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PRACTICE AND POLICY

Knowledge coproduction on the impact of decisions for waterbird habitat in a changing climate

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Abstract

Scientists, resource managers, and decision makers increasingly use knowledge coproduction to guide the stewardship of future landscapes under climate change. This process was applied in the California Central Valley (USA) to solve complex conservation problems, where managed wetlands and croplands are flooded between fall and spring to support some of the largest concentrations of shorebirds and waterfowl in the world. We coproduced scenario narratives, spatially explicit flooded waterbird habitat models, data products, and new knowledge about climate adaptation potential. We documented our coproduction process, and using the coproduced models, we determined when and where management actions make a difference and when climate overrides these actions. The outcomes of this process provide lessons learned on how to cocreate usable information and how to increase climate adaptive capacity in a highly managed landscape. Actions to restore wetlands and prioritize their water supply created habitat outcomes resilient to climate change impacts particularly in March, when habitat was most limited; land protection combined with management can increase the ecosystem's resilience to climate change; and uptake and use of this information was influenced by the roles of different stakeholders, rapidly changing water policies, discrepancies in decision-making time frames, and immediate crises of extreme drought. Although a broad stakeholder group contributed knowledge to scenario narratives and model development, to coproduce usable information, data products were tailored to a small set of decision contexts, leading to fewer stakeholder participants over time. A boundary organization convened stakeholders across a large landscape, and early adopters helped build legitimacy. Yet, broadscale use of climate adaptation knowledge depends on state and local policies, engagement with decision makers that have legislative and budgetary authority, and the capacity to fit data products to specific decision needs.

KEYWORDS

agriculture, climate adaptation, decision support, land use change, participatory modeling, scenario planning, water supply, wetland restoration

Coproducción de información sobre el impacto de las decisiones para el hábitat de las aves acuáticas en un clima cambiante

Resumen: Hay un incremento del uso que dan los científicos, gestores de recursos y los órganos decisorios a la coproducción de información para guiar la administración de los futuros paisajes bajo el cambio climático. Se aplicó este proceso para resolver problemas complejos de conservación en el Valle Central de California (EE. UU.), en donde los humedales y campos de cultivos manejados se inundan entre el otoño y la primavera para mantener una de las mayores concentraciones de aves playeras y acuáticas del mundo.

Coproducimos narrativas de escenarios, modelos espacialmente explícitos de hábitats inundados de las aves acuáticas, productos de datos y conocimiento nuevo sobre el potencial de adaptación climática. Documentamos nuestro proceso de coproducción y usamos los modelos resultantes para determinar cuándo y en dónde marcan una diferencia las acciones de manejo y cuándo el clima anula estas acciones. Los resultados de este proceso proporcionan aprendizaje sobre cómo cocrear información útil y cómo incrementar la capacidad adaptativa al clima en un paisaje con mucha gestión. Las acciones de restauración de los humedales y la priorización del suministro de agua originaron un hábitat resiliente al impacto del cambio climático, particularmente en marzo, cuando el hábitat estaba más limitado; la protección del suelo combinado con el manejo puede incrementar la resiliencia del ecosistema al cambio climático; y la captación y uso de esta información estuvo influenciada por el papel de los diferentes actores, el cambio rápido de las políticas del agua, discrepancias en los marcos temporales de la toma de decisiones y las crisis inmediatas de la sequía extrema. Mientras que un grupo amplio de accionistas contribuyó conocimiento para las narrativas de escenarios y el desarrollo del modelo, para coproducir información útil, los productos de datos fueron adaptados para un conjunto pequeño de contextos decisivos, lo que con el tiempo llevó a una reducción en la participación de los actores. Una organización fronteriza convocó a los actores de todo un paisaje y los primeros adoptantes ayudaron a construir la legitimidad. A pesar de esto, el uso a gran escala de la información sobre la adaptación climática depende de las políticas locales y estatales, la participación de los órganos decisorios que tienen autoridad legislativa y presupuestaria y de la capacidad para ajustar los productos de datos a las necesidades específicas de las decisiones.

