/ca.v070n02p77

Alston, M., and Kent, J. (2004). Social impacts of drought: A report to NSW agriculture. Centre for rural social research. New South Wales: Charles Sturt University.

Altieri, M., and Nicholls, C. (2018). Biodiversity and Pest Management in Agroecosystems. *2nd* Edn: CRC Press.

Anderies, J., Janssen, M., and Schlager, E. (2016). Institutions and the performance of coupled infrastructure systems. *Int. J. Commons* 10, 495–516. doi: 10.18352/ijc.651

Anderson, K. (2005). Tending the wild: Native American knowledge and the Management of California's natural resources: University of California Press.

Ashraf, U., Morelli, T. L., Smith, A. B., and Hernandez, R. R. (2024). Aligning renewable energy expansion with climate-driven range shifts. *Nat. Clim. Chang.* 14, 242–246. doi: 10.1038/s41558-024-01941-3

Ayres, A., Kwon, J., and Collins, J. (2022a). Land transitions and dust in the San Joaquin Valley—How proactive management can support air quality improvements. Available online at: https://www.ppic.org/publication/land-transitions-and-dust-in-the-san-joaquin-valley/

Ayres, A., Rosser, A., Hanak, E., Escriva-Bou, A., Wheeles, D., De, M., et al. (2022b). Solar energy and groundwater in the San Joaquin Valley: PPIC. Available online at: https://www.ppic.org/publication/solar-energy-and-groundwater-in-the-san-joaquin-valley/

Babbitt, C., Hall, M., Dooley, D. M., Moss, R. M., Orth, D. L., and Sawyers, G. W. (2018). Groundwater pumping allocations under California's sustainable groundwater management act: Environmental Defense Fund.

Balazs, C. L., and Ray, I. (2014). The drinking water disparities framework: on the origins and persistence of inequities in exposure. *Am. J. Public Health* 104, 603–611. doi: 10.2105/AJPH.2013.301664

Baldy, C. R. (2013). Why we gather: traditional gathering in native Northwest California and the future of bio-cultural sovereignty. *Ecol. Process.* 2:17. doi: 10.1186/2192-1709-2-17

Benbrook, C., Kegley, S., and Baker, B. (2021). Organic farming lessens reliance on pesticides and promotes public health by lowering dietary risks. *Agronomy* 11:7. doi: 10.3390/agronomy11071266

Benevolenza, M. A., and DeRigne, L. (2019). The impact of climate change and natural disasters on vulnerable populations: a systematic review of literature. *J. Hum. Behav. Soc. Environ.* 29, 266–281. doi: 10.1080/10911359.2018.1527739

Bennett, D. H., Sellen, J., Moran, R., Alaimo, C. P., and Young, T. M. (2024). Personal air sampling for pesticides in the California San Joaquin Valley. *J. Expo. Sci. Environ. Epidemiol.* 35, 486–492. doi: 10.1038/s41370-024-00708-4

Bennett, N. J., Whitty, T. S., Finkbeiner, E., Pittman, J., Bassett, H., Gelcich, S., et al. (2018). Environmental stewardship: a conceptual review and analytical framework. *Environ. Manag.* 61, 597–614. doi: 10.1007/s00267-017-0993-2

Bezner Kerr, R., Liebert, J., Kansanga, M., and Kpienbaareh, D. (2022). Human and social values in agroecology: a review. *Elementa* 10:00090. doi: 10.1525/elementa.2021.00090

Biggs, R., Schlüter, M., Biggs, D., Bohensky, E. L., BurnSilver, S., Cundill, G., et al. (2012). Toward principles for enhancing the resilience of ecosystem services. *Annu. Rev. Environ. Resour.* 37, 421–448. doi: 10.1146/annurev-environ-051211-123836

Biggs, N. B., Shivaram, R., Lacarieri, E. A., Varkey, K., Hagan, D., Young, H., et al. (2022). Landowner decisions regarding utility-scale solar energy on working lands: a qualitative case study in California. *Environmental Research Communications* 4:055010. doi: 10.1088/2515-7620/ac6fbf

Bond, N. R., Burrows, R. M., Kennard, M. J., and Bunn, S. E. (2019). "Water scarcity as a driver of multiple stressor effects" in Multiple stressors in river ecosystems (Amsterdam, Netherlands: Elsevier), 111–129.

Börk, K. (2022). *Time Limits for Western Water Rights* 37. Available at SSRN: https://ssrn.com/abstract=4472562

Borum, J., Bruno, E., Castle, S., Chiartas, J., Crowley, R., Decock, C., et al. (2024). Cover cropping in the SGMA era: A comprehensive overview of water impacts, policy implications, and recommendations for California's water managers. (The Soil-Water Interface Expert Convening Series: Cover Crop Impacts on Water Budgets, California). Available online at: https://suscon.org/wp-content/uploads/2024/05/SC-Cover-Crop-SGMA-Report.pdf

Bourque, K., Schiller, A., Loyola Angosto, C., McPhail, L., Bagnasco, W., Ayres, A., et al. (2019). Balancing agricultural production, groundwater management, and biodiversity goals: a multi-benefit optimization model of agriculture in Kern County, California. *Sci. Total Environ.* 670, 865–875. doi: 10.1016/j.scitotenv.2019.03.197

Bruce, M., Sherman, L., Bruno, E., Fisher, A. T., and Kiparsky, M. (2023). Recharge net metering (ReNeM) is a novel, cost-effective management strategy to incentivize groundwater recharge. Nature. *Water* 1, 855–863. doi: 10.1038/s44221-023-00141-1

Bryant, B. P., Kelsey, T. R., Vogl, A. L., Wolny, S. A., MacEwan, D., Selmants, P. C., et al. (2020). Shaping land use change and ecosystem restoration in a water-stressed agricultural landscape to achieve multiple benefits. *Front. Sustain. Food Systems* 4:138. doi: 10.3389/fsufs.2020.00138

Butterfield, H. S., Kelsey, T. R., and Hart, A. K. (2020). Rewilding agricultural landscapes: a California study in rebalancing the needs of people and nature. Washington, DC: Island Press. Available online at: https://islandpress.org/books/rewilding-agricultural-landscapes

CalEPA. (2022). Final Designation of Disadvantaged Communities Pursuant to Senate Bill:535. Available online at: https://calepa.ca.gov/wp-content/uploads/2022/05/Updated-Disadvantaged-Communities-Designation-DAC-May-2022-Eng.a.hp_-1.pdf

California State Parks. (2020). Park access tool. Available online at: https://www.parksforcalifornia.org/parkaccess/

Calverley, C. M., and Walther, S. C. (2022). Drought, water management, and social equity: analyzing Cape Town, South Africa's water crisis. *Frontiers in Water* 4, 1–21. doi: 10.3389/frwa.2022.910149

Cameron, D. R., Schloss, C. A., Theobald, D. M., and Morrison, S. A. (2022). A framework to select strategies for conserving and restoring habitat connectivity in complex landscapes. *Conservation Science and Practice* 4:e12698. doi: 10.1111/csp2.12698

Carlisle, K., and Gruby, R. L. (2019). Polycentric Systems of Governance: a theoretical model for the commons. *Policy Stud. J.* 47, 927–952. doi: 10.1111/psj.12212

Castaldo, G., Visser, A., Fogg, G. E., and Harter, T. (2021). Effect of groundwater age and recharge source on nitrate concentrations in domestic Wells in the San Joaquin Valley. *Environ. Sci. Technol.* 55, 2265–2275. doi: 10.1021/acs.est.0c03071

CDFW (2024). Cutting the Green tape: Report to the legislature. California Department of Fish and Wildlife. Available online at: https://nrm.dfg.ca.gov/FileHandler.ashx?DocumentID=228316&inline (Accessed August 13, 2025).

