## Title

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# Linkages between land-use change and groundwater management foster long-term resilience of water supply in California

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ABSTRACT

*Study Region:* We created a 270-m coupled model of land-use and groundwater conditions, LUCAS-W[ater], for California's Central Coast. This groundwater-dependent region is undergoing a dramatic reorganization of groundwater management under California's 2014 Sustainable Groundwater Management Act (SGMA).
*Study Focus:* Understanding land-use and land-cover change supports long-term sustainable water management. Anthropogenic water demand has depleted groundwater aquifers worldwide, while future water shortages will likely affect land-use change, creating system feedbacks. Our novel participatory approach fused changes in land-use and associated water use from county-scale data to local water agencies' estimates of total sustainable supply, scaling up local hydro-geologic knowledge from heterogeneous aquifers and diverse management approaches to a regional level. We assessed five stakeholder-driven scenarios with the same historic rates of urban and agricultural land-use change, but different water and land-use management, analyzing how management strategies altered both the spatial pattern of development and subsequent water sustainability from 2001 to 2061.
*New Hydrological Insights for the Region:* Transformative strategies using demand-side interventions that coupled water availability to land-use more effectively achieved long-term sustainability than adaptive strategies using supply-side interventions to increase water supplies. Limiting water withdrawals within SGMA regulated basins resulted in leakage of development into unregulated basins, increasing groundwater pumping there. Protecting ecosystems, farmlands, and recharge areas from development reduced leakage into undeveloped basins without negatively affecting water sustainability.

## 1. Introduction

Groundwater is an essential life-sustaining resource for billions of people worldwide, providing a buffer against precipitation variability and water shortages during drought (FAO, 2016). However, many groundwater basins worldwide are already experiencing ongoing and long-term declines in groundwater levels (Famiglietti, 2014; Stonestrom et al., 2009; Wada et al., 2012). Chronic groundwater overdraft—where water extractions exceed recharge—can cause loss of water quality, saltwater intrusion, land subsidence, and the drying of groundwater-dependent ecosystems and elimination of fish and wildlife populations that depend on them

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(Kløve et al., 2011). Moreover, there can be disproportionate impacts on socio-economically disadvantaged communities which rely on the resource (Dobbin, 2018).

The sustainable management of groundwater is inextricably linked to land-use/land-cover (hereafter "land-use" for brevity) change and the long-term resilience of local communities. Agricultural expansion and urbanization will further deplete groundwater supplies (Wilson et al., 2016), and future water shortages will likely in turn affect land-use change, creating feedbacks within the system (Biggs et al., 2010; Venot et al., 2010). Despite the importance of feedbacks, most integrated models of land-use and hydrology have only used one-way couplings (Chen et al., 2016; Yalew et al., 2018). Hydrological models frequently estimate changes in runoff, recharge, transpiration, and other watershed processes under different, external land-use scenarios (Bhaduri et al., 2000; Fohrer et al., 2001; Karvonen et al., 1999; Tong et al., 2012; Zhang et al., 2017). Land-use change models rarely simulate hydrology (De Rosa et al., 2016), and when they have included hydrological components it has often been a one-way assessment of impacts (c.f., Howells et al., 2013; Liu et al., 2017). Modeling feedbacks is particularly important for predicting how systems will respond to policy change (Chen et al., 2016), including adequate institutional rules and management strategies to address groundwater depletion and achieve water sustainability (Foster and Garduño, 2013). Socio-hydrology has emerged as a relatively new discipline that uses models to understand the dynamic feedbacks between water systems and human systems (Di Baldassarre et al., 2015; Pan et al., 2018).

California is an ideal location for studying the linkages between land-use, groundwater, and potentially transformative governance following the state's passage in 2014 of the Sustainable Groundwater Management Act (SGMA). This law mandates the formation of new groundwater sustainability agencies (GSAs) for the state's 127 groundwater basins in unsustainable overdraft. These agencies must develop groundwater sustainability plans (GSPs) to manage their basins (WAT §10720–10735; California Water Code, 2015). This process is overseen by the California Dept. of Water Resources (CDWR). Our study site was California's Central Coast, a region with agriculture-dominated valleys, coastal tourist oases, and extensive unique natural lands (Langridge, 2018). Ongoing development—which we define as the conversion of rangelands to cropland, of rangelands and cropland to domestic or industrial uses, and of annual crops to higher-value perennial vineyards and orchards—presents challenges in planning for future water supplies (Wilson et al., 2020). These problems may be exacerbated under climate change, with higher temperatures and more extreme droughts projected to reduce surface water supplies and affect groundwater recharge (Langridge, 2018). The region will likely be profoundly impacted by SGMA: local groundwater basins make up 86% of the average water supply and over 40% are already in overdraft (CDWR, 2015; Martin, 2013).

We created a regional coupled model of land-use and water use, LUCAS-W[ater], to assess potential development pathways for California's Central Coast from 2001 to 2061 at 270-meter resolution. Appendix S1.1 provides a stand-alone document with detailed methods describing the parameterization of the model, and the finished model and spatial data are available as data releases (Van

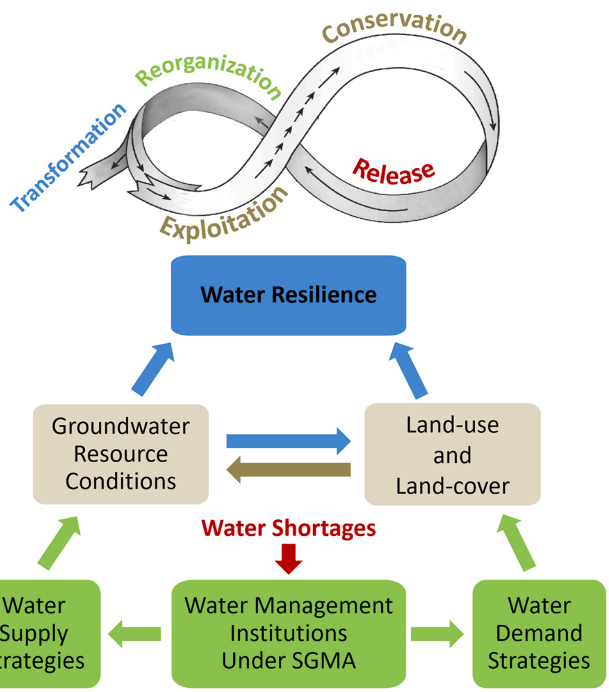


**Fig. 1.** The adaptive cycle (top; adapted from Gunderson and Holling, 2002) aligns with groundwater development as a socio-ecological system in California (bottom). We hypothesized that supply-side management strategies that emphasize adaptation by only increasing the total sustainable supply would be relatively less effective at achieving resilience in the context of future land-use change. In contrast, demand-side strategies would be more effective because they create a new feedback from groundwater resource conditions to land-use change, which can transform the system's behavior, exiting the historical cycle of unsustainable groundwater extraction and achieving water resilience (Walker et al., 2006).

Schmidt et al., 2021). LUCAS-W was empirically fit from historic land-use rates and local hydrology studies. We worked with local water agencies, land-use planners, and other stakeholders to create a scenario-based approach identifying vulnerabilities and adaptive capacity under multiple plausible futures (Appendix S1.1.1). Our focus in this paper is not on exploring alternative economic development pathways (scenarios held the underlying historical rates of land-use change constant) or predicting a precise future state (a task that is challenging and impossible to validate for land-use change models; Messina et al., 2008). Rather, we sought to assess the Central Coast's adaptive capacity by modeling how management strategies proposed under SGMA could work with local zoning strategies to alter the spatial pattern of land-use change and associated stress on water systems at a regional scale. Our goal was "exploring possible future solution spaces" where novel processes could change historic trajectories (Messina et al., 2008). Following predictions of resilience theory (Walker et al., 2006), we hypothesized that management strategies using demand-side interventions would be more capable of mitigating long-term overdraft than supply-side interventions because the former are *transformative*—they add new couplings between water usage and water sustainability—while the latter are only *adaptive*—they alter a water supply variable to adjust to a specific water need (Walker et al., 2006).

## 2. Theory

We use a resilience theory framework to tackle two central questions for socio-ecological systems research: (1) how will land-use patterns change with ongoing changes in water availability, and (2) what is the role of reciprocal relationships (i.e., couplings and feedbacks) in transforming systems from fragile configurations into resilient ones (Kramer et al., 2017)? Resilience theory is a broad interdisciplinary approach combining examinations of complex system behavior, effective governance, cooperation, and social learning (Bakker and Morinville, 2013; Folke, 2006; Walker et al., 2006).

Resilience scholars use the adaptive cycle (Fig. 1, top) as a conceptual model to understand the dynamics of socio-ecological systems (Folke, 2006). Systems adapt by alternating between long periods of resilient growth (*exploitation*) and accumulation of resource-dependent structures that cause fragility (*conservation*), and shorter periods of disturbance-induced change (*release*) and restructuring to a new normal (*reorganization*), after which the cycle repeats (Gunderson and Holling, 2002).

In California, groundwater management can be aligned with the adaptive cycle (Fig. 1, bottom). Groundwater extraction historically had little coordinated institutional oversight, an "exploitation" phase where abundant resources increased water-dependent developed (Leahy, 2016). This led to a "conservation" phase where the development's accumulated water demands created increasing rigidity (political resistance to statewide regulations) and fragility (groundwater declines in many basins; Leahy, 2016). A severe 2012–2016 drought led to a "release" phase of disturbance-induced change wherein the unsustainable demands contributed to unprecedented well failures, water shortages, and emergency water restrictions (Leahy, 2016). These pressures contributed to the passage in 2014 of SGMA (WAT §10720–10737.8; California Water Code, 2015), marking the "reorganization" phase with the potential for transformative new sustainable groundwater management (Leahy, 2016). Resilience theory states that management strategies that only alter the system's existing state variables (e.g., supply-side strategies that only change the amount of water in the system) are *adaptive* in nature. These are hypothesized to be less capable of achieving sustainability than strategies that *transform* system function by adding new linkages (Walker et al., 2006). Thus resilience theory predicts that demand-side SGMA strategies—which newly link water sustainability to land-use—should be more effective at achieving long-term sustainability.