PALABRAS CLAVE
adaptación climática, agricultura, apoyo a las decisiones, cambios en el uso de suelo, modelado participativo, planeación de escenarios, restauración de humedales, suministro de agua

【摘要】
科学家、资源管理者和决策者正越来越多地使用知识共创来指导气候变化下的未来景观管理。美国加州中央谷也应用这一过程来解决复杂的保护问题, 以支持世界上最大的滨鸟和水鸟聚集地。在这里, 受管理的湿地和耕地会在秋季和春季之间被水淹没。我们共同创造了情景叙述、空间显式的水鸟栖息地模型、数据产品, 以及关于气候适应潜力的新知识。我们记录了这一共同创造的过程, 并利用共同创造的模型确定了有效管理行动的时间、地点, 以及气候推翻这些行动的时间。这个过程的成果提供了关于如何共同创造可用信息, 以及如何在一个高度管理的景观中增加气候适应能力的经验教训。恢复湿地和优先考虑其供水服务的行动创造了可以抵抗气候变化影响的栖息地, 特别是在栖息地面积最为有限的三月; 土地保护与管理相结合可以增加生态系统对气候变化的抵抗力; 不同利益相关者的角色、快速变化的水政策、决策时间框架的差异以及极端干旱的直接危机, 共同影响了对这些信息的吸收和利用。虽然广泛的利益相关者群体为情景叙述和模型开发贡献了知识, 但为了共同创造出可用的信息, 数据产品是按照部分的决策环境而特定制作的, 导致参与的利益相关者逐渐减少。一个边界组织召集了大范围内的利益相关者, 而早期参与者帮助确立了合法性。然而, 气候适应知识是否能得到广泛使用, 还取决于国家和地方政策、与掌握立法和预算权力的决策者的联系, 以及使数据产品适应具体决策需求的能力。**【翻译: 胡怡思; 审校: 聂永刚】**

关键词: 供水, 情景规划, 参与式建模, 湿地恢复, 农业, 土地利用变化, 决策支持、气候适应

INTRODUCTION

Engagement between researchers and decision makers, resource managers, and boundary spanners (those who work in the science decision-making interface) has been essential to finding climate change adaptation solutions (Allison et al., 2018). Early, iterative engagement encourages coproduction of knowledge, a concept with roots in public administration that is now applied in sustainability science (Lemos & Morehouse, 2005; Norström et al., 2020). A pragmatic approach to knowledge coproduction may include the production of actionable science through collaboration between scientists and those who use the science to make policy and management decisions (Meadow et al., 2015).

The coproduction process entails multiple steps: context factors, inputs, process, outputs, and outcomes–impact (Djenontin & Meadow, 2018). A process with frequent engagement may guide the direction of research so that "the original outlook is fundamentally changed by the relationship itself" (Lemos & Morehouse, 2005). Three often-cited elements influence outcomes–impact: salience, the relevance of the information provided; legitimacy, the perception that the process is respectful and fair; and credibility, the trust in the technical results (Cash et al., 2003). Frequent, 2-way interactions among equal partners help achieve these elements, especially if mature preexisting relationships are present (Ferguson et al., 2022).

Engagement with decision makers and resource managers is particularly needed for the stewardship of landscapes under climate change (Mitchell et al., 2016). Large, complex landscapes with diverse land-use pressures and competition for resources form social–ecological systems. The complexity of interactions across these systems can create wicked problems (i.e., problems are difficult to define, potential solutions can have counterproductive consequences, and there are multiple, conflicting stakeholder values) (Allison et al., 2018; Rittel & Webber, 1973). Climate change issues are often wicked problems (Meadow et al., 2015), creating imperatives for engagement to coproduce knowledge (Djenontin & Meadow, 2018).