Chaffin, B. C., Gosnell, H., and Cosens, B. A. (2014). A decade of adaptive governance scholarship: synthesis and future directions. *Ecol. Soc.* 19:art56. doi: 10.5751/ES-06824-190356

Chen, J., He, D., and Cui, S. (2003). The response of river water quality and quantity to the development of irrigated agriculture in the last 4 decades in the Yellow River Basin, China. *Water Resour. Res.* 39, 1–11. doi: 10.1029/2001WR001234

Chiarelli, D. D., D'Odorico, P., Müller, M. F., Mueller, N. D., Davis, K. F., Dell'Angelo, J., et al. (2022). Competition for water induced by transnational land acquisitions for agriculture. *Nat. Commun.* 13:505. doi: 10.1038/s41467-022-28077-2

Bijay-Singh, and Craswell, E. (2021). Fertilizers and nitrate pollution of surface and ground water: An increasingly pervasive global problem. *SN Applied Sciences* 3:518. doi: 10.1007/s42452-021-04521-8

CSWRCB. (2024). SAFER Dashboard Failing and At-Risk Drinking Water Systems. Available online at: https://data.ca.gov/dataset/safer-failing-and-at-risk-drinking-water-systems

Cundill, G., Leitch, A. M., Schultz, L., Armitage, D., and Peterson, G. (2015). "Principle 5 – encourage learning" in Principles for building resilience. eds. R. Biggs, M. Schlüter and M. L. Schoon. *1st* ed (Cambridge University Press), 174–200.

Cuppari, R. I., Higgins, C. W., and Characklis, G. W. (2021). Agrivoltaics and weather risk: a diversification strategy for landowners. *Appl. Energy* 291:116809. doi: 10.1016/j.apenergy.2021.116809

CVC. (2025). Sierra San Joaquin Jobs. Central Valley Community Foundation S2J2 Initiative. Available online at: https://www.s2j2initiative.org/about

Dearing, J. W. (2009). Applying diffusion of innovation theory to intervention development. *Res. Soc. Work. Pract.* 19, 503–518. doi: 10.1177/1049731509335569

Deines, J. M., Schipanski, M. E., Golden, B., Zipper, S. C., Nozari, S., Rottler, C., et al. (2020). Transitions from irrigated to dryland agriculture in the Ogallala aquifer: land use suitability and regional economic impacts. *Agric. Water Manag.* 233:106061. doi: 10.1016/j.agwat.2020.106061

DeVincentis, A., Solis, S., Rice, S., Zaccaria, D., Snyder, R., Maskey, M., et al. (2022). Impacts of winter cover cropping on soil moisture and evapotranspiration in California's specialty crop fields may be minimal during winter months. *Calif. Agric.* 76, 37–45. doi: 10.3733/ca.2022a0001

Di Baldassarre, G., Wanders, N., AghaKouchak, A., Kuil, L., Rangecroft, S., Veldkamp, T. I. E., et al. (2018). Water shortages worsened by reservoir effects. *Nature Sustainability* 1, 617–622. doi: 10.1038/s41893-018-0159-0

Dilling, L., Berggren, J., Henderson, J., and Kenney, D. (2019). Savior of rural landscapes or Solomon's choice? Colorado's experiment with alternative transfer methods for water (ATMs). *Water Security* 6:100027. doi: 10.1016/j.wasec.2019.100027

Dobbin, K. B., and Lubell, M. (2021). Collaborative governance and environmental justice: disadvantaged community representation in California sustainable groundwater management. *Policy Stud. J.* 49, 562–590. doi: 10.1111/psj.12375

DOC. (2025a). Round 1 land repurposing program guidelines. California Department of Conservation. Available online at: https://www.conservation.ca.gov/dlrp/grant-programs/Documents/MLRP%20Round%201%20Guidelines_Amended%20April%202025.pdf (Accessed August 14, 2025).

DOC. (2025b). Round 2 land repurposing program guidelines. California Department of Conservation. Available online at: https://www.conservation.ca.gov/dlrp/grant-programs/Documents/MLRP%20Round%202%20Guidelines_Amended%20April%202025.pdf (Accessed August 14, 2025).

DPR. (2024). Pesticide Use Reporting. Available online at: https://www.cdpr.ca.gov/docs/pur/purmain.htm

DWR. (2023). California Aqueduct Hydraulic Conveyance Capacity. Department of Water Resources, California Natural Resources Agency. Available online at: https://water.ca.gov/-/media/DWR-Website/Web-Pages/Programs/Engineering-And-Construction/Files/Subsidence/CASP_2023_HCC_Report_Final.pdf (Accessed August 14, 2025).

DWR. (2024a). 2023 Statewide Crop Mapping. Available online at: https://data.cnra.ca.gov/dataset/statewide-crop-mapping (Accessed August 14, 2025).

DWR. (2024b). Dry Well Reporting System. Available online at: https://mydrywatersupply.water.ca.gov/report/ (Accessed August 14, 2025).

DWR. (2024c). TRE ALTAMIRA InSAR Subsidence Data [Dataset]. Available online at: https://data.ca.gov/dataset/tre-altamira-insar-subsidence-data (Accessed August 14, 2025).

DWR. LandFlex Grant Program Guidelines. Department of Water Resources, California Natural Resources Agency. (2025). Available online at: https://water.ca.gov/-/media/DWR-Website/Web-Pages/Work-With-Us/Grants-And-Loans/LandFlex/RevisedlandflexguidelinesOct2024-Final-002-Approved.pdf (Accessed August 14, 2025).

EDF. (2020a). Building Multibenefit Recharge Basins. Environmental Defense Fund. Available online at: https://www.edf.org/sites/default/files/Groundwater-recharge-guidelines-checklist_07-spreads.pdf

EDF. (2020b). Central Valley habitat exchange: A new solution for saving species, Benefitting Landowners. Environmental Defense Fund.

EDF. (2021). Advancing strategic land repurposing and groundwater sustainability in California. Environmental Defense Fund. Available online at: https://www.edf.org/sites/default/files/documents/EDF_AdvancingLandRepurposing_March2021_0.pdf (Accessed August 13, 2025).

Ekkel, E. D., and de Vries, S. (2017). Nearby green space and human health: evaluating accessibility metrics. *Landsc. Urban Plan.* 157, 214–220. doi: 10.1016/j.landurbplan.2016.06.008

Escriva-Bou, A., Hanak, E., Cole, S., and Medellín-Azuara, J. (2023). Policy brief: The future of agriculture in the San Joaquin Valley: Public Policy Institute of California. Available online at: https://www.ppic.org/publication/policy-brief-the-future-of-agriculture-in-the-san-joaquin-valley/

Espinoza, V., Bernacchi, L. A., Eriksson, M., Schiller, A., Hayden, A., and Viers, J. H. (2023). From fallow ground to common ground: perspectives on future land uses in the San Joaquin valley under sustainable groundwater management. *J. Environ. Manag.* 333:117226. doi: 10.1016/j.jenvman.2023.117226

Fernández-Bou, A. S., Cuppari, R. I., Rodríguez-Flores, J. M., and Yang, V. (2024). Agrivoltaics and Ecovoltaics: how solar power can deliver water savings, farm success, and a healthier environment. *Union Concerned Scientists*. doi: 10.47923/2024.15501