## 3. Material and methods

### 3.1. Study area

California's Central Coast is a 28,534 km$^2$ region covering five counties: Santa Cruz, San Benito, Monterey, San Luis Obispo, and Santa Barbara. The Mediterranean climate has hot, dry summers and cool, wet winters. It is a global hotspot of biodiversity with high potential vulnerability to climate change (Langridge, 2018; Rundel et al., 2016). At the region's center is the Salinas Valley, an agricultural area of national importance, and the City of Salinas, the Central Coast's largest municipality (population of ~158,000; Monterey County Farm Bureau, 2018). It is among the region's 48 cities or census areas classified by the state as "disadvantaged communities" (California EPA, 2018) and the 68 census areas at risk for water inaffordability (Mack and Wrase, 2017), many of which are economically disadvantaged agricultural communities. Water use is dominated by agriculture and water demand varies significantly across crop types (Allan et al., 1998). In some areas, such as the Paso Robles region, a rapid transition from rangeland to perennial agriculture has changed underlying groundwater basins from stable to critically overdrafted in a decade (Giffin et al., 2011). Groundwater depletion has caused the drying of wells and seawater intrusion into aquifers (Monterey County Water Resources Agency, 2017).

Land-use change models project significant expansions of agricultural and urban areas by the end of the century that will likely worsen groundwater overdraft (Wilson et al., 2016, 2017, 2020). These trends threaten the region's extensive undeveloped distinctive coastal, grassland, and shrubland ecosystems, including areas surrounding national and state parks and major tourist destinations such as the Big Sur coast (Wilson et al., 2020). Development and falling groundwater tables jointly imperil endangered species such as California red-legged frogs (*Rana draytonii*) and the Southwestern willow flycatcher (*Empidonax traillii extimus*; U.S. Fish and Wildlife Service, 2002a, 2002b).

### 3.2. The LUCAS-W model

#### 3.2.1. Modeling framework

Our land-use change model, LUCAS-W (Van Schmidt et al., 2021), is a modified version of the LUCAS model (Land Use and Carbon Scenario Simulator; Sleeter et al., 2015; Wilson et al., 2016, 2017, 2020), a spatially explicit, empirical state-and-transition simulation model developed in the ST-SIM package of program SyncroSim v2.2.13 (ApexRMS, 2019; Daniel et al., 2016). The model divides the landscape into spatially discrete simulation cells (i.e., a raster), each with assigned land-use state classes that can change annually. Each anthropogenic land-use class is attributed with an historic, area-based water use estimate, enabling land-use projections to track related water demand over the scenario simulations (Wilson et al., 2016). We previously developed a LUCAS model specifically for the Central Coast at 270-m resolution (391,421 cells; Wilson et al., 2020), which we updated to create LUCAS-W. Each cell is also attributed to a (1) county, (2) GSA and adjudicated basin management area, and (3) groundwater basin based on data from CDWR (2015b).

#### 3.2.2. Land-use change parameterization

The following land-use classes formed the initial landscape conditions in the LUCAS-W model: *rangeland*, *forest*, *wetland*, *water*, *barren*, *transportation*, *developed* (i.e., residential or industrial), and *perennial cropland* and *annual cropland* and (Appendix A.1.2.1). These land-use classes could change with the following land-use transitions: urbanization (*rangeland* or *annual/perennial cropland* converting into *developed*), agricultural expansion (*rangeland* to *annual/perennial cropland*), agricultural contraction (*annual/perennial cropland* to *rangeland*), and agricultural intensification (*annual cropland* to *perennial cropland*). We refer to all anthropogenic land-use changes as "development" for brevity, but italicize "*developed*" when referring to the specific modeled land-use class. The rates of transitions are set as county-specific annual targets, randomly sampled from distributions of historical rates observed from 1992 to 2016 (Appendix A.1.2.2) in the five counties' "Historic Land Use Conversion" data tables obtained from California Department of Conservation (2017). Transitions are stochastically placed based on adjacency rules and "spatial multipliers" that prevent or prioritize land-use transitions within certain areas (Daniel et al., 2016).

#### 3.2.3. Water demand parameterization

To parameterize LUCAS-W's water demand, *developed*, *annual cropland*, and *perennial cropland* cells were attributed with county-specific water demand values in acre-feet per year (AFY; 1 acre-foot = 1233.5 $m^3$) per $km^2$ for each cell (Fig. A.1; Appendix A.1.2.3; Wilson et al., 2016, 2017, 2020). *Developed* water use represented both domestic and industrial demand and was estimated from Maupin et al. (2014). *Cropland* water use was based on the CDWR Agricultural Land and Water Use 1998–2010 dataset (CDWR, 2014).

#### 3.2.4. Model validation

We followed standard approaches to validation in system dynamics research by performing validation tests over the historic period prior to the management strategy analysis stage (Barlas, 1996). We first performed structure validation by rigorously proofing the model and resulting datasets with internal testing and an external data and code review. Our process was iterative and we made revisions to the model parameterization and structure (described in Appendix A.1.1–A.1.2.3) until the model achieved reasonable validation.

We next performed empirical structure tests (Barlas, 1996) by simulating the historic period using each year's actual annual rate of land-use change from the 1992–2016 data (California Dept. of Conservation, 2017). Inspection of outputs showed that the model simulated the input historic rates of land-use change nearly 1:1 ($R^2 > 0.99$ for expected vs. observed rates 2001–2016, mean over 10 iterations; Van Schmidt et al., 2021). LUCAS-W accurately predicted total land-use and associated water-demand when comparing our modeled estimates of county-wide water demand to independent external datasets. We compared LUCAS-W's projected *annual cropland* + *perennial cropland* water demand estimates to independent USGS 2005 and 2010 datasets (Maupin et al., 2014). The mean *cropland* error across counties and time periods was − 7800 AFY (RMSE = 30,847 AFY), equivalent to 4.1% of the water use of a county on average (Fig. A.2a). We compared LUCAS-W's *developed* water demand estimates to an independent CDWR dataset from 2005 to 2010 (CDWR, 2014). The mean *developed* error was − 4637 AFY (RMSE = 7403 AFY), equivalent to 8.9% of the water use of a county on average (Fig. A.2b). For all measures, there was no clear trend of over- or underestimation across counties (Fig. A.2). The model's estimates therefore reasonably represented independent empirical estimates, validating the model.

Quantitative validation of the accuracy of future projections and management strategy impacts was not possible because these represented hypothetical futures, a common issue in such models (Messina et al., 2008). In lieu of external quantitative validation, a process-based approach of engaging with stakeholders in participatory workshops and interviews has been recommended as an alternative way to ensure models reasonably represent real-world dynamics and emerging policies (Messina et al., 2008; Moss, 2008). We did this via interviews and workshops with agency staff during model design, parameterization, and presentation of results.

### 3.3. Participatory scenario development

We used a stakeholder-driven scenario development approach to create an evidence-based body of research about the impacts of specific land-use and water management adaptation strategies. We held a series of six meetings with local institutions and non-profits (hereafter, stakeholders) to oversee model development, identify local priorities and potential adaptations for land and water management, and aid in interpretation of results (Appendix A.1.1). Meetings were informal discussions, with no quantitative data gathered. Partners included the California Climate Change Collaborative (a network of diverse organizations), representatives from the City of Salinas and other city and county land-use agencies, and the Elkhorn Slough Foundation (an environmental non-profit). Stakeholders identified the following water sustainability goals: (1) sufficient water (especially during drought), (2) reduce or halt groundwater level declines, and (3) reduce water pollution. Key sustainable land-use goals were: (1) address the loss of prime farmland, (2) maintain healthy ecosystems, and (3) develop sufficient low- and medium-income housing. Quantitative modeling of strategies to address low- and medium-income housing needs were determined to be beyond the scope of this study.

We identified two water and two land management strategies to quantitatively assess for their ability to achieve regional sustainability, and to identify any tradeoffs between these different goals. Water management strategies were: (1) demand-side interventions to reduce water-dependent development in overdrafted areas, and (2) supply-side interventions to increase water supplies. Land-use management strategies were: (3) preserving the best agricultural lands and recharge areas, and (4) conservation of priority habitat areas.

### 3.4. Modeling water management strategies

#### 3.4.1. SGMA and defining total sustainable supply

We assessed water management strategies based on new SGMA requirements that local GSAs formulate and implement GSPs that would achieve “sustainable groundwater management” (WAT §10720–10735; California Water Code, 2015). SGMA defines sustainability as avoiding “chronic lowering of groundwater levels indicating a significant and unreasonable depletion of supply, groundwater storage, seawater intrusion, land subsidence and surface water depletions” (WAT §10727; California Water Code, 2015). Basins ranked by the CDWR as high- or medium-priority due to chronic groundwater overdraft have until 2040 to achieve sustainability, while low-priority basins are exempt. Court-adjudicated basins established prior to 2015 are largely exempt from these requirements, but were included in our model because they generally have court mandates to reduce future overdraft and must provide reports to ensure consistency with SGMA (WAT §10720.8; California Water Code, 2015). SGMA provides sustainability standards but leaves it to GSAs to create GSPs that implement new rules to achieve compliance to those standards. Within the Central Coast, GSPs included (1) demand-side intervention programs to limit or reduce pumping (only proposed in severely overdrafted basins), and more commonly (2) increasing supplies to meet water demands (e.g., conjunctive use of surface and groundwater, recycling, and desalination projects).

GSPs must calculate a quantitative “sustainable yield” that incorporates the condition of water supplies, projected climate change, and societal considerations of undesirable impacts (WAT §10721, 10727; California Water Code, 2015). Overdraft or surpluses may occur in any given year due to climate variability as long as the long-term yield is sustainable. Approaches varied due to the diverse management strategies employed by GSAs (Langridge and Van Schmidt, 2020). We defined a parameter, *total sustainable supply*, as “the total amount of water demand that can be sustained on average (accounting for intra-year variability) without causing undesirable impacts on the groundwater subbasin.” This slightly broader definition includes not just the sustainable yield of aquifers but also other supplies (e.g., water recycling), and any further reductions that agencies used as management targets (e.g., not exceeding 90% of their yield to generate a drought reserve). We “scaled-up” these local hydrological studies that accounted for diverse groundwater conditions into the regional LUCAS-W model, allowing us to develop a coupled model for the full Central Coast without data-intensive modeling of aquifer dynamics (Van Schmidt et al., 2021).

#### 3.4.2. Review of agency management plans

We assessed demand reduction strategies and estimated *total sustainable supply* by reviewing all available draft or final GSPs, as well as adjudication documents, annual reports, technical reports and other relevant documents that identified sustainable yield and current or proposed management strategies (Langridge and Van Schmidt, 2020). A list of data sources is in Table A.1. We also interviewed staff from each agency to better understand proposed management changes, and confirm our review’s accuracy in lieu of validation with an external dataset (Appendix A.1.2.4; Langridge and Van Schmidt, 2020). Response rate was high: we corresponded with 22 of 27 (81%) regional water agencies.