The knowledge coproduction approach relies on multiple tools, including participatory scenario planning and participatory modeling. These tools engage stakeholder knowledge to produce a simplification of the natural world to inform decision-making and actions (Allison et al., 2018). Participatory scenario planning can be used to identify management actions that would lead to desired outcomes under multiple scenarios, given uncertainty in the future (Abrahms et al., 2017). Participatory modeling relies on multiple participants working together to ensure that models are useful, used appropriately, and relevant to decision-making (Allison et al., 2018). Although adoption of these tools has increased, scientists are being called on to robustly document their engagement methods to strengthen future coproduction work and achieve more effective outcomes (Kujala et al., 2022).

We conducted participatory scenario planning and modeling coproduction work on the future of flooded habitat for waterbirds and wetland-dependent species in California's Central Valley (USA) (Figure 1). This semiarid, Mediterranean-climate region is a classic example of a highly managed social–ecological system with intense competition for land and water resources. Large-scale modification of waterways led to agricultural and urban development and loss of natural lands, including more than 90% of naturally occurring wetlands (CVJV, 2020). This growth increased water demand for a multibillion-dollar agriculture industry and an expanding human population. Projections of more extreme and frequent drought in the future further challenge land and water resources planning in the region (Diffenbaugh et al., 2015).

Despite past land-use changes, the Central Valley remains a critical component of the Pacific Flyway. Between fall and spring, some of the largest concentrations of migratory shorebirds (Charadriiformes) and waterfowl (Anseriformes) in the world rely on the Central Valley's network of managed wetlands and croplands. Remaining wetlands, totaling 83,000 ha, are impounded (water levels are controlled by levees, berms, and water control structures) and managed as seasonal, semipermanent, or permanent wetlands through the use and redirection of surface water and groundwater (CVJV, 2020). Rice and other crops are flooded after harvest to decompose crop residue, which also provides winter habitat for waterbirds.

We explored a multiyear engagement and knowledge coproduction process to support planning for future Central Valley waterbird habitat. We traced the extent to which researcher–stakeholder interactions changed the course of research to shape products and outcomes. We documented our engagement process designed to coproduce data-driven models from future scenario narratives of waterbird habitat and explored how this process was used to create new knowledge about climate adaptation potential. We used these coproduced models to determine when and where management actions would make a difference and when climate would override these actions. We addressed the role of different stakeholder groups in producing usable knowledge and described what we learned about the role of management. Finally, we documented challenges and lessons learned when developing information about how to increase climate adaptive capacity in a highly managed landscape.

METHODS

Central Valley conservation community

In the Central Valley, an established network of state and federal agencies, nongovernmental organizations (NGOs), private industry (e.g., California Rice Commission), and water districts is coordinated by the Central Valley Joint Venture (CVJV, a coalition of these groups), and they work together to manage waterbird populations. This network aims to enhance and restore waterbird habitats by acquiring land and water supplies. Conservation objectives are achieved through partnerships with public and private landowners. For our engagement process, we leveraged preexisting, mature 10-year partnerships (Ferguson et al., 2022) with decision makers, resource managers, and boundary spanners (definitions and stakeholders in Appendices S2 & S3) across water management, planning, and conservation sectors. Engagement occurred over 6 years in several steps (Figure 2). Although our community outreach was broad, existing relationships helped us partner with stakeholder groups (predominately public agencies and NGOs) interested in developing regional conservation planning information.

Future scenario narratives

In 2015, the Central Valley Landscape Conservation Project (CVLCP), led by the California Landscape Conservation