Fernandez-Bou, A. S., Ortiz-Partida, J. P., Classen-Rodriguez, L. M., Pells, C., Dobbin, K. B., Espinoza, V., et al. (2021a). 3 challenges, 3 errors, and 3 solutions to integrate frontline communities in climate change policy and research: lessons from California. *Front. Climate* 3. doi: 10.3389/fclim.2021.717554

Fernandez-Bou, A. S., Ortiz-Partida, J. P., Dobbin, K. B., Flores-Landeros, H., Bernacchi, L. A., and Medellín-Azuara, J. (2021b). Underrepresented, understudied, underserved: gaps and opportunities for advancing justice in disadvantaged communities. *Environ. Sci. Pol.* 122, 92–100. doi: 10.1016/j.envsci.2021.04.014

Fernandez-Bou, A. S., Rodríguez-Flores, J. M., Guzman, A., Ortiz-Partida, J. P., Classen-Rodriguez, L. M., Sánchez-Pérez, P. A., et al. (2023). Water, environment, and socioeconomic justice in California: a multi-benefit cropland repurposing framework. *Sci. Total Environ.* 858:159963. doi: 10.1016/j.scitotenv.2022.159963

Fernandez-Bou, A. S., Rodriguez-Flores, J. M., Ortiz-Partida, J. P., Fencl, A., Classen-Rodriguez, L. M., Yang, V., et al. (2025). Cropland repurposing as a tool for water sustainability and just land transition in California: review and best practices. *Frontiers in Water* 7, 1–31. doi: 10.3389/frwa.2025.1510413

Ferris, J., Norman, C., and Sempik, J. (2001). People, land and sustainability: community gardens and the social dimension of sustainable development. *Soc. Policy Adm.* 35, 559–568. doi: 10.1111/1467-9515.t01-1-00253

Flegal, C., Rice, S., Mann, J., and Tran, J. (2013). California unincorporated: Mapping disadvantaged communities in the San Joaquin Valley: PolicyLink. Available online at: https://www.policylink.org/sites/default/files/CA%20UNINCORPORATED_FINAL.pdf (Accessed August 14, 2025).

Flood, R. L., and Romm, N. R. A. (1996). Plurality revisited: diversity management and triple loop learning. *Systems Practice* 9, 587–603. doi: 10.1007/BF02169215

Foster, S., Chilton, J., Nijsten, G.-J., and Richts, A. (2013). Groundwater—A global focus on the 'local resource'. *Curr. Opin. Environ. Sustain.* 5, 685–695. doi: 10.1016/j.cosust.2013.10.010

Friant Water Authority. (2019). Subsidence, A Critical 1304 Challenge to Friant-Kern Canal Water Deliveries. Available online at: https://static1.squarespace.com/static/58c2eccc15d5db46200ea426/t/5df2e69ea705f61846a258bd/1576199845717/FWA_Subsidence_Challenge_V3_web.pdf (Accessed August 13, 2025).

Galaz, V., Crona, B., Österblom, H., Olsson, P., and Folke, C. (2012). Polycentric systems and interacting planetary boundaries—emerging governance of climate change–ocean acidification–marine biodiversity. *Ecol. Econ.* 81, 21–32. doi: 10.1016/j.ecolecon.2011.11.012

Gardiner, B. D. (2021). To fight off a California dust bowl, the state will pay farmers to reimagine idle land. San Francisco Chronicle https://www.sfchronicle.com/politics/article/To-fight-off-a-California-dust-bowl-the-state-16596612.php (Accessed November 10, 2021).

Gardner, R., Moore, M. R., and Walker, J. M. (1997). Governing a groundwater commons: a strategic and laboratory analysis of western water law. *Econ. Inq.* 35, 218–234. doi: 10.1111/j.1465-7295.1997.tb01905.x

Gardner, R., Ostrom, E., and Walker, J. M. (1990). The nature of common-Pool resource problems. *Ration. Soc.* 2, 335–358. doi: 10.1177/1043463190002003005

Garone, P. (2020). The fall and rise of the wetlands of California's great Central Valley, Berkeley, CA: Universuty of California Press.

Gerlak, A. K., Heikkila, T., and Lubell, M. (2012). "The promise and performance of collaborative governance" in The Oxford handbook of U.S. environmental policy. eds. M. E. Kraft and S. Kamieniecki (Oxford University Press).

GreenInfo Network. (2024). CPAD and CCED. California Protected Areas Database. Available online at: https://calands.org/

Grimm, M., Serra-Llobet, A., Bruce, M., and Kiparsky, M. (2025). Siloed funding of multibenefit projects highlights the need for funding programs that integrate cobenefits. *Frontiers in Water* 7:1566458. doi: 10.3389/frwa.2025.1566458

Gunier, R. B., Bradman, A., Harley, K. G., and Eskenazi, B. (2017). Will buffer zones around schools in agricultural areas be adequate to protect children from the potential adverse effects of pesticide exposure? *PLoS Biol.* 15:e2004741. doi: 10.1371/journal.pbio.2004741

Guzman, A., Chase, M., and Kremen, C. (2019). On-farm diversification in an agriculturally-dominated landscape positively influences specialist pollinators. *Front. Sustainable Food Systems* 3, 1–9. doi: 10.3389/fsufs.2019.00087

Guzman, A., Montes, M., Hutchins, L., DeLaCerda, G., Yang, P., Kakouridis, A., et al. (2021). Crop diversity enriches arbuscular mycorrhizal fungal communities in an intensive agricultural landscape. *New Phytol.* 231, 447–459. doi: 10.1111/nph.17306

Hall, M., Babbitt, C., Saracino, A., and Leake, S. A. (2018). Addressing regional surface water depletions in California. *Environmental Defense Fund*. Available online at: http://edf.org/california-surface-water-report

Hanak, E., Ayres, A., Peterson, C., Escriva-Bou, A., Cole, S., and Joaquín, Z. (2023). Managing water and farmland transitions in the San Joaquin Valley. Available online at: https://www.ppic.org/publication/managing-water-and-farmland-transitions-in-the-san-joaquin-valley/ (Accessed August 13, 2025).

Hanak, E., Escriva-Bou, A., Gray, B., Green, S., Harter, T., Jezdimirovic, J., et al. (2019). *Water Future San Joaquin Valley*. doi: 10.13140/RG.2.2.24360.83208

Hankins, D. L. (2024). Climate resilience through ecocultural stewardship. *Proc. Natl. Acad. Sci.* 121:e2310072121. doi: 10.1073/pnas.2310072121

Harris, L. (2023). Farmer response to policy induced water reductions: evidence from the Colorado River (SSRN scholarly paper no. 4527866). doi: 10.2139/ssrn.4527866

Heisey, S., Ryals, R., Maaz, T. M., and Nguyen, N. H. (2022). A single application of compost can leave lasting impacts on soil microbial community structure and Alter cross-domain interaction networks. *Front. Soil Sci.* 2, 1–16. doi: 10.3389/fsoil.2022.749212

Henry, L. (2024). Kern County farmland values continue downward slide. SJV Water. Available online at: https://sjvwater.org/kern-county-farmland-values-continue-downward-slide/ (Accessed August 13, 2025).