We estimated two values of *total sustainable supply* in AFY (Table A.1; accessible in model release of Van Schmidt et al., 2021). First, the *current supply* value included the long-term average sustainable yield of groundwater plus other current or in-progress water supplies (e.g., surface water reservoirs). A second *enhanced supply* value added water from projects that are projected in the future as part of GSPs and which interviewees described as “likely to be implemented.” Factors determining *total sustainable supply* varied across basins due to differences in aquifers and management. We did not explicitly model climate change because sustainable yield calculations in GSPs generally accounted for climate change.

#### 3.4.3. Water demand caps

Our first water management strategy, “water demand caps”, sought to limit estimated water demand within a GSA or adjudication’s jurisdiction to its *total sustainable supply* by prohibiting new development and incentivizing the placement of agricultural contraction within basins in a condition of long-term average overdraft. Of the 27 water agencies, nine (33%) had proposed plans to limit total water demand (references in Table A.1). For example, Salinas Valley Basin GSA proposed a cap-and-trade-like program that provides economic incentives to gradually reduce pumping over time via a system of water allocations, with associated cost tiers and exceedance charges (Salinas Valley Basin GSA, 2020). This is a potentially *transformative* adaptation strategy because it adds a new feedback between water demand and supply.

These feedbacks were modeled in LUCAS-W by coupling LUCAS to R (v3.4.3) via ST-SIM’s *External Program* functionality and the package *rsyncrosim* (v1.2.4; R Core Team, 2017). The submodel was turned “off” until 2024, which is the year when the Salinas Valley

Basin GSA (the region's largest GSA) planned to implement their pumping allocation system. At the end of each simulated year from 2024 to 2061, per-pixel water use is exported to R and summed across each water agency's management area. If their sum water demand exceeded their *total sustainable supply* (Fig. 2a), three rules were enacted within that area: (1) urbanization and agricultural expansion were prohibited (spatial multiplier of 0); (2) agricultural contraction was prioritized by an order of magnitude (spatial multiplier of 10); and (3) agricultural intensification (*annual* to *perennial cropland*) was prohibited if it would increase water demand. This third rule only applied to San Benito county because all other counties' perennial cropland was mostly vineyards, which were less water-intensive than their local annual crops (Fig. A.1).

This model made two key assumptions. First, the three rules only change where land-use transitions occur, not the underlying rates. Thus, strategies that limit water demand within individual GSAs will shift these land-use changes into other areas within that county. This assumption is made given the small scale of GSAs management areas relative to national and global-scale drivers of agricultural

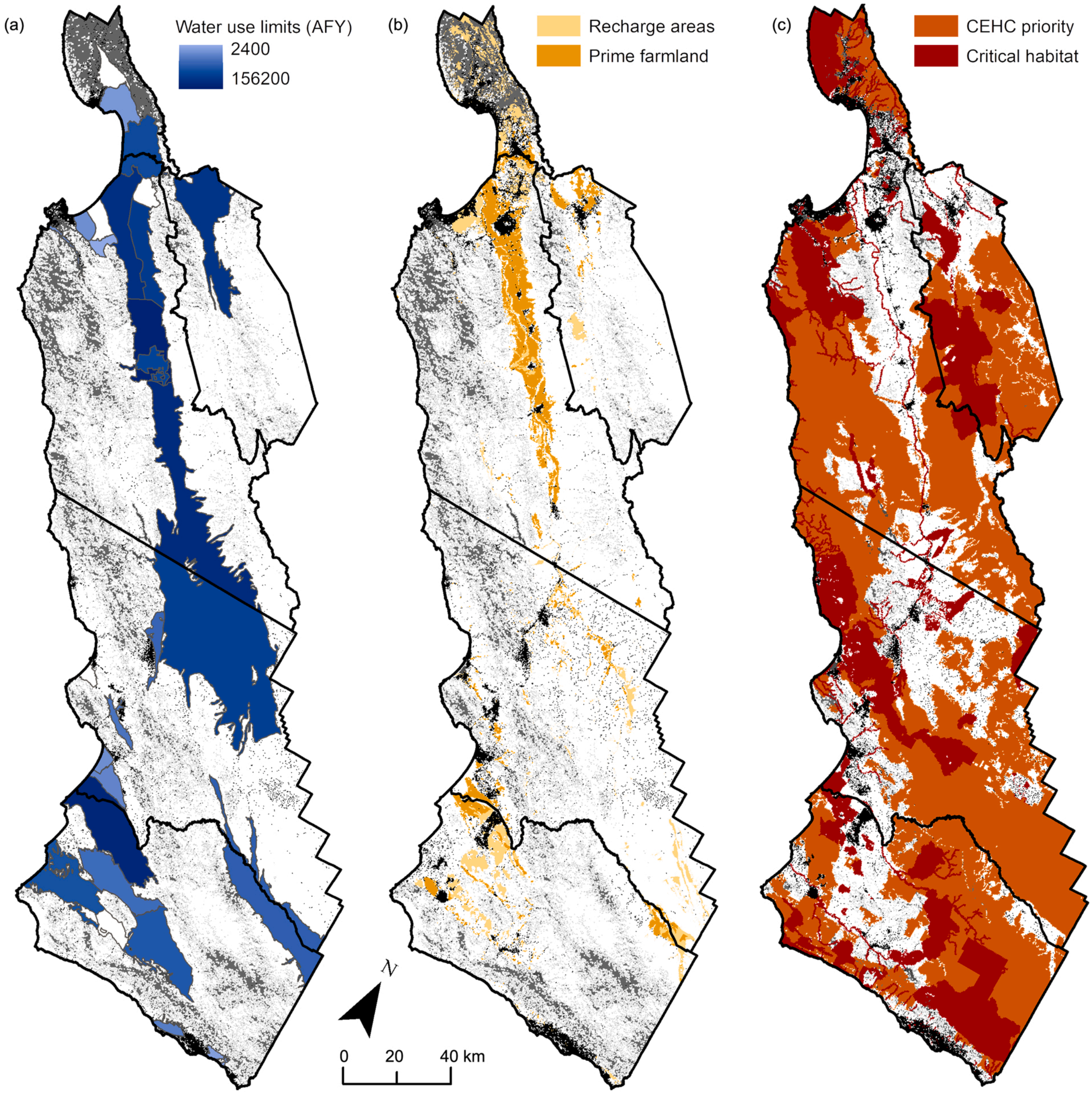


**Fig. 2.** Spatial representation of land-use and water management policies assessed for California's Central Coast. (a) Groundwater agencies' *water demand caps* based on *current supply* (see Table A.1 for *enhanced supply*). (b) Recharge areas and prime farmland where urbanization was prohibited under the *urban sprawl limits* strategy. (c) Critical habitat and California Essential Habitat Connectivity (Spencer et al., 2010) core areas and corridors where urbanization and cropland expansion were prohibited under the *ecosystem preservation* strategy. See Appendix A.1 for methodology and Van Schmidt et al. (2021) for spatial and tabular data.

production demand (Lambin and Meyfroidt, 2011). Second, while not all agencies have proposed demand management regulations, such limitations are still included in our model. We make this assumption because if long-term overdraft occurs by 2061 such restrictions would be necessary to ensure legal compliance with SGMA, which the state can intervene to enforce (WAT §10735.2; California Water Code, 2015).

#### 3.4.4. Water supply enhancement

The second "water supply enhancement" strategy increased the *total sustainable supply* parameter from the *current supply* value to the *enhanced supply* value. This is an *adaptive* strategy because it only alters the existing state variable without adding new couplings between system components (Walker et al., 2006). Of the 27 reviewed agencies, half had no plans to develop further water supplies, including 5 lower priority groundwater basins that had not yet developed their GSPs (Table A.1; Van Schmidt et al., 2021).

### 3.5. Modeling land-use management strategies

#### 3.5.1. Land-use planning objectives

The following land-use management strategies were considered to address stakeholder goals: (1) preserving the best agricultural lands and recharge areas, and (2) conservation of priority habitat areas. To model these strategies, we created spatial multipliers for LUCAS-W to prohibit (spatial multiplier = 0) certain land-use change transitions within target conservation areas. These were in addition to local data on land-use zoning, planned developments, and protected areas that had previously been incorporated into LUCAS (Wilson et al., 2020), which were included in all scenarios assessed.

#### 3.5.2. Urban sprawl limits

Two protections were included in limiting urban sprawl (Fig. 2b). First, the preservation of prime farmland was modeled by prohibiting any new urbanization on areas ranked by the USDA as Prime Farmland or Farmland of Statewide Importance (California Dept. of Conservation, 2016). Second, the protection of recharge areas from urbanization was modeled (Appendix A.1.2.5; Van Schmidt et al., 2021) using soil spatial data and county maps of recharge areas (Table A.2; County of County of County of Santa Cruz Information Services Department, 2015; Monterey County, 2015; RMC Water and Environment, 2015; Soil Survey Staff, 2014).

#### 3.5.3. Ecosystem preservation

Lands identified by state and federal agencies as priorities for conservation were prevented from *urbanization* or *agricultural expansion* to conserve priority habitat areas (Fig. 2c). First, we prohibited these transitions on critical habitats of all state- and federally-listed threatened species (Thorne et al., 2019). Second, we prohibited them on areas identified as key habitat core areas or connecting corridors identified by a joint state agency conservation prioritization assessment, California Essential Habitat Connectivity (Spencer et al., 2010; Thorne et al., 2019).