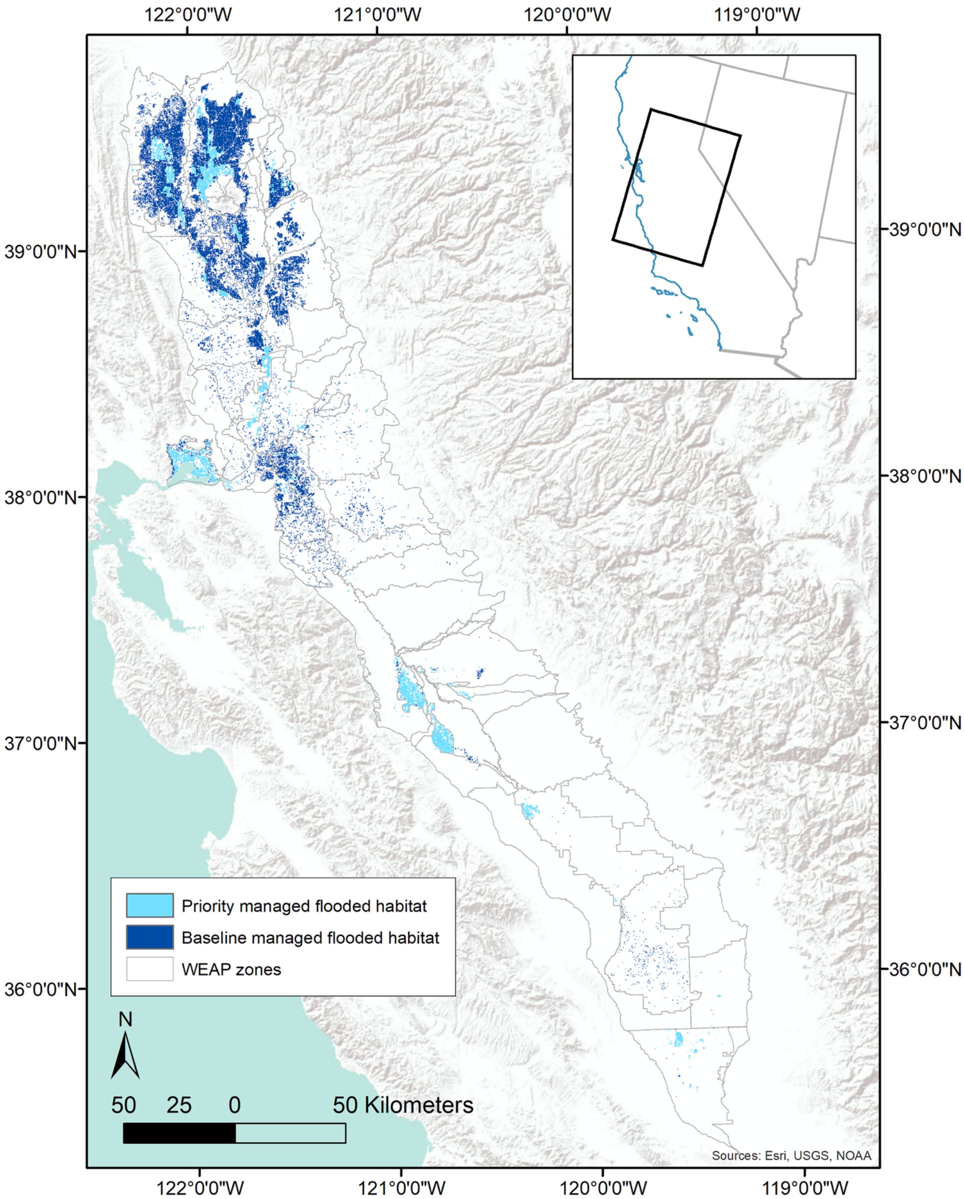

FIGURE 1 Study area in the Central Valley of California, showing zones for the Water evaluation and planning model adapted for California Central Valley waterbird habitats (WEAP-CV_{wh}), the modeled baseline extent of managed flooded habitat in January, and the baseline highly ranked managed flooded habitat extent in January (i.e., subset of all managed flooded habitat ranked in the 90th percentile or higher in a spatial prioritization for shorebirds and waterfowl with Zonation and existing waterbird distribution maps [Appendix S1]). For our analysis, we define the 38° latitude as the boundary between northern and southern Central Valley.