Hernandez, R. R., Armstrong, A., Burney, J., Ryan, G., Moore-O'Leary, K., Diédhiou, I., et al. (2019). Techno–ecological synergies of solar energy for global sustainability. *Nature Sustainability* 2, 560–568. doi: 10.1038/s41893-019-0309-z

Hibbett, E., Rushforth, R. R., Roberts, E., Ryan, S. M., Pfeiffer, K., Bloom, N. E., et al. (2020). Citizen-led community innovation for food energy water Nexus resilience. *Front. Environ. Sci.* 8, 1–17. doi: 10.3389/fenvs.2020.571614

Hoang, N. T., Taherzadeh, O., Ohashi, H., Yonekura, Y., Nishijima, S., Yamabe, M., et al. (2023). Mapping potential conflicts between global agriculture and terrestrial conservation. *Proc. Natl. Acad. Sci.* 120:e2208376120. doi: 10.1073/pnas.2208376120

Hoffacker, M. K., Allen, M. F., and Hernandez, R. R. (2017). Land-sparing opportunities for solar energy development in agricultural landscapes: a case study of the great Central Valley, CA, United States. *Environ. Sci. Technol.* 51, 14472–14482. doi: 10.1021/acs.est.7b05110

Holling, C. S. (2001). Understanding the complexity of economic, ecological, and social systems. *Ecosystems* 4, 390–405. doi: 10.1007/s10021-001-0101-5

Hoogesteger, J., and Wester, P. (2017). Regulating groundwater use: the challenges of policy implementation in Guanajuato, Central Mexico. *Environ. Sci. Pol.* 77, 107–113. doi: 10.1016/j.envsci.2017.08.002

Howard, J. K., Dooley, K., Brauman, K. A., Klausmeyer, K. R., and Rohde, M. M. (2023). Ecosystem services produced by groundwater dependent ecosystems: a framework and case study in California. *Front. Water* 5:1115416. doi: 10.3389/frwa.2023.1115416

Huang, X., and Swain, D. L. (2022). Climate change is increasing the risk of a California megaflood. Science *Advances*, 8:eabq0995. doi: 10.1126/sciadv.abq0995

Iqbal, J., Su, C., Abbas, H., Jiang, J., Han, Z., Baloch, M. Y. J., et al. (2025). Prediction of nitrate concentration and the impact of land use types on groundwater in the Nansi Lake Basin. *J. Hazard. Mater.* 487:137185. doi: 10.1016/j.jhazmat.2025.137185

Ishtiaque, A., Sangwan, N., and Yu, D. J. (2017). Robust-yet-fragile nature of partly engineered social-ecological systems: a case study of coastal Bangladesh. *Ecol. Soc.* 22, 1–13. doi: 10.5751/ES-09186-220305

Jerrett, M., Connolly, R., Garcia-Gonzales, D. A., Bekker, C., Nguyen, J. T., Su, J., et al. (2024). Climate change and public health in California: a structured review of exposures, vulnerable populations, and adaptation measures. *Proc. Natl. Acad. Sci.* 121:e2310081121. doi: 10.1073/pnas.2310081121

Kalra, N., Lempert, R. J., Park, H. M., Rojas Aguilera, J., Wright, G. C., Sytsma, T., et al. (2024). Informing clean energy planning in California's San Joaquin Valley. RAND Corporation. Available online at: https://www.rand.org/pubs/research_reports/RRA3115-1.html

Kaye, J. P., and Quemada, M. (2017). Using cover crops to mitigate and adapt to climate change. A review. *Agronomy Sustainable Development* 37:4. doi: 10.1007/s13593-016-0410-x

Keeley, A. T. H., Basson, G., Cameron, D. R., Heller, N. E., Huber, P. R., Schloss, C. A., et al. (2018). Making habitat connectivity a reality. *Conserv. Biol.* 32, 1221–1232. doi: 10.1111/cobi.13158

Kelsey, R., Hart, A., Butterfield, H. S., and Vink, D. (2018). Groundwater sustainability in the San Joaquin Valley: multiple benefits if agricultural lands are retired and restored strategically. *Calif. Agric.* 72, 151–154. doi: 10.3733/ca.2018a0029

Kim, J. H., Keane, T. D., and Bernard, E. A. (2015). Fragmented local governance and water resource management outcomes. *J. Environ. Manag.* 150, 378–386. doi: 10.1016/j.jenvman.2014.12.002

Kiparsky, M. (2016). Unanswered questions for implementation of the sustainable groundwater management act. *Calif. Agric.* 70, 165–168. doi: 10.3733/ca.2016a0014

Kiparsky, M., Owen, D., Christian-Smith, J., Cosens, B., Doremus, H., Fisher, A., et al. (2016). Designing effective groundwater sustainability agencies: Criteria for evaluation of local governance options.

Kocis, T. N., and Dahlke, H. E. (2017). Availability of high-magnitude streamflow for groundwater banking in the Central Valley, *California. Environmental Research Letters*, 12:84009. doi: 10.1088/1748-9326/aa7b1b

Koebele, E. A., Méndez-Barrientos, L. E., Nadeau, N., and Gerlak, A. K. (2024). Beyond engagement: enhancing equity in collaborative water governance. *WIREs Water* 11:e1687. doi: 10.1002/wat2.1687

Koebele, E. A., Singletary, L., Hockaday, S. E., and Ormerod, K. J. (2022). A role for water markets in enhancing water security in the western United States?: lessons from the Walker River basin. *Water Policy* 24, 1757–1771. doi: 10.2166/wp.2022.071

Krasner, N. Z., Fox, J., Armstrong, A., Ave, K., Carvalho, F., Li, Y., et al. (2025). Impacts of photovoltaic solar energy on soil carbon: a global systematic review and framework. *Renew. Sust. Energ. Rev.* 208:115032. doi: 10.1016/j.rser.2024.115032

Larsen, A. E., Gaines, S. D., and Deschênes, O. (2017). Agricultural pesticide use and adverse birth outcomes in the San Joaquin Valley of California. *Nat. Commun.* 8:302. doi: 10.1038/s41467-017-00349-2

Larsen, A. E., and Noack, F. (2021). Impact of local and landscape complexity on the stability of field-level pest control. *Nature Sustainability* 4, 120–128. doi: 10.1038/s41893-020-00637-8

Larsen, A. E., Noack, F., and Powers, L. C. (2024). Spillover effects of organic agriculture on pesticide use on nearby fields. *Science* 383:eadf2572. doi: 10.1126/science.adf2572

Larsen, A. E., Quandt, A., Foxfoot, I., Parker, N., and Sousa, D. (2023). The effect of agricultural land retirement on pesticide use. *Sci. Total Environ.* 896:165224. doi: 10.1016/j.scitotenv.2023.165224

Leach, W. D., An, B. Y., and Tang, S.-Y. (2021). Evaluating California's sustainable groundwater management act: the first five years of governance and planning. *JAWRA J. American Water Resources Association* 57, 972–989. doi: 10.1111/1752-1688.12967

Leahy, T. C. (2015). Desperate times call for sensible measures: the making of the California sustainable groundwater management act symposium edition: the waste of water in 21st century California. *Golden Gate University Environmental Law Journal* 9, 5–40.

Levy, Z. F., Jurgens, B. C., Burow, K. R., Voss, S. A., Faulkner, K. E., Arroyo-Lopez, J. A., et al. (2021). Critical aquifer overdraft accelerates degradation of groundwater quality in California's Central Valley during drought. *Geophys. Res. Lett.* 48:e2021GL094398. doi: 10.1029/2021GL094398

Levy, M. A., Lubell, M. N., and McRoberts, N. (2018). The structure of mental models of sustainable agriculture. *Nature Sustainability* 1, 413–420. doi: 10.1038/s41893-018-0116-y

Levy, M. C., Neely, W. R., Borsa, A. A., and Burney, J. A. (2020). Fine-scale spatiotemporal variation in subsidence across California's San Joaquin Valley explained by groundwater demand. *Environ. Res. Lett.* 15:104083. doi: 10.1088/1748-9326/abb55c

Li, S., Ritz, B., Gong, Y., Cockburn, M., Folle, A. D., Del Rosario, I., et al. (2023). Proximity to residential and workplace pesticides application and the risk of progression of Parkinson's diseases in Central California. *Sci. Total Environ.* 864:160851. doi: 10.1016/j.scitotenv.2022.160851

Lin, B. B., and Egerer, M. H. (2020). Global social and environmental change drives the management and delivery of ecosystem services from urban gardens: a case study from central coast, California. *Global Environmental Change* 60:102006. doi: 10.1016/j.gloenvcha.2019.102006

London, J. K. (2021). Disadvantaged Unincorporated Communities and the Struggle for Water Justice in California. 14. Available at: https://scholarship.law.columbia.edu/faculty_scholarship/3598 (Accessed August 13, 2025).