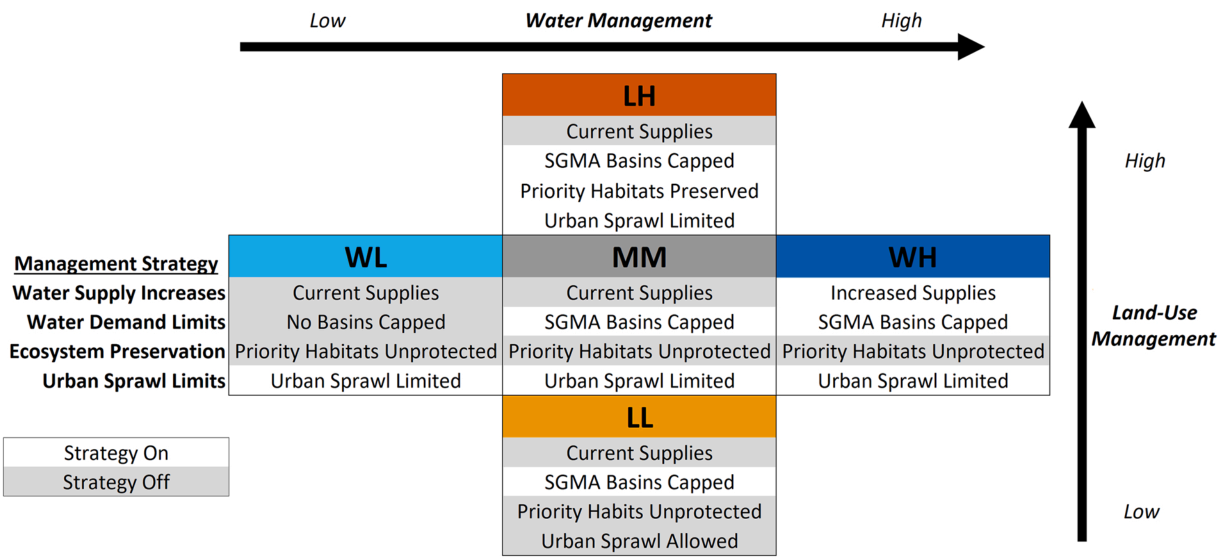


**Fig. 3.** Management scenarios for California's Central Coast. Four management strategies were grouped along two axes (water and land-use). Two strategies were switched "on" additively along each axis while the other axis was held constant at "moderate" management intensity. Strategies with white boxes were included in the scenario, while grey indicates it was inactive.

### 3.6. Designing the scenario analysis

We used feedback from stakeholder workshops to group these land and water management strategies into five scenarios along two axes: Water management intensity Low to High (WL to WH) and Land-use management intensity Low to High (LL to LH; Fig. 3). We varied one management axis at a time to examine the influence of each strategy on land development patterns and groundwater sustainability separately. We used a central "Moderate water management intensity/Moderate land-use management intensity" (MM) to serve as the intersection of these axes.

Water management strategies were grouped into policies as follows:

- **WL** – a continuation of pre-SGMA "business-as-usual" strategies with no water demand limits;
- **MM** – added water demand caps to *current supply* within SGMA-regulated basins;
- **WH** – added water supply enhancement proposed in GSPs, increasing water caps to the *enhanced supply* value.

Land management strategies were grouped as follows:

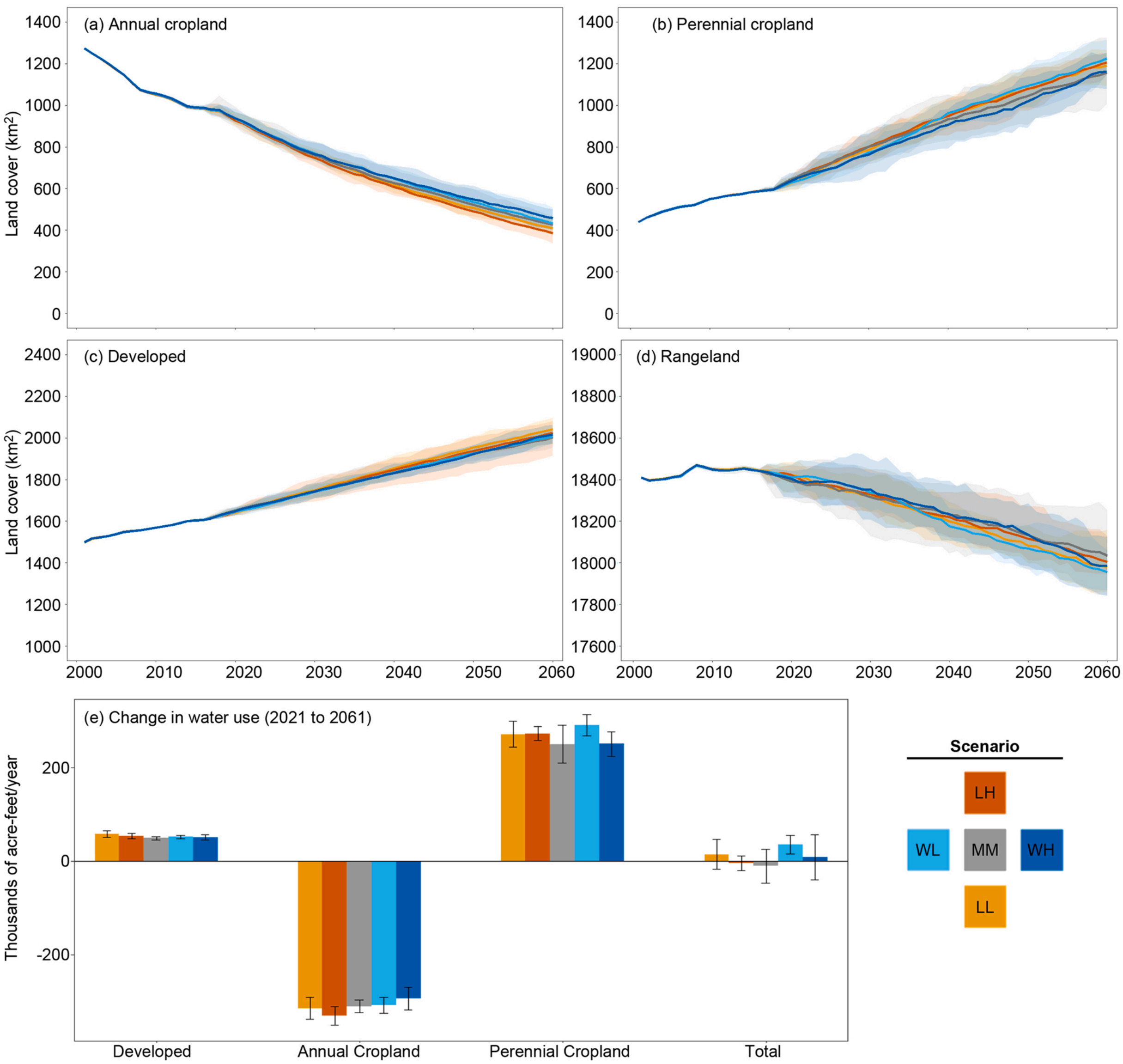


**Fig. 4.** Projected changes in (a) *annual cropland*, (b) *perennial cropland*, (c) *developed*, and (d) *rangeland* land-use classes, as well as (e) associated water use for California's Central Coast region. Results show means across 10 Monte Carlo replicates; shaded regions (a–d) show the ranges, while error bars (e) show standard deviations. Scenarios ranged in Water and Land-use management intensity from Low to Medium to High (abbreviations bolded). Data are accessible via the LUCAS-W model data release (Van Schmidt et al., 2021).

- **LL** – had no new land-use strategies implemented (but existing protected areas were included);
- **MM** – added urban sprawl limits that protected prime farmland and recharge areas;
- **LH** – added ecosystem preservation that prevented urbanization or cropland expansion on priority habitats.

### 3.7. Model analysis

Each scenario was run in LUCAS-W over 60 annual time steps (2001–2061). During the spin-up period covering the historic land-use data (2001–2016), the actual annual land-use change rates were used. For example, 2010 data was sampled deterministically from the observed rate in 2010. Afterwards, sampling was stochastic with the rate from one year from 1992 to 2016 chosen at random. Following Sleeter et al. (2017) and Wilson et al. (2020), we simulated 10 Monte Carlo replicates to capture variability in stochastic processes. All strategies were first turned "on" in 2019, except for water demand feedbacks, which were activated in 2024.

Model projections were post-processed to assess the influence of management strategies on land-use and water use across the 10 Monte Carlo replicates (Appendix A.1.2.6). Spatial patterns of land-use change were summarized as transition probability maps, which represent the average annual probability of each transition occurring on each pixel from 2001 to 2061 across the 10 Monte Carlos (Daniel et al., 2016). To assess the impact of management strategies, we mapped places where the strategies made each land-use transition more or less likely (Appendix A.1.3).