Cooperative, a U.S. Department of Interior management–science partnership, worked with over 40 agencies and organizations to identify climate-smart conservation actions to support an ecologically connected landscape. A first step was to convene a scenario planning workshop, held on 3 March 2015, to determine a common understanding of the range of possible future conditions and define how conditions might influence the mosaic of natural resources in the region.

The CVLCP team selected an expert-driven quadrant approach that uses 2 independent axes to represent the most uncertain and impactful drivers of change and 4 quadrants representing the driver combinations to develop future scenario narratives for the Central Valley. During the workshop, 31 participants from 16 organizations (Appendix S3) decided on the key drivers and developed the narratives. First, participants ranked a list of potential drivers. Then, small groups discussed how to narrow down the ranked list. In a subsequent large-group discussion, participants selected the final drivers: water availability from precipitation (a nature-based driver) and management for conservation (a human-based driver). Participants with years of experience described the 4 resulting scenarios in terms of the environmental and societal conditions and the challenges to be faced by resource managers.

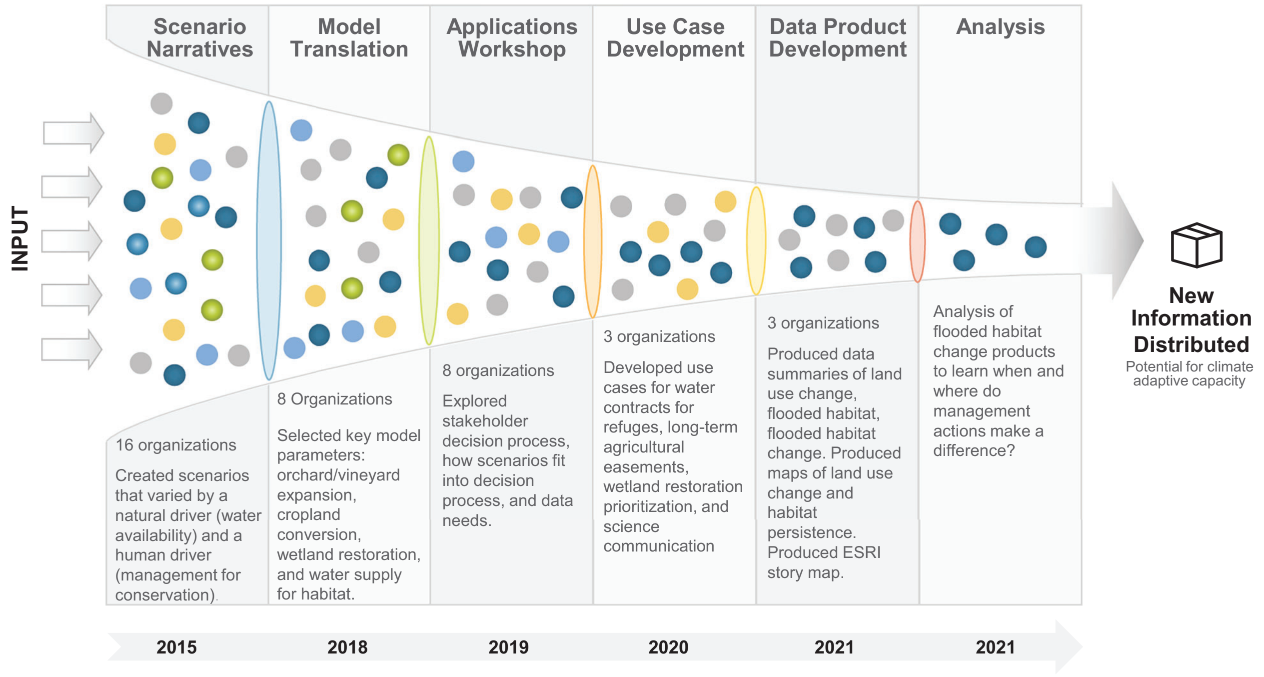

FIGURE 2 Engagement steps used in a coproduction process to develop scenario narratives, translate narratives to models, select key model parameters and applications for model outputs, and develop and deliver data products.