Long, J. W., Goode, R. W., and Lake, F. K. (2022). Recentering ecological restoration with tribal perspectives. *Fremontia.* 48, 14–19.

Long, J. W., and Lake, F. K. (2018). Escaping social-ecological traps through tribal stewardship on national forest lands in the Pacific northwest, United States of America. *Ecol. Soc.* 23, 1–14. doi: 10.5751/ES-10041-230210

Lortie, C. J., Filazzola, A., Kelsey, R., Hart, A. K., and Butterfield, H. S. (2018). Better late than never: a synthesis of strategic land retirement and restoration in California. *Ecosphere* 9:e02367. doi: 10.1002/ecs2.2367

Lubell, M. (2007). Familiarity breeds trust: collective action in a policy domain. *J. Polit.* 69, 237–250. doi: 10.1111/j.1468-2508.2007.00507.x

Lubell, M., Blomquist, W., and Beutler, L. (2020). Sustainable groundwater Management in California: a grand experiment in environmental governance. *Soc. Nat. Resour.* 33, 1447–1467. doi: 10.1080/08941920.2020.1833617

Lukanov, B. R., and Krieger, E. M. (2019). Distributed solar and environmental justice: exploring the demographic and socio-economic trends of residential PV adoption in California. *Energy Policy* 134:110935. doi: 10.1016/j.enpol.2019.110935

Madera County. (2021). Resolution establishing groundwater allocation requirements (no. 2021–113) [PDF]. Madera County Groundwater Sustainability Agency. Available online at: https://www.maderacountywater.com/wp-content/uploads/2021/08/21.08-Updated-Groundwater-Allocation-Reso.pdf (Accessed August 14, 2025).

Madera County. (2024). Madera County multibenefit agricultural land repurposing plan (MALRP)—administrative draft. Madera County Water. Available online at: https://www.maderacountywater.com/wp-content/uploads/2024/09/Madera-County-MALRP-Admin-Draft-9-23-24-v2-1.pdf (Accessed August 14, 2025).

Madera County. (2025a). (CRM 55312) first amendment to La Vina AG, LLC agreement 4897-6385-3864 1.

Madera County. (2025b). Madera MLRP project portfolio recommendation for public comment. Available online at: https://www.maderacountywater.com/wp-content/uploads/2025/06/Madera-MLRP-Project-Portfolio-Recommendation-Memo-6-11-2025-2.pdf (Accessed August 13, 2025).

Madera County Department of Agriculture (2024). 2023 Crop & Livestock Report. Available online at: https://www.maderacounty.com/home/showpublisheddocument/41890/638689241475630000

Madera County Water. (2025). Madera County Multibenefit Land Repurposing Program (MLRP). Madera County - Water & Natural Resources. Available online at: https://www.maderacountywater.com/multibenefit-land-repurposing-program/ (Accessed August 14, 2025).

Marshall, G. R., and Alexandra, J. (2016). Institutional path dependence and environmental water recovery in Australia's Murray-Darling basin. *Water Alternatives* 9, 679–703.

Marwaha, N., Kourakos, G., Levintal, E., and Dahlke, H. E. (2021). Identifying agricultural managed aquifer recharge locations to benefit drinking water supply in rural communities. *Water Resour. Res.* 57:e2020WR028811. doi: 10.1029/2020WR028811

McComb, S., Powers, L. C., and Larsen, A. E. (2022). Evaluating climate-driven fallowing for ecological connectivity of species at risk. *Landsc. Ecol.* 37, 3059–3077. doi: 10.1007/s10980-022-01522-9

Medellín-Azuara, J., Escriva-Bou, A., Gaudin, A. C. M., Schwabe, K. A., and Sumner, D. A. (2024). Cultivating climate resilience in California agriculture: adaptations to an increasingly volatile water future. *Proc. Natl. Acad. Sci.* 121:e2310079121. doi: 10.1073/pnas.2310079121

Melton, F. S., Huntington, J., Grimm, R., Herring, J., Hall, M., Rollison, D., et al. (2022). OpenET: filling a critical data gap in water Management for the Western United States. *JAWRA J. American Water Resources Association* 58, 971–994. doi: 10.1111/1752-1688.12956

Mendez-Barrientos, L. E., Bostic, D., and Lubell, M. (2019). Implementing SGMA: Results from a stakeholder survey. Davis, CA: University of California Davis.

Meng, L., Yan, Y., Jing, H., Baloch, M. Y. J., Du, S., and Du, S. (2024). Large-scale groundwater pollution risk assessment research based on artificial intelligence technology: a case study of Shenyang City in Northeast China. *Ecol. Indic.* 169:112915. doi: 10.1016/j.ecolind.2024.112915

Merenlender, A. M., Crall, A. W., Drill, S., Prysby, M., and Ballard, H. (2016). Evaluating environmental education, citizen science, and stewardship through naturalist programs. *Conserv. Biol.* 30, 1255–1265. doi: 10.1111/cobi.12737

Micklin, P. (2007). The Aral Sea disaster. *Annu. Rev. Earth Planet. Sci.* 35, 47–72. doi: 10.1146/annurev.earth.35.031306.140120

Milman, A., and Kiparsky, M. (2020). Concurrent governance processes of California's sustainable groundwater management act. *Soc. Nat. Resour.* 33, 1555–1566. doi: 10.1080/08941920.2020.1725696

Miraee-Ashtiani, S., Dehghani, N. L., Vahedifard, F., Shafieezadeh, A., and Karimi-Ghartemani, M. (2023). Toward equitable grid resilience: operationalizing climate adaptation strategies to mitigate flooding impacts. *Environmental Research* 3:045009. doi: 10.1088/2634-4505/ad111e

Mitchell, J. P., Shrestha, A., Mathesius, K., Scow, K. M., Southard, R. J., Haney, R. L., et al. (2017). Cover cropping and no-tillage improve soil health in an arid irrigated cropping system in California's San Joaquin Valley, USA. *Soil Tillage Res.* 165, 325–335. doi: 10.1016/j.still.2016.09.001

Mitchell, J., Singh, P., Wallender, W., Munk, D., Wroble, J., Horwath, W., et al. (2012). No-tillage and high-residue practices reduce soil water evaporation. *Calif. Agric.* 66, 55–61. doi: 10.3733/ca.v066n02p55

Monat, J. P., and Gannon, T. F. (2015). What is systems thinking? A review of selected literature plus recommendations. *American J Systems Science* 4, 11–26. doi: 10.5923/j.ajss.20150401.02

Mooney, D. F., and Hansen, K. M. (2024). Agricultural producer decision making around water conservation in the upper Colorado River basin. *Choices Magazine* 39, 1–8.