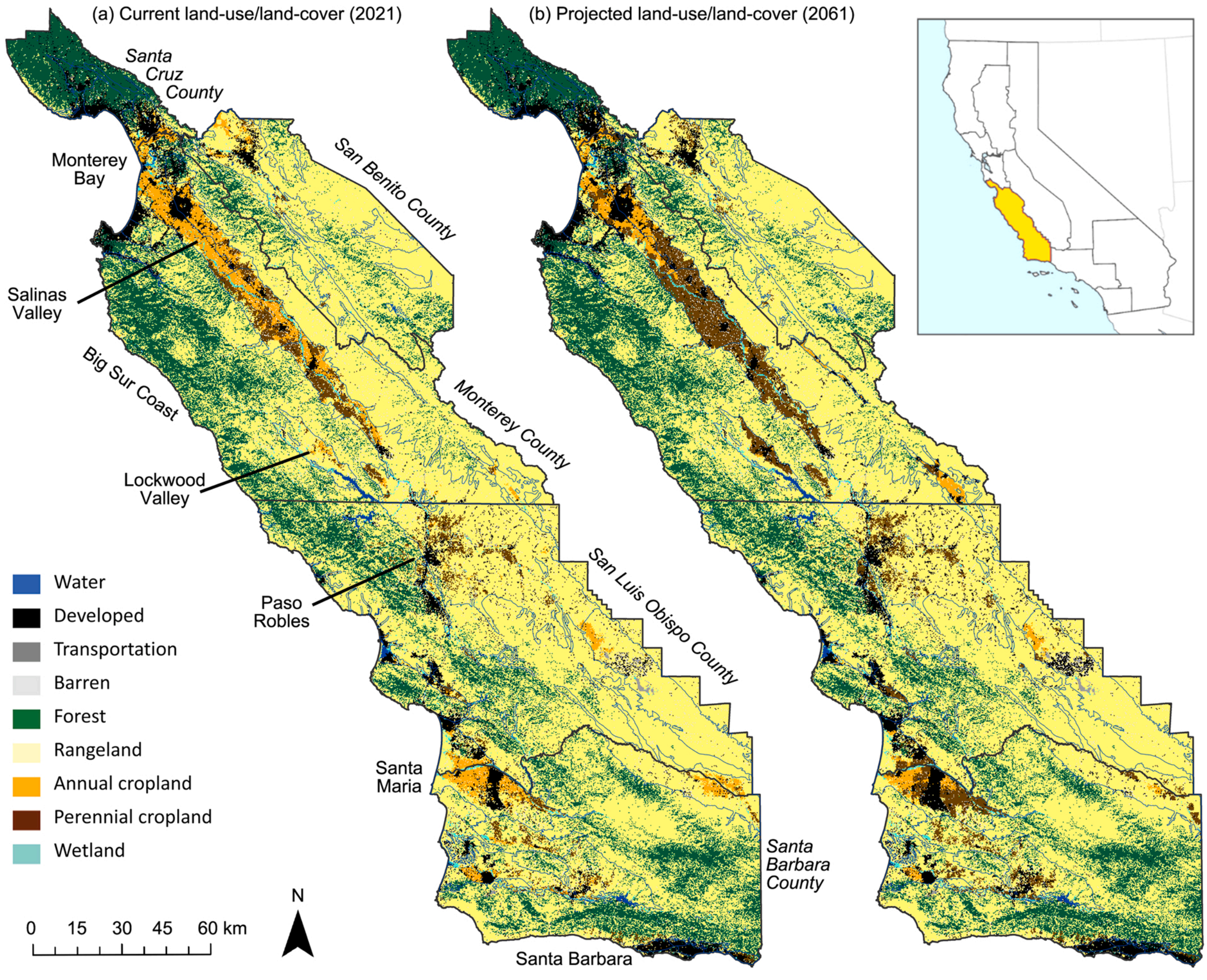


**Fig. 5.** Projected changes in land-use/land-cover for California's Central Coast from (a) 2021 to (b) 2061. Representative example taken from a single replicate of the "Medium water management intensity, Medium land-use management intensity" scenario; decadal maps for every scenario are available in the LUCAS-W outputs data release (Van Schmidt et al., 2021).

## 4. Results

### 4.1. Regional change in land-use

Overall, land-use projections show *annual cropland* will continue to decline from 2021 to 2061, contracting by − 502 km$^2$ (mean

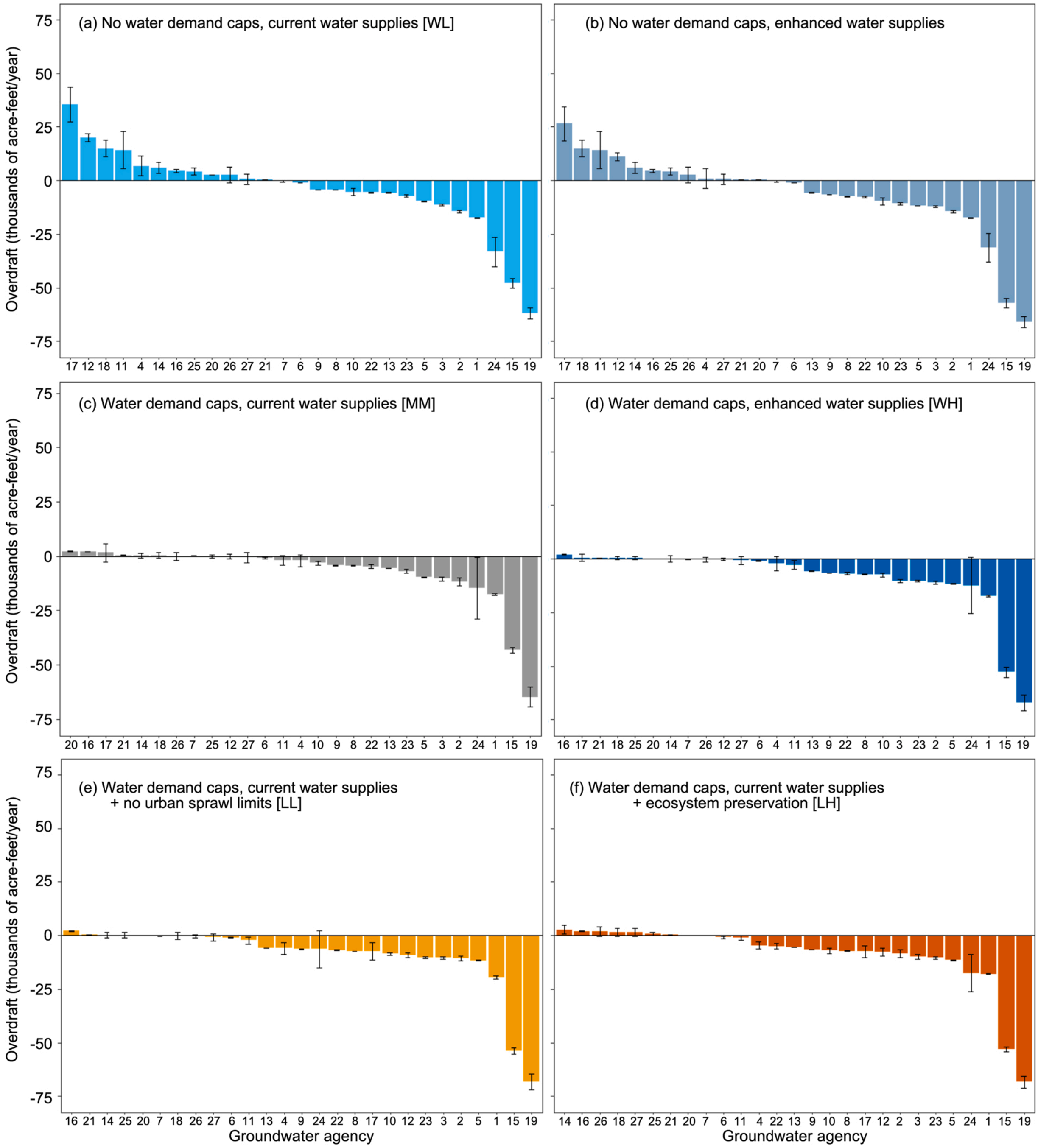


**Fig. 6.** Projected 2061 overdraft (y-axis; mean ± SD *total water use / total sustainable supply*) for each water agency (see Table A.1 for index key) in California's Central Coast under future land-use change. Positive values indicate percent overdraft, while negative values indicate percent of the sustainable water supply that is not extracted. Panels show changes as a result of six combinations of management strategies: the addition of water demand caps (a,b vs. c,d), water supply enhancement (a,c vs. b,d), and land-use management (c vs. e,f). Data are accessible via the LUCAS-W model data release (Van Schmidt et al., 2021).

across scenarios, range −415 to −570 $km^2$; Fig. 4a). This will be outpaced by expansions of *perennial cropland* (549 $km^2$, range 361–710; Fig. 4b) and *developed* areas (370 $km^2$, range 262–451; Fig. 4c). The end result will be a mean total loss of − 417 $km^2$ of natural rangeland (range −167 to −581 $km^2$; Fig. 4d). Management scenarios altered the spatial patterning of where land-use change occurs within counties, not the underlying county-specific rates of land-use change. Therefore, *at regional scale* the range of variability in projections within scenarios (i.e., due to Monte Carlo stochasticity; Fig. 4a–d, shaded areas) was greater than the differences among the scenarios (Fig. 4a–d, bold lines).

While there were county-specific differences in the degree to which these changes occur by 2061, these general trends were present in all five counties (Fig. 5). Agricultural intensification and widespread replacement of *annual cropland* with *perennial cropland* were projected to be extensive within the large agricultural areas in Salinas Valley and Santa Maria Valley. The more rural San Benito County continued to experience the greatest agricultural contraction, resulting in a projected near-total loss of *annual cropland* by 2061.

### 4.2. Regional change in water demand

Despite an overall loss of rangeland and the spread of *developed* land and *perennial cropland*, most scenarios projected water demand to stay roughly the same over time (Fig. 4e). Across scenarios, the region-wide mean change from 2021 to 2061 was + 8916 AFY (range

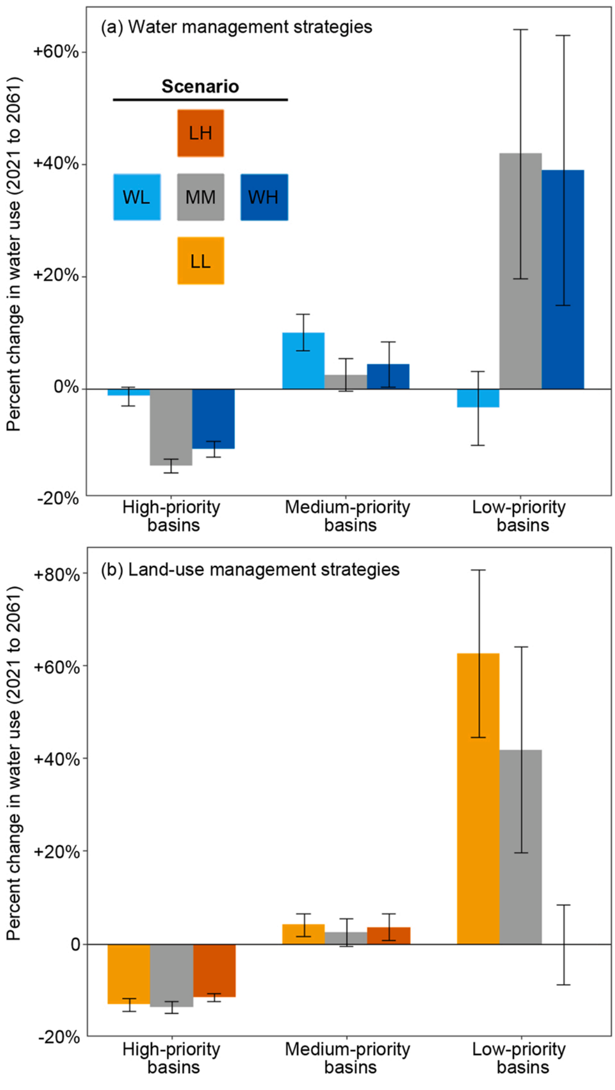


**Fig. 7.** Effect of alternative (a) water management strategies, and (b) land-use management strategies on mean ( ± SD) percent change in water demand (2021–2061) within groundwater basins ranked high, medium, and low-priority by the California Dept. Scenarios ranged in Water and Land-use management intensity from Low to Medium to High (abbreviations bolded). Data are accessible via the LUCAS-W model data release of water resoureces (Van Schmidt et al., 2021).