The CVLCP team then wrote 4 detailed narratives of plausible, real-world scenarios based on the high–low combinations of each axis. Workshop participants labeled the 4 narratives: California dreamin' (dream) (plentiful water, good management), bad business as usual (BBAU) (plentiful water, poor management), everyone equally miserable (EEM) (scarce water, good management), and Central Valley dustbowl (dust) (scarce water, poor management) (Figure 3). Detailed notes about this process are available at http://climate.calcommons.org/cvlcp/scenario-planning-workshop.

Translating scenario narratives to data-driven models

Following the 2015 scenario planning workshop, we worked with stakeholders from 2018 to 2021 to translate the scenario narratives into spatially explicit models that focused on the waterbird habitat component of the landscape, select applications for model outputs, and develop and deliver data products. We held a second workshop on 1 March 2018 with 16 individuals from 8 organizations with whom we had established relationships to translate the narratives into models (Figure 2; Appendix S3). Our goal was to develop the first spatially explicit projections of dynamic flooded habitat for waterbirds and other wetland-dependent species (Wilson et al., 2022) by combining a climate-driven water resources model, the water evaluation and planning model, adapted for Central Valley's waterbird habitat (WEAP-CV$_{wh}$) (Matchett & Fleskes, 2017) with a spatially explicit land-change model, the land-use and carbon scenario simulator (LUCAS) model (Sleeter et al., 2017).

Overall, there was consensus among participants in the selection of model parameters that would represent the future

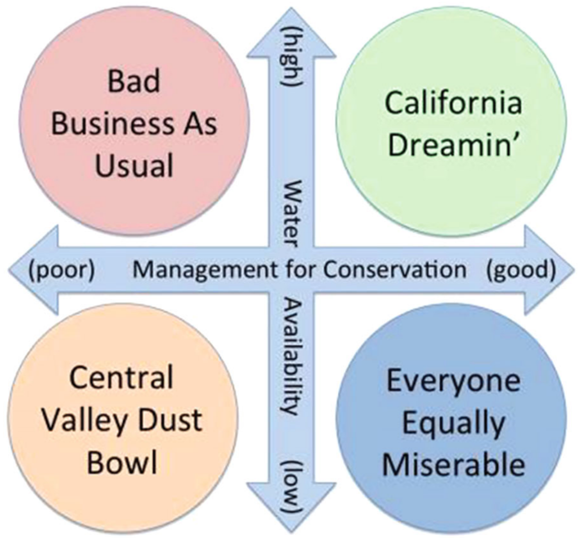

FIGURE 3 Future scenarios of flooded habitat for waterbirds and wetland-dependent species in California's Central Valley (USA). Scenarios represent 4 possible combinations of 2 independent and influential drivers of change: management for conservation and availability of water. California dreamin' is an expression that refers to prosperity, good luck, and freedom from hardship.

scenario storylines (Table 1). The final parameters addressed key stakeholder concerns and defined our 2 scenario drivers. We defined the water availability axis with downscaled (270 m) monthly precipitation projections for 2011–2101 from 2 representative concentration pathway (RCP) 8.5 climate models: one projecting warmer temperatures with increased but variable precipitation and one projecting hot, dry conditions.

TABLE 1 Parameters selected from scenario narratives used in a model of the future of flooded habitat for waterbirds and wetland-dependent species in California's Central Valley (USA) (from Wilson et al. [2022])