Moore-O'Leary, K. A., Hernandez, R. R., Johnston, D. S., Abella, S. R., Tanner, K. E., Swanson, A. C., et al. (2017). Sustainability of utility-scale solar energy – critical ecological concepts. *Front. Ecol. Environ.* 15, 385–394. doi: 10.1002/fee.1517

Morris, K. S., and Bucini, G. (2016). California's drought as opportunity: redesigning U.S. agriculture for a changing climate. *Elementa* 4:000142. doi: 10.12952/journal.elementa.000142

Mount, J., Gray, B., Bork, K., Cloern, J. E., Davis, F. W., Grantham, T., et al. (2019). A path forward for California's freshwater ecosystems: Public Policy Institute of California. Available online at: https://www.ppic.org/publication/a-path-forward-for-californias-freshwater-ecosystems/

Murphy, P. M., Kinkhabwala, Y., Kwoka, B., Nunez, Y., Dillon, A., Amezcua-Smith, A., et al. (2024). Modeling and design of solar + storage-powered community resilience hubs across California. *Risk Analysis* 45, 56–77. doi: 10.1111/risa.14341

NASS. (2024). Land values and cash rents. National Agricultural Statistics Service. Available online at: https://www.nass.usda.gov/Publications/Highlights/2024/2024LandValuesCashRents.pdf

Nath, S., Vyas, J. N., Deogade, R. B., and Chandra, P. (2023). "Integrated water resources Management in Developing Nation: status and challenges toward water sustainability" in The route towards global sustainability: Challenges and management practices. eds. P. Singh, Y. Milshina, A. Batalhão, S. Sharma and M. M. Hanafiah (Cham: Springer International Publishing), 367–378. doi: 10.1007/978-3-031-10437-4_18

Nicholson, C. C., and Williams, N. M. (2021). Cropland heterogeneity drives frequency and intensity of pesticide use. *Environ. Res. Lett.* 16:074008. doi: 10.1088/1748-9326/ac0a12

Niles, M. T., and Hammond Wagner, C. (2018). Farmers share their perspectives on California water management and the sustainable groundwater management act. *Calif. Agric.* 72, 1–6. doi: 10.3733/ca.2017a0040

Nordberg, E. J., Julian Caley, M., and Schwarzkopf, L. (2021). Designing solar farms for synergistic commercial and conservation outcomes. *Sol. Energy* 228, 586–593. doi: 10.1016/j.solener.2021.09.090

Nuñez-Bolaño, Y., Flores-Landeros, H., Rodríguez-Flores, J. M., Fernandez-Bou, A. S., Medellín-Azuara, J., and Harmon, T. C. (2025). A participatory approach for developing a geospatial toolkit for mapping the suitability of California's multibenefit land repurposing program (MLRP) in support of groundwater sustainability. *Front. Water* 7, 1–25. doi: 10.3389/frwa.2025.1539834

O'Connell, D., Serrano, F., Livingston, A., and Fontanilla, A. (2023). Finding connection local communities and habitat conservation in the Tulare Basin of California. Available online at: https://centralvalleypartnership.org/wp-content/uploads/2023/07/Finding-Connection-Local-Communities-and-Habitat-Conservation-in-the-Tulare-Basin-of-California.pdf (Accessed August 13, 2025).

Olmstead, A. L., and Rhode, P. W. (2020). "A history of California agriculture" in California agriculture: Dimensions and issues. *2nd* ed (University of California Giannini Foundation of Agricultural Economics). Available online at: https://giannini.ucop.edu/publications/cal-ag-book/ (Accessed August 14, 2025)

Ostrom, E. (2005). Understanding institutional diversity. Princeton, NJ: Princeton University Press.

Overpeck, J. T., and Udall, B. (2020). Climate change and the aridification of North America. *Proc. Natl. Acad. Sci.* 117, 11856–11858. doi: 10.1073/pnas.2006323117

Owen, D., Cantor, A., Nylen, N. G., Harter, T., and Kiparsky, M. (2019). California groundwater management, science-policy interfaces, and the legacies of artificial legal distinctions. *Environ. Res. Lett.* 14:45016. doi: 10.1088/1748-9326/ab0751

Pace, C., Balazs, C., Bangia, K., Depsky, N., Renteria, A., Morello-Frosch, R., et al. (2022). Inequities in drinking water quality among domestic well communities and community water systems, California, 2011–2019. *Am. J. Public Health* 112, 88–97. doi: 10.2105/AJPH.2021.306561

Pahl-Wostl, C. (2009). A conceptual framework for analysing adaptive capacity and multi-level learning processes in resource governance regimes. *Glob. Environ. Chang.* 19, 354–365. doi: 10.1016/j.gloenvcha.2009.06.001

Palerm, J.-V. (2000). Farmworkers putting down roots in Central Valley communities. *Calif. Agric.* 54, 33–34. doi: 10.3733/ca.v054n01p33

Pancorbo, J. L., Quemada, M., and Roberts, D. A. (2023). Drought impact on cropland use monitored with AVIRIS imagery in Central Valley, California. *Science Total Environment* 859:160198. doi: 10.1016/j.scitotenv.2022.160198

Pastor, M., Cha, J. M., Méndez, M., and Morello-Frosch, R. (2024). California dreaming: why environmental justice is integral to the success of climate change policy. *Proc. Natl. Acad. Sci.* 121:e2310073121. doi: 10.1073/pnas.2310073121

Pathak, T., Maskey, M., Dahlberg, J., Kearns, F., Bali, K., and Zaccaria, D. (2018). Climate change trends and impacts on California agriculture: a detailed review. *Agronomy* 8:25. doi: 10.3390/agronomy8030025

Pauloo, R. A., Escriva-Bou, A., Dahlke, H., Fencl, A., Guillon, H., and Fogg, G. E. (2020). Domestic well vulnerability to drought duration and unsustainable groundwater management in California's Central Valley. *Environ. Res. Lett.* 15:044010. doi: 10.1088/1748-9326/ab6f10

Pauloo, R. A., Fogg, G. E., Guo, Z., and Harter, T. (2021). Anthropogenic basin closure and groundwater salinization (ABCSAL). *J. Hydrol.* 593:125787. doi: 10.1016/j.jhydrol.2020.125787

Pecharroman, L. C., Williams, C., Nylen, N. G., and Kiparsky, M. (2021). How can we govern large-scale green infrastructure for multiple water security benefits? *Blue-Green Systems* 3, 62–80. doi: 10.2166/bgs.2021.015

Penny, G., Srinivasan, V., Apoorva, R., Jeremiah, K., Peschel, J., Young, S., et al. (2020). A process-based approach to attribution of historical streamflow decline in a data-scarce and human-dominated watershed. *Hydrol. Process.* 34, 1981–1995. doi: 10.1002/hyp.13707

Penny, G., Srinivasan, V., Dronova, I., Lele, S., and Thompson, S. (2016). Spatial characterization of long-term hydrological change in the Arkavathy watershed adjacent to Bangalore, India. *Hydrol. Earth Syst. Sci. Discuss.* 2016, 1–25. doi: 10.5194/hess-2016-562

Pfefferbaum, R. L., Pfefferbaum, B., Van Horn, R. L., Klomp, R. W., Norris, F. H., and Reissman, D. B. (2013). The communities advancing resilience toolkit (CART): An intervention to build community resilience to disasters. *J. Public Health Manag. Pract.* 19, 250–258. doi: 10.1097/PHH.0b013e318268aed8

Pholsim, S., and Inaba, Y. (2022). Roles of policy brokers in collaborative governance: evidence from Khon Kaen and Bueng Kan cities in Thailand. *Asian Politics Policy* 14, 374–387. doi: 10.1111/aspp.12651