= −66,354 to +70,563 AFY). While the acreage of new *perennial cropland* and *developed* areas significantly outpaced the acreage declines of *annual cropland*, their growth in water demand did not because *annual* cropland was the most water-intensive land-use in every county but San Benito (Fig. A.1; Van Schmidt et al., 2021). Contracting *annual cropland* therefore led to a mean reduction in water demand of − 311,886 AFY (range = −356,251 to −264,334 AFY) that roughly balanced out increases in water demand for *perennial cropland* (mean = 267,876 AFY, range 191,257–333,205) and *developed* areas (mean = 52,927 AFY, range 39,110–67,651). Assuming that the current region-wide 9:1 ratio of domestic:industrial water use continues (Maupin et al., 2014), this equates to 47, 046 AFY of new domestic demand and 5881 AFY of new industrial demand by 2061.

Scenarios showed little influence on region-wide water demand. The addition of water demand caps (Fig. 4e, WL vs. MM) did appear to slightly decrease the average water demand region-wide, with the mean of the "no water caps" WL scenario higher than the

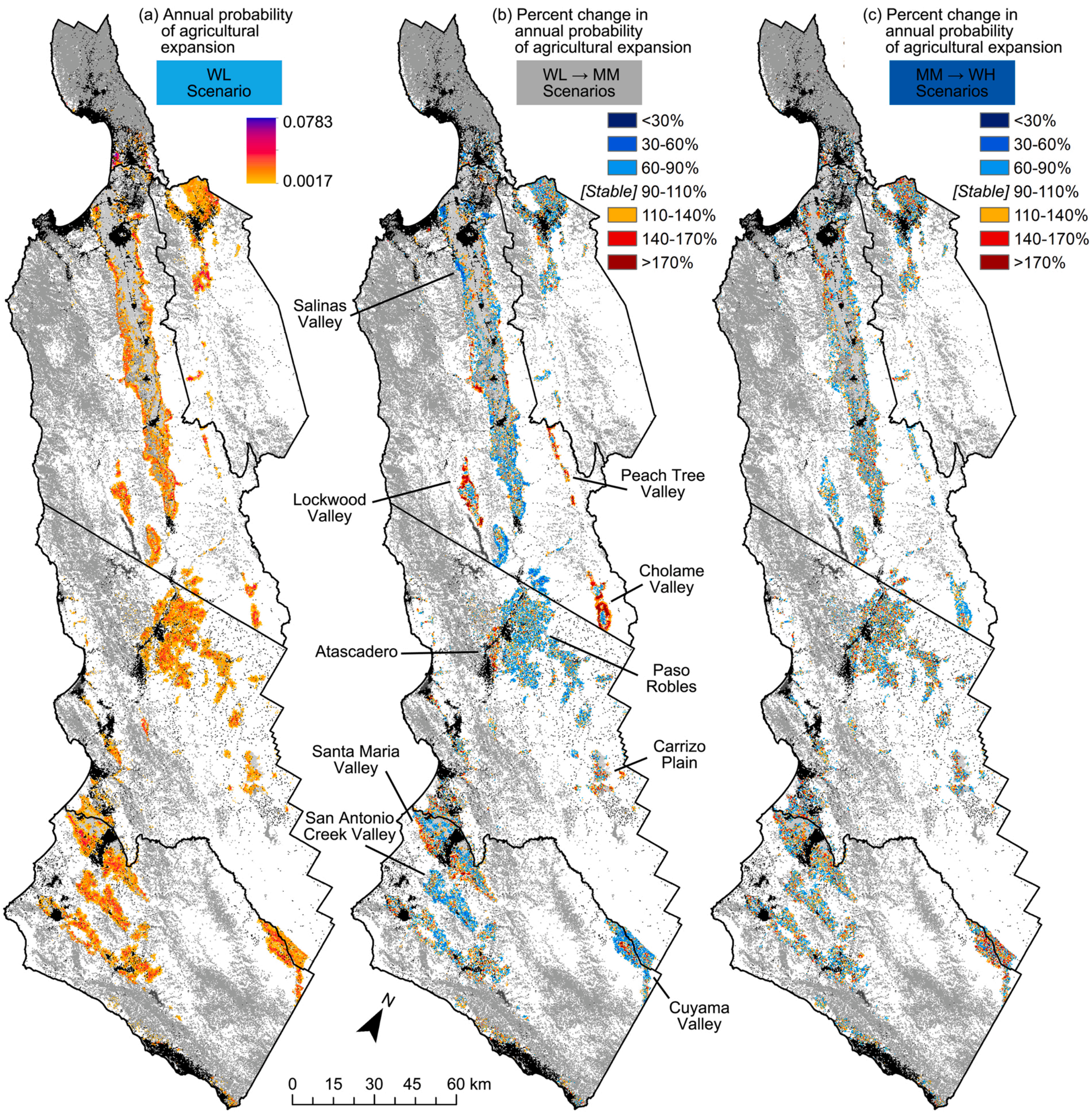


**Fig. 8.** Spatial influence of water management strategies on development patterns within California's Central Coast. Scenarios ranged in Water management intensity from Low (WL) to Medium (MM) to High (WH). (a) Mean annual probability (2001–2061) of agricultural expansion under a "business-as-usual" scenario with no new management. (b) Change in probability (MM / WL) from this baseline with the addition of *water demand caps*; agricultural expansion pressure was pushed from the blue areas into the red areas. (c) Change in probability (WH / MM), keeping water demand caps but adding new *water supply enhancements*. Maps for every transition probability are available in the LUCAS-W outputs data release (Van Schmidt et al., 2021).

rest (mean = 35,745). However, the difference was within the range of variability observed in the MM scenario with water demand caps (−66,354 to +46,255 AFY).

### 4.3. Effects of water management strategies

#### 4.3.1. Overdraft

Water demand caps were much more effective at reducing groundwater overdraft than water supply enhancement (Fig. 6). To analyze the effect of water management strategies, land management strategies were kept constant with only urban sprawl limits. With current water supplies and without water demand caps (i.e., business-as-usual), nine subbasins were projected to remain in overdraft (Fig. 6a). Adding water supply enhancements without demand caps was insufficient to significantly reduce overdraft in the context of future land-use change, achieving sustainability in only two basins (Fig. 6b). This may be because the *enhanced supply* represented only a relatively modest increase from the *current supply*. Only half of agencies planned supply enhancements, and within those, the average increase + 15.4% (Table A.1).

The addition of water demand caps to *current supply* successfully reduced groundwater overdraft in all basins and achieved sustainability in most basins (Fig. 6c). In the two basins that could not achieve sustainability with water demand caps alone, pairing water demand caps with water supply enhancements further reduced projected overdraft (Fig. 6d).

#### 4.3.2. Percent change in water use

Water demand caps shifted development and associated water use from basins designated as high- and medium-priority by the CDWR to basins designated low-priority, which are not regulated by SGMA (Fig. 7a). CDWR rankings were based on estimated overdraft and amount of development. Adding water supply enhancement produced a comparatively small effect. Major trends were:

1) With no water demand caps (Fig. 7a, WL), water use was projected to remain the same in unsustainable high priority basins (−1.39% ± 1.63%; mean ± SD). It notably increased in medium priority basins (9.94% ± 3.23%), and remained the same in low-priority basins (−3.49% ± 6.56%).
2) Capping water demand at *current supply* reversed these trends (Fig. 7a, MM). Water use fell by − 13.77 ± 1.30% in high-priority basins; remained near current levels in medium-priority basins (2.44 ± 2.95); and increased dramatically in low-priority basins (41.79% ± 22.23%). Overdraft (Fig. 6) could not be calculated for low-priority basins because these undeveloped basins' aquifer characteristics are largely unknown.
3) Enhancing water supplies (with water demand caps) shifted the pattern of percent change to make it slightly more similar to the no caps scenario (Fig. 7a, WH vs. MM). The magnitude of the percent decrease in water use in high-priority basins (−10.76% ± 1.34%) was reduced from the MM scenario. Medium-priority basins again showed a slight increase in water demand (4.33% ± 4.06%). The percent increase in low-priority basins was smaller than in the MM scenario, but still substantial (38.82% ± 24.03%).

#### 4.3.3. Influence of water management on development patterns

Changing spatial patterns of development in response to water management strategies drove these trends. Without water demand caps, agricultural expansion continued to be clustered in well-developed groundwater basins around the fringes of current development (Fig. 8a). The addition of water demand caps (WL→MM) pushed projected agricultural expansion (Fig. 8b) and urbanization (Fig. A.6) out of well-developed areas, notably the critically overdrafted northern Salinas Valley, Paso Robles area, San Antonio Creek Valley, and Cuyama Valley. Growth was correspondingly intensified in less developed and mostly unregulated basins—Lockwood Valley, Cholame Valley, Peach Tree Valley, and Carrizo Plain—as well as within two regulated basins, Atascadero and southern Santa Maria Valley (Fig. 8b).

Enhancing water supplies raised the water caps (MM→WH) and once again intensified growth throughout the currently developed, overdrafted areas, particularly the northeastern Salinas Valley, Paso Robles area, and Cuyama Valley (Fig. 8c). There was then less agricultural growth in the undeveloped basins. Figures A.3–A.8 map the impact of water management strategies on the other LULC transitions.

### 4.4. Effects of land-use management strategies

#### 4.4.1. Impact on water sustainability

When assessing the influence of land-use management strategies, water management strategies were kept constant with water demand caps based on *current supply*. Limiting urban sprawl and priority habitat conservation together prevented water demand caps from causing leakage of water demand into relatively pristine, unregulated low-priority basins (Fig. 7b):

1) Urban sprawl limits reduced the percent increase in water demand in low-priority basins from 62.60% ± 18.14% to 41.79 ± 22.23% (Fig. 7b, LL vs. MM). Further adding ecosystem preservation eliminated the increase (−0.18% ± 8.68%; Fig. 7b, LH). These prohibitions on *urbanization* and *agricultural expansion* covered most of the current pristine rangeland of the Central Coast (Fig. 2c).
2) Some of this water demand moved back into high-priority basins (Fig. 7b, LH vs. MM). Water use in high-priority basins was still projected to decrease from current levels in the LH scenario (−11.60% ± 0.82%), but the magnitude of this decrease was lower

than in the MM scenario (−13.77% ± 1.30%). Limiting urban sprawl alone did not produce a notable overall effect on high-priority basins, with the change in the LL scenario (−13.10% ± 1.35%) very close to the MM scenario (Fig. 7b, MM vs. LL).

3) High-intensity land-use management did not markedly hinder regional water sustainability overall, with only one basin showing a statistically discernable increase in groundwater overdraft under these policies (Fig. 6e,f).