Scenario	Climate	Wetland restoration	Perennial crop expansion	Water for wetlands	Winter flooded agriculture	Urbanization
Historical business as usual (HBAU)	Historical (1980–2010)	Current rate to CVJV objective	Current	Current	Current	Current
Central Valley dust bowl (DUST)	Hot dry (HadGEM2-CC RCP 8.5[a])	None	Low	Reduced priority of CVPIA water and private wetlands	Reduced priority	Current
Everyone equally miserable (EEM)	Hot dry (HadGEM2-CC RCP 8.5[a])	Current rate to CVJV objective	Low	Increased priority for wetlands	Increased priority	Current
Bad business as usual (BBAU)	Warm wet variable (CanESM2 RCP 8.5[a])	None	Current	Reduced priority of CVPIA water and private wetlands	Reduced priority	Current
California dreamin' (dream)	Warm wet variable (CanESM2 RCP 8.5[a])	Current rate to CVJV objective	Current	Increased priority for wetlands	Increased priority	Current

Abbreviations: CVJV objective, Central Valley Joint Venture 2006 Implementation Plan wetland restoration objectives (CVJV, 2006); CVPIA, 1992 Central Valley Project Improvement Act (has improved water supply for many national wildlife refuges, state wildlife areas, and private wetlands in the Central Valley). Further information on water supply prioritization and values can be found in table 2 of Wilson et al. (2022).

[a]Downscaled (270 m) climate projections from 2 Representative Concentration Pathway (RCP) 8.5 climate models: wet variable CanESM2 and dry HadGEM2-CC, a subset of models with good simulation of California's historical climate and selected for use in California's Fourth Climate Change Assessment (Flint & Flint, 2012; Pierce et al., 2018). Precipitation projections for the 2070–2099 climate period and California hydrologic region are HadGEM2-CC (mean [SD] = 553 mm [208]) and CanESM2 (858 mm [346]).

Participants defined the management for conservation axis by wetland restoration rate (square kilometers per year), crop conversion rate (square kilometers per year), and prioritization of water for wetland and cropland habitats. Wetland restoration rates were based on published regional goals (CVJV, 2006), and new wetland restoration sites were prioritized based on suitable clay soil type, land-cover type (cropland and grassland), and proximity to other wetlands (Wilson et al., 2022).

We then modeled the 4 narratives plus a baseline or historical business as usual (HBAU) scenario for comparison, which represented historical climate conditions (1980–2010) and land change. We modeled the scenarios in the empirical WEAP-CV_{wh} model, which simulates climate-driven streamflow, runoff, groundwater recharge, water demand, and water supply by WEAP hydrologic zones. We converted WEAP projections of annual land use and monthly flooded habitat area into map outputs in the LUCAS model. Maps were generated using remote-sensing-derived probability surface maps and grid cell neighborhood rules to best guide logical placement of each transition on the landscape. Outputs included 270 m monthly flooded cropland and wetland habitat maps and annual land-use change maps from 2011 to 2101. Monthly flood probability maps were created by averaging the flooding in each 30-year climate period (Wilson et al., 2022).

Moving from models to use cases to data products

After model outputs were generated, we invited the Central Valley conservation community to attend an open webinar on model results (10 October 2019). During the webinar, we solicited interest in continued engagement with the project to develop applications, use cases of the model outputs, and data products. Those who expressed interest were invited to an applications workshop held on 13 November 2019. Here, we sought input from participants representing 8 organizations about their preferences for data products and formats. We asked participants to describe a decision-making activity that may benefit from the use of the data products and how the product use would fit into their decision process. Three of the 8 groups developed use cases for the data products. We then developed a menu of data products with multiple options for data product design and format. Participants from 3 organizations representing a range of decision-support needs worked with us to refine final products. Ultimately, final data products and project outputs were distributed to the community as data releases (Byrd et al., 2021; Wilson et al., 2021), an interactive ESRI story map, https://geonarrative.usgs.gov/centralvalleyfutures/ (a web-based multimedia presentation), fact sheets, blog, and email blast.

Analyses

Most partners requested a flooded habitat change data product, which was a summary by geographic zone (e.g., WEAP zone) of the change in flooded habitat area and its relative causes. To create this product, for each scenario, WEAP zone, and for the 2072–2101 30-year climate period, we calculated change in the amount of flooded habitat area likely flooded from land use, change in water availability, and both. We analyzed this climate period because it represents the greatest divergence in precipitation between the climate projections and variation in scenarios.