Plassin, S., Koch, J., Wilson, M., Neal, K., Friedman, J. R., Paladino, S., et al. (2021). Multi-scale fallow land dynamics in a water-scarce basin of the U.S, Southwest. *J Land Use Sci.* 16, 291–312. doi: 10.1080/1747423X.2021.1928310

Porkka, M., Virkki, V., Wang-Erlandsson, L., Gerten, D., Gleeson, T., Mohan, C., et al. (2024). "Notable Shifts beyond Pre-Industrial Streamflow and Soil Moisture Conditions Transgress the Planetary Boundary for Freshwater Change." *Nature Water* 2, 62–73. doi: 10.1038/s44221-024-00208-7

Prokopy, L. S., Floress, K., Arbuckle, J. G., Church, S. P., Eanes, F. R., Gao, Y., et al. (2019). Adoption of agricultural conservation practices in the United States: evidence from 35 years of quantitative literature. *J. Soil Water Conserv.* 74, 520–534. doi: 10.2489/jswc.74.5.520

Quandt, A., Larsen, A. E., Bartel, G., Okamura, K., and Sousa, D. (2023). Sustainable groundwater management and its implications for agricultural land repurposing. *Reg. Environ. Chang.* 23:120. doi: 10.1007/s10113-023-02114-2

Rahman, M. M., Penny, G., Mondal, M. S., Zaman, M. H., Kryston, A., Salehin, M., et al. (2019). Salinization in large river deltas: drivers, impacts and socio-hydrological feedbacks. *Water Security* 6:100024. doi: 10.1016/j.wasec.2019.100024

Ranjan, P., Church, S. P., Floress, K., and Prokopy, L. S. (2019). Synthesizing conservation motivations and barriers: what have we learned from qualitative studies of farmers' behaviors in the United States? *Soc. Nat. Resour.* 32, 1171–1199. doi: 10.1080/08941920.2019.1648710

Rasmussen, L. V., Grass, I., Mehrabi, Z., Smith, O. M., Bezner-Kerr, R., Blesh, J., et al. (2024). Joint environmental and social benefits from diversified agriculture. *Science* 384, 87–93. doi: 10.1126/science.adj1914

Rawlins, J. (2019). Political economy of water reallocation in South Africa: insights from the Western cape water crisis. *Water Security* 6:100029. doi: 10.1016/j.wasec.2019.100029

Reicosky, D., Brandt, D., Reeder, R., Lal, R., and Montgomery, D. R. (2023). Plowing: dust storms, conservation agriculture, and need for a "soil health act". *J. Soil Water Conserv.* 78, 105A–108A. doi: 10.2489/jswc.2023.0619A

Richmond, J. Q., Wood, D. A., Westphal, M. F., Vandergast, A. G., Leaché, A. D., Saslaw, L. R., et al. (2017). Persistence of historical population structure in an endangered species despite near-complete biome conversion in California's San Joaquin Desert. *Mol. Ecol.* 26, 3618–3635. doi: 10.1111/mec.14125

Richter, B., Brown, J., DiBenedetto, R., Gorsky, A., Keenan, E., Madray, C., et al. (2017). Opportunities for saving and reallocating agricultural water to alleviate water scarcity. *Water Policy* 19, 886–907. doi: 10.2166/wp.2017.143

Rising, J., and Devineni, N. (2020). Crop switching reduces agricultural losses from climate change in the United States by half under RCP 8.5. *Nature Communications* 11:1. doi: 10.1038/s41467-020-18725-w

Rodríguez-Flores, J. M., Fernandez-Bou, A. S., Ortiz-Partida, J. P., and Medellín-Azuara, J. (2023). Drivers of domestic wells vulnerability during droughts in California's Central Valley. *Environ. Res. Lett.* 19:014003. doi: 10.1088/1748-9326/ad0d39

Rogers, E. M. (2003). Diffusion of innovations. *5th* Edn. New York, NY: Free Press.

Rohde, M. M., Matsumoto, S., Howard, J., Liu, S., Riege, L., and Remson, E. J. (2018). Groundwater dependent ecosystems under the sustainable groundwater management act: Guidance for preparing groundwater sustainability plans: The Nature Conservancy. Available online at: https://www.scienceforconservation.org/assets/downloads/GDEsUnderSGMA.pdf (Accessed August 14, 2025)

Ross, J., Brawley, S., Lowrey, J., and Hankins, D. L. (2008). Creating common ground: A collaborative approach to environmental reclamation and cultural preservation. In Partnerships for Empowerment: Routledge.

Rowland-Shea, J., Doshi, S., Edberg, S., and Fanger, R. (2020). The nature gap: Confronting racial and economic disparities in the destruction and protection of nature in America: Center for American Progress and Hispanic Access Foundation. Available online at: https://www.americanprogress.org/article/the-nature-gap/ (Accessed August 14, 2025)

Rudnick, J., Lubell, M., Khalsa, S. D. S., Tatge, S., Wood, L., Sears, M., et al. (2021). A farm systems approach to the adoption of sustainable nitrogen management practices in California. *Agric. Hum. Values* 38, 783–801. doi: 10.1007/s10460-021-10190-5

Scudiero, E., Corwin, D. L., Anderson, R. G., Yemoto, K., Clary, W., and Wang, Z. (2017). Remote sensing is a viable tool for mapping soil salinity in agricultural lands. *Calif. Agric.* 71, 231–238. doi: 10.3733/ca.2017a0009

Self-Help Enterprises, Environmental Defense Fund, and Environmental Incentives. (2024). Multibenefit land repurposing program annual report 2023. MLRP Statewide Support Entity. Available online at: https://www.edf.org/sites/default/files/documents/MLRP%20Annual%20Report_2022-23_0.pdf

Self-Help Enterprises, Environmental Defense Fund, and Environmental Incentives. (2025). Multibenefit land repurposing program annual report 2024. MLRP Statewide Support Entity. Available online at: https://www.conservation.ca.gov/dlrp/grant-programs/Documents/2024%20MLRP%20Annual%20Report.pdf (Accessed August 13, 2025).

Serra-Llobet, A., Jähnig, S. C., Geist, J., Kondolf, G. M., Damm, C., Scholz, M., et al. (2022). Restoring Rivers and floodplains for habitat and Flood risk reduction: experiences in multi-benefit floodplain management from California and Germany. *Front. Environ. Sci.* 9, 1–24. doi: 10.3389/fenvs.2021.778568

Shah, T. (2010). Taming the anarchy: Groundwater governance in South Asia. Washington, DC: Routledge.

Shanono, N. J., Nasidi, N. M., Maina, M. M., Bello, M. M., Ibrahim, A., Umar, S. I., et al. (2019). Socio-hydrological study of water users' perceptions on the management of irrigation schemes at Tomas irrigation project, Kano, Nigeria. *Nigeria J. Eng. Sci. Technol. Res.* 5, 139–145.

Shew, A. M., Saettele, K. D., George, K., Lipke, D., and Tester, C. (2024). Farmland values: The California report (no. April 2024). Acres. Available online at: https://22215745.fs1.hubspotusercontent-na1.net/hubfs/22215745/Free%20Reports/Acres%20California%20Farmland%20Values%20Report%202024.pdf?utm_campaign=California%20Report%20-%202024&utm_medium=email&_hsenc=p2ANqtz--YVF_P1CEEJvDmLytMQrvC9LGFKWiwDZvnm3cjy5FN88esgnPtgyjDc5QP6ddtCsrHpj0mbfJvTzQCabdMxGYgocnR_Q&_hsmi=305044199&utm_content=305044199&utm_source=hs_automation (Accessed August 13, 2025).