#### 4.4.2. Influence of land-use management on development patterns

These trends were driven by changing spatial patterns of development in response to land-use management. Without protecting prime farmland and groundwater recharge areas from urbanization (LL), development was most likely around city edges (Fig. 9a). Adding urban sprawl limits (LL→MM) reduced growth near cities surrounded by agriculture such as Watsonville, Hollister, Santa

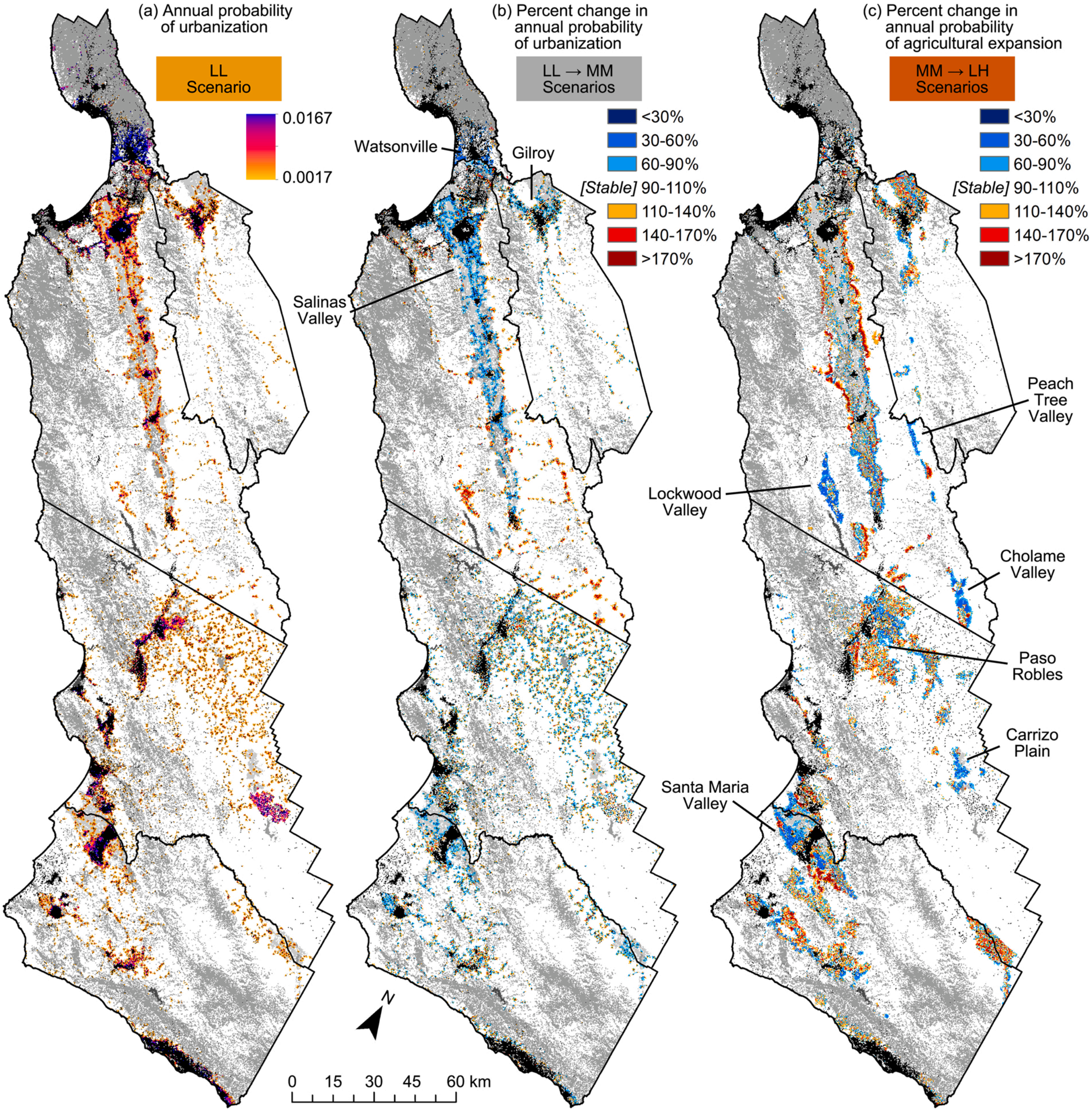


**Fig. 9.** Spatial influence of land-use management strategies on patterns of (a, b) urbanization and (c) agricultural expansion within California's Central Coast. Scenarios ranged in Land-use management intensity from Low (LL) to Medium (MM) to High (LH). (a) Mean annual probability (2001–2061) of urbanization under a "business-as-usual" scenario with no new management. (b) Change in probability of urbanization (MM / LL) from this baseline with the addition of *urban sprawl limits*; urbanization pressure was pushed from the blue areas into the red areas. (c) Change in probability of agricultural expansion (LH / MM; compare to Fig. 7) when adding new *ecosystem preservation* of priority habitats. Maps for every transition probability are available in the LUCAS-W outputs data release (Van Schmidt et al., 2021).

Maria, and Salinas (as well as around smaller towns along the Salinas Valley to the south; Fig. 9b). Development occurred instead in small rangeland towns and undeveloped groundwater basins, particularly in parts of Monterey County such as Cholame Valley (Fig. 9b).

Conserving areas prioritized by state habitat preservation goals (MM→LH) had less impact on urbanization probability (Fig. A.14) because urban areas were generally not near areas designated as priorities for preservation (Fig. 2c). Rather, it notably reduced agricultural growth in outlying rangeland areas—Lockwood Valley, Cholame Valley, Peach Tree Valley, and Carizzo Plain—moving it back into concentrated portions of current major agricultural areas such as the less-overdrafted central Salinas Valley and around the City of Paso Robles (Fig. 9c; compare to Fig. 8 for baseline pattern of agricultural expansion). In the Santa Maria Valley, protecting critical habitat for La Graciosa thistle (*Cirsium scariosum* var. *loncholepis;* Thorne et al., 2019) concentrated development in the southwestern portion of the valley. Figures A.9–A.14 map the impact of land-use management strategies on other land-use transitions.

## 5. Discussion

### *5.1. Management strategies for sustainable development*

Our results suggest that demand management strategies under consideration by GSAs could be widely effective at achieving aquifer sustainability based on *current supply* of water (Fig. 6b). These included programs designed to incentivize reduced withdrawals and fallow agricultural land. In contrast, *solely* enhancing supply performed little better than no interventions, leaving most currently overdrafted basins in a state of overdraft (Fig. 6a,c). Similar results have been found for other semi-arid regions of the world (Johannsen et al., 2016). In California, the Water Evaluation And Planning System (WEAP) has been used to assess whether demand-side interventions could achieve sustainability under land-use change and climate change in the North Coast (Mehta et al., 2013) and Central Valley (Joyce et al., 2006, 2011; Purkey et al., 2008). This model simulated feedbacks between farmer's decision-making on crop plantings and surface water availability and groundwater depth. They found future water needs could be met only by combining both fallowing (or shifting crops) and increasing irrigation efficiency using drip irrigation. However, drip irrigation could reduce groundwater recharge (Mehta et al., 2013) and is already utilized by vineyards, the predominant driver of the agricultural growth projected for the Central Coast.

One issue is that water demand management strategies were also projected to cause leakage of agricultural development pressure (Lambin and Meyfroidt, 2011) to groundwater basins currently unregulated by SGMA (Fig. 8b). This resulted in dramatic increases in water demand within these basins (Fig. 7a), which are relatively undeveloped, potentially worsening local overdraft and degrading natural habitats. These findings are corroborated by other recent studies (Liu et al., 2017; Priess et al., 2011). At a global scale, Liu et al. (2017) projected that cutting irrigation usage would cause leakage of cropland into other areas with sufficient water. In semi-arid Mongolia, Priess et al. (2011) found that constraining water use to availability would reduce crop yields and subsequently require a 10% increase in cultivated area. Their model, SITE-SWIM, is the only other model that has included water and land-use feedbacks between model water availability, crop yields, and subsequently farmer's fallowing decisions. Thus despite using completely different models, these studies also predicted that demand-side management can cause leakage of agricultural development.

Importantly, we found this leakage could be prevented by using land-use planning to achieve major stakeholder goals: the preservation of priority ecosystems, recharge areas, and prime farmland (Fig. 9c). Moreover, reducing rates of agricultural or urban development was not necessary to achieve sustainability (Fig. 4a–c). Rather, it was theoretically feasible to achieve sustainability goals by strategic placement of cropland expansion and contraction within each county at the same rates they have occurred historically. These results suggests that management strategies could work within existing socio-economic forces driving changes in land-use. A combination of existing management options such as conservation easements, implementation of laws protecting threatened species, and zoning to cluster development could support such land-use management. Similarly, Gao et al. (2017) found that localized prohibitions on certain land-uses in China could allow for agricultural expansion without significant new negative impacts. Alternatively, Liu et al. (2017) simulated that inter-basin water transfers could suppress leakage (i.e., a supply-side intervention). Our empirical model found water supply enhancement (including water transfers, which were used by some agencies; see citations in Table A.1) was much less effective at reducing leakage into undeveloped areas (Fig. 8c) than land-use planning (Fig. 9c).

Imposing land-use management did not significantly impede groundwater sustainability (Fig. 6e,f) and intensive water management did not change overall projected rangeland loss (Fig. 4d), suggesting limited trade-offs at a regional scale. Integrated water and land-use management was thus projected to be a "win-win" scenario for sustainable water, agriculture, and ecosystems (Figs. 6, 7). However,

### *5.2. Resilience theory and feedbacks*

In socio-ecological systems theory, supply-side solutions are *adaptive* in nature because they alter existing state variables (water supply) but do not fundamentally change the linkages that control system behavior (Walker et al., 2006). In California, a recent disturbance (the severe 2012–2016 drought) led to a qualitative shift in the social system's controlling structures (new SGMA regulations), but the water-dependent development that accumulated during the unregulated historical "exploitation" period remains and continues to stress water supplies (Leahy, 2016). While 33% of agencies planned management strategies to reduce or limit water demand, supply-side strategies were more common in GSPs (50% of agencies; Table A.1 and citations therein). These included water recycling and desalination plants, conjunctive use programs, removal of invasive species to reduce evapotranspiration, and cloud seeding (citations in Table A.1). We argue supply-side strategies risk treating water management as a "steady state" problem: overdraft can be solved by adding additional water supplies until the new total inputs balance the unsustainable withdrawals. They risk simply repeating a new cycle of "exploitation" of the enhanced resource (Fig. 1), and were thus rarely sufficient for eliminating groundwater overdraft under future land-use change (Fig. 6b).