Sister, C., Wolch, J., and Wilson, J. (2010). Got green? Addressing environmental justice in park provision. *GeoJournal* 75, 229–248. doi: 10.1007/s10708-009-9303-8

Solomon, D., Ishtiaque, A., Agarwal, A., Gray, J. M., Carmen Lemos, M., Moben, I., et al. (2024). The role of rural circular migration in shaping weather risk management for smallholder farmers in India, Nepal, and Bangladesh. *Glob. Environ. Chang.* 89:102937. doi: 10.1016/j.gloenvcha.2024.102937

Srinivasan, V., Lakshmikantha, N. R., Manjunatha, G., and Shinde, G. N. (2025). Chasing the water table: the impact of groundwater depletion on rural drinking water supply in peninsular India. *PLOS Water* 4:e0000138. doi: 10.1371/journal.pwat.0000138

Stevens, M. L. (2020). Eco-cultural restoration of riparian wetlands in California: case study of White root (*Carex barbarae* Dewey; Cyperaceae). *Wetlands* 40, 2461–2475. doi: 10.1007/s13157-020-01323-3

Stewart, J. A. E., Butterfield, H. S., Richmond, J. Q., Germano, D. J., Westphal, M. F., Tennant, E. N., et al. (2019). Habitat restoration opportunities, climatic niche contraction, and conservation biogeography in California's San Joaquin Desert. *PLoS One* 14:e0210766. doi: 10.1371/journal.pone.0210766

Subedi, Y. R., Kristiansen, P., and Cacho, O. (2022). Drivers and consequences of agricultural land abandonment and its reutilisation pathways: a systematic review. *Environmental Development* 42:100681. doi: 10.1016/j.envdev.2021.100681

Sunding, D., and Roland-Holst, D. (2020). Blueprint economic impact analysis: phase one results. Berkeley, CA: University of California. Available online at: https://www.restorethedelta.org/wp-content/uploads/SJV-Blueprint-for-Extinction-Economic-Study-2-15-2020.pdf (Accessed August 13, 2025).

Swain, D. L., Langenbrunner, B., Neelin, J. D., and Hall, A. (2018). Increasing precipitation volatility in twenty-first-century California. *Nat. Clim. Chang.* 8, 427–433. doi: 10.1038/s41558-018-0140-y

Taylor, R., and Zilberman, D. (2017). Diffusion of drip irrigation: the case of California. *Appl. Econ. Perspect. Policy* 39, 16–40. doi: 10.1093/aepp/ppw026

Tosey, P., Visser, M., and Saunders, M. N. (2012). The origins and conceptualizations of 'triple-loop' learning: a critical review. *Manag. Learn.* 43, 291–307. doi: 10.1177/1350507611426239

Tully, K., and Ryals, R. (2017). Nutrient cycling in agroecosystems: balancing food and environmental objectives. *Agroecol. Sustain. Food Syst.* 41, 761–798. doi: 10.1080/21683565.2017.1336149

Twiss, J., Dickinson, J., Duma, S., Kleinman, T., Paulsen, H., and Rilveria, L. (2003). Community gardens: lessons learned from California healthy cities and communities. *Am. J. Public Health* 93, 1435–1438. doi: 10.2105/AJPH.93.9.1435

Ulibarri, N., Escobedo Garcia, N., Nelson, R. L., Cravens, A. E., and McCarty, R. J. (2021). Assessing the feasibility of managed aquifer recharge in California. *Water Resour. Res.* 57, 1–18. doi: 10.1029/2020WR029292

United Nations. (2024). The United Nations world water development report 2024: water for prosperity and peace. UNESCO. Available online at: https://www.unwater.org/publications/un-world-water-development-report-2024 (Accessed August 13, 2025).

USDA NASS. (2022). National Agricultural Statistics Service—California County ag commissioners' data listing. USDA's National Agricultural Statistics Service California Field Office. Available online at: https://www.nass.usda.gov/Statistics_by_State/California/Publications/AgComm/index.php (Accessed August 13, 2025).

van der Ploeg, J. D., Barjolle, D., Bruil, J., Brunori, G., Costa Madureira, L. M., Dessein, J., et al. (2019). The economic potential of agroecology: empirical evidence from Europe. *J. Rural. Stud.* 71, 46–61. doi: 10.1016/j.jrurstud.2019.09.003

Varela-Ortega, C., Blanco-Gutiérrez, I., Swartz, C. H., and Downing, T. E. (2011). Balancing groundwater conservation and rural livelihoods under water and climate uncertainties: An integrated hydro-economic modeling framework. *Glob. Environ. Chang.* 21, 604–619. doi: 10.1016/j.gloenvcha.2010.12.001

Vendig, I., Guzman, A., De La Cerda, G., Esquivel, K., Mayer, A. C., Ponisio, L., et al. (2023). Quantifying direct yield benefits of soil carbon increases from cover cropping. *Nature Sustainability* 6, 1125–1134. doi: 10.1038/s41893-023-01131-7

Vicente-Serrano, S. M., Peña-Gallardo, M., Hannaford, J., Murphy, C., Lorenzo-Lacruz, J., Dominguez-Castro, F., et al. (2019). Climate, irrigation, and land cover change explain streamflow trends in countries bordering the Northeast Atlantic. *Geophys. Res. Lett.* 46, 10821–10833. doi: 10.1029/2019GL084084

Wang, T., Park, S. C., and Jin, H. (2015). Will farmers save water? A theoretical analysis of groundwater conservation policies. *Water Resources Economics* 12, 27–39. doi: 10.1016/j.wre.2015.10.002

Wang, J., Ulibarri, N., Scott, T. A., and Davis, S. J. (2023). Environmental justice, infrastructure provisioning, and environmental impact assessment: evidence from the California environmental quality act. *Environ. Sci. Pol.* 146, 66–75. doi: 10.1016/j.envsci.2023.05.003

Warmann, E., Jenerette, G. D., and Barron-Gafford, G. A. (2024). Agrivoltaic system design tools for managing trade-offs between energy production, crop productivity and water consumption. *Environ. Res. Lett.* 19:034046. doi: 10.1088/1748-9326/ad2ab8

Wei, Y., Langford, J., Willett, I. R., Barlow, S., and Lyle, C. (2011). Is irrigated agriculture in the Murray Darling basin well prepared to deal with reductions in water availability? *Glob. Environ. Chang.* 21, 906–916. doi: 10.1016/j.gloenvcha.2011.04.004

Wescoat, J. L., Siddiqi, A., and Muhammad, A. (2018). Socio-hydrology of channel flows in complex river basins: Rivers, canals, and distributaries in Punjab. Pakistan: Water Resources Research.

Wreford, A., Ignaciuk, A., and Gruère, G. (2017). Overcoming barriers to the adoption of climate-friendly practices in agriculture (OECD food, agriculture and fisheries papers no. 101; OECD food, agriculture and fisheries papers, Vol. 101). doi: 10.1787/97767de8-en

Wu, G. C., Jones, R. A., Leslie, E., Williams, J. H., Pascale, A., Brand, E., et al. (2023). Minimizing habitat conflicts in meeting net-zero energy targets in the western United States. *Proc. Natl. Acad. Sci.* 120:e2204098120. doi: 10.1073/pnas.2204098120

Wunder, S., Fraccaroli, C., Bull, J. W., Dutta, T., Eyres, A., Evans, M. C., et al. (2025). Biodiversity credits: An overview of the current state, future opportunities, and potential pitfalls. *Bus. Strateg. Environ.* 1–30. doi: 10.1002/bse.70018

You, J. (2024). Connecting land and water planning in Colorado. *J. Plan. Educ. Res.* 44, 1970–1987. doi: 10.1177/0739456X221131240