In contrast, demand-side strategies (e.g., incentives to reduce development in overdrafted basins) can be *transformative* because they alter the nature of the system by creating new cross-scale linkages (Walker et al., 2006). The new feedback between land-use-driven water demand and water supplies dramatically transformed patterns of future development (Fig. 8) and fixed almost all overdraft (Fig. 6), confirming our hypothesis that transformative demand-side strategies would be more effective in producing long-term water sustainability. This supports a key tenet of socio-ecological systems research: that utilizing feedbacks and couplings to manage a system increases long-term resilience (Kramer et al., 2017). Models exploring feedbacks between flooding and land-use have likewise shown that development pathways that link these processes can greatly reduce eventual flood damages due to dynamic co-evolution (Di Baldassarre et al., 2015).

Two previous models have simulated feedbacks between land-use and water supplies. Joyce et al. (2011) similarly showed that demand-side management strategies more reliably achieved water sustainability in the face of climate uncertainty because feedbacks allowed water use to respond flexibly to the unpredictable future climate. However, groundwater-dependent regions had reduced demand-side feedbacks because increasing depth-to-groundwater was not an economically meaningful constraint on growers' decision-making in the absence of policy incentives (Joyce et al., 2006). Yalew et al. (2018) also found that including such feedbacks only marginally improved model fit. Both previous approaches modeled feedbacks based on individual farmer's decision-making, rather than the broader scale of agency management we assessed. The contrast in results between these studies and ours suggests that institutions may create stronger feedbacks than purely economic drivers.

### 5.3. *Trends in land-use and water use*

Uncertainty in future projections is greater than the modeled range of projected land-use changes (i.e., Fig. 4) because uncertainty also arises from input parameters and data collection, model design choices and assumptions, and errors in model construction (Evans, 2012). We have therefore focused on assessing system dynamics rather than predicting a precise future state (Huss, 1988), but we here briefly discuss our historic and projected rates of land-use change.

Historic land-use change showed an overall expansion of development, but with declining *annual cropland* balancing the expansion of *perennial cropland* and *developed* areas. These trends have been measured elsewhere in California (Anderson et al., 2018) and other highly developed agricultural regions of the United States (Schilling et al., 2008). Our average projection of rangeland loss from 2021 to 2061 of − 417 km$^2$ (Fig. 4c) was greater than the − 195 km$^2$ projected by the earlier LUCAS version (Wilson et al., 2020). This was due to the removal of an assumption that prevented *perennial cropland* from growing when *annual cropland* became locally scarce in the future, which improved model performance (Appendix A.1.2.2). We projected 370 km$^2$ of new domestic and industrial development from 2021 to 2061 (Fig. 2c), a 22% increase that was close to the state's 19% projected population increase (291,438 individuals) over the same timeframe (California Dept. of Finance, 2018). Stakeholders reported that housing shortages are already an issue, which the "urban sprawl limits" strategy to protect prime farmland could exacerbate by shifting urbanization away from major cities and into outlying rangeland towns (Fig. 9).

We estimated little change in total water use from current levels (Fig. 4e), which may have assisted the ability of demand caps to achieve sustainability. The earlier version of LUCAS (Wilson et al., 2020) predicted regional expansions of water demand exceeding 1 million AFY. However, these models used different parameterization methods that we found overestimated perennial water demand and performed poorly in validation tests compared to the revised methods used in this paper (Appendix A.1.2.3). While the projected shift from annual to perennial cropland results in significant "average year" water savings (Fig. 4e), perennial crops cannot be easily fallowed and live for decades. This could increase vulnerability by creating an inflexible water demand during drought (Anderson et al., 2018).

### 5.4. *Modeling approach and limitations*

Land-use models have generally not included social, hydrological, or climate feedbacks (Chen et al., 2016). We used multiple local agencies' groundwater modeling efforts to estimate a key parameter—*total sustainable supply*—which we could directly link to estimated historical water use rates and scale up to regional-scale coupled projections of land-use change and water sustainability. This participatory approach enabled the incorporation of local knowledge about heterogeneous aquifers and management strategies into LUCAS-W. Our focus on understanding feedbacks driven by governance structures aligns our work in the emerging field of socio-hydrology (Di Baldassarre et al., 2015; Pan et al., 2018), and complements earlier feedback models that focused on farmer-level decision-making (Joyce et al., 2006; Priess et al., 2011).

A key caveat is that we could not quantitatively validate the accuracy of LUCAS-W's projections under proposed management strategies—including how realistically the model simulated the feedbacks introduced by water demand caps—because these were hypothetical future policies that have not existed historically (Barlas, 1996; Leahy, 2016; Messina et al., 2008). LUCAS-W performed well at estimating water demand over the historic period, with predicted values generally within 10% of values from independent datatsets (Fig. A.2). For future projections and novel management scenarios, Barlas (1996) suggest examining whether long-term patterns in graphs qualitatively match known or reasonable behavior. As expected, trajectories of future land-use change under all five scenarios smoothly continued along historical trends without any dramatic shift in behavior (Fig. 4a–d) or major deviations in water use (Fig. 4e). Nevertheless, LUCAS-W's outputs should be viewed as resulting from the empirical input data *under the specific* *assumptions of the model*, not a precise prediction of a future state. In the coming decades, empirical research comparing areas with and without demand caps under SGMA could confirm whether LUCAS-W's outcomes are accurate.

We assumed water use per $km^2$ stays the same within each anthropogenic land-use class, precluding water demand changes due to shifts in cropland types due to changing global dietary preferences (Aleksandrowicz et al., 2016), improvements in water use efficiency (Mehta et al., 2013), or increasing evapotranspiration under climate change (Wada et al., 2012). We found efficiency improvements were not a major strategy in most GSPs, and therefore assumed decreases in efficiency improvement and increases due to evaporative water demand under climate change would balance out. Nevertheless, farmers could respond to GSP regulations by adopting more efficient irrigation or converting to less water-intensive crops (Joyce et al., 2011; Purkey et al., 2008). Likewise, our use of area-based transition targets for new *developed* land-use prevented the assessment of infill housing developments, a major focus of current land-use planning (Landis et al., 2006). Integrating infill development to assess housing needs will be a useful component of future development and future analyses could explore the sensitivity of our LUCAS-W model to alternate trends in development and applied water needs.

Complex interrelationships between climate, land-use, and water use make projecting the future of such systems very difficult, and our model makes key simplifications that limit its realism (Stonestrom et al., 2009). Land-use alters the hydrologic cycle at fundamental levels, altering evapotranspiration, precipitation, and temperatures, runoff, and recharge (Anderson et al., 2018; Calder et al., 2003; Feddema et al., 2005; Kueppers et al., 2007; Pielke et al., 2007; Spera et al., 2016). These potential feedbacks were not included in our models. Our estimates of groundwater sustainability within specific basins are not substitutes for the detailed hydrological studies that water agencies conducted to create their management plans. Rather, we view these approaches as complementary. Many hydrological models can ingest land-use scenarios as inputs and then simulate more detailed aquifer and management dynamics (Johannsen et al., 2016; Öztürk et al., 2013; Tong et al., 2012). These models are data-intensive and challenging to parameterize at a regional scale, but their outputs can feed into LUCAS-W. Our regional model can in turn produce annual land-use projections under a range of development trajectories, and corresponding estimates of water sustainability that are uniquely informed by regional-scale linkages. Coupling these approaches into a dynamic cross-scale model would be a promising direction for future research.

## 6. Conclusions

We showed that water demand caps could largely achieve sustainability with current water supplies whereas solely enhancing supply may not. Water demand management strategies caused leakage of agricultural land development pressure to groundwater basins currently unregulated by SGMA, dramatically increasing local water demand. Land-use management strategies, particularly prioritizing habitat conservation, could prevent leakage into pristine areas. These results suggest California's Central Coast has high adaptive capacity to cope with future changes via coordinated water and land-use planning.

Our assessment did not consider the vulnerabilities of different regions, changes in water efficiency or housing density, sensitivity of results to different possible land-use futures, grower decision-making, or feedbacks between land-use and hydrological processes (e.g., recharge). Ongoing research efforts include comprehensive vulnerability assessment including regional sensitivities, and integrating housing density into projections. Future work could integrate LUCAS-W with other hydrological models to assess a broader range of feedbacks.

By working with stakeholders to scale up local hydrological studies and management strategies into a regional-scale land-use model, we were able to incorporate governance-mediated feedbacks between land-use and water availability. Parameterizing LUCAS-W with actual management plans allowed us to more realistically assess the relative potential of land-use and water management strategies to achieve water sustainability and prevent leakage, which can inform implementation of SGMA throughout California. This approach is readily extensible to other regions where water supply and demand is known.

## CRediT authorship contribution statement

**Nathan D. Van Schmidt:** Conceptualization, Methodology, Software (LUCAS updates, management scenarios), Validation, Formal analysis, investigation, stakeholder interviews, Data curation, Writing – original draft, Visualization. **Tamara S. Wilson:** Funding acquisition, Conceptualization, Methodology, Software (original LUCAS), Writing – review & editing. **Ruth Langridge**: Supervision, Project administration, Funding acquisition, Conceptualization, Methodology, Workshop and meeting organization, Stakeholder interviews, Resources, Writing – review & editing.

## Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

## Data Availability

Data generated in this study, including model output rasters and the LUCAS-W SyncroSim model and its input data, are available from U.S. Geological Survey (Van Schmidt et al., 2021): https://doi.org/10.5066/P9209XW4.

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All modeling for this study was done using the ST-SIM software application which can be downloaded, free of charge, from APEX Resource Management Solutions (http://apexrms.com). Any use of trade, firm, or product names is for descriptive purposes only and does not imply endorsement by the U.S. Government. This work was supported by the California Strategic Growth Council Climate Change Research Program, USA (Grant #CCRP0023) and the U.S. Geological Survey's Climate and Land Use Research Program, USA. Lastly, we thank Paul Selmants and our anonymous reviewers for his helpful peer review.

### *Conflict of interest*

The authors have no conflicts of interest to report. As disclosed in our manuscript, project was funded by the State of California's Strategic Growth Council Climate Change Research Program (Grant #CCRP0023) and the U.S. Geological Survey's Climate and Land Use Research Program.

## Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.ejrh.2022.101056.

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