We analyzed this flooded habitat change data product to answer our key question about when, where, and in what future climate management decisions influence habitat outcomes. We analyzed flooded habitat loss associated with good management relative to that with poor management for each water availability scenario and for all flooded habitat and highly ranked flooded habitat. We defined highly ranked habitat as the subset of initial baseline flooded area determined to provide habitat of high quality according to a set of shorebird and waterfowl species distribution models (Conlisk et al., 2021, 2023) and Zonation land-use planning software or any modeled newly restored wetland (Appendix S1). We also analyzed the extent that best-case scenarios may vary spatially and seasonally across the Central Valley.

For all habitats and highly ranked habitats, we analyzed each WEAP zone from October to March where initial flooding was ≥1 km^2. We conducted analyses separately for each water availability scenario to determine the relative influence of management decisions in each climate type. For each zone, we calculated the percent difference in habitat loss in the EEM scenario relative to that of the dust scenario and the percent difference in habitat loss in the dream scenario relative to that of the BBAU scenario. We also calculated the average and standard deviation of relative percent differences in flooded habitat loss across WEAP zones for the northern (latitude >38°) and southern (latitude ≤38°) Central Valley because rainfall typically decreases as latitude decreases in the region.

For each WEAP zone and month, we defined the best-case scenario as having over 1 km^2 more habitat on average than any other scenario in the 2072–2101 climate period. If 2 scenarios differed by <1 km^2 and both had over 1 km^2 more flooded habitat than the other scenarios, then they were coded as a tie for best case. We tallied the number of WEAP zones for each best-case outcome and calculated change in flooded habitats for each scenario and month for the entire valley. Analyses were replicated for the set of all habitats and the set of highly ranked habitats.

RESULTS

Engagement with resource managers, decision makers, and boundary spanners

The collaborative scenario planning process produced narratives defined by variations in a nature-based driver (climate-driven water availability) and a human-based driver, which allowed us to address questions about the impact of management decisions in a changing climate. During the model translation workshop, primarily boundary spanners and some decision makers (Appendix S3) identified key management concerns: reliability of water supply for habitats and loss of cropland that supports wetland-dependent wildlife. These concerns were translated into model parameters for wetland-restoration targets, prioritization of water for wetlands and postharvest flooding, conversion of cropland, and expansion of orchards and vineyards.

Over time as the project and products became more defined, the number of stakeholders who chose to engage declined. Those remaining saw potential relevance of the project to their program and decision needs. Most stakeholder decline occurred after the scenario narratives workshop because it addressed many resource management areas, whereas subsequent workshops focused on waterbirds. Additional stakeholders left because they had different resource management priorities, for example, riparian corridors, or had a stronger interest in year-to-year dynamic conservation. Stakeholder roles were also a factor. Boundary spanners contributed knowledge to scenario narratives and model development, but not all had the ability to use the final products. Given existing relationships with stakeholders, these reasons were documented via personal communication to the project leads.

Ultimately 3 decision makers and 2 boundary spanners from California Department of Fish and Wildlife (CDFW), U.S. Fish and Wildlife Service (USFWS), and Audubon California identified 4 decision-making activities and use cases representing different organizational priorities (Figure 2; Appendix S3). The Audubon use case addressed the need for public communication about habitat threats, conservation, and management of wildlife-friendly lands. Three other use cases addressed spatial prioritization decision needs: selecting water supply acquisitions for refuges, prioritizing lands for wetland restoration, and ranking fee title or easement opportunities on farmland or parcels with a wetland to upland transition. The USFWS decision makers working in wetland restoration wanted to know which areas with high habitat value were at most risk to land conversion, whereas the CDFW decision makers involved in water acquisitions wanted to know which areas had persistent water supply (or were near areas with persistent water). The 4 use cases influenced the design of the final data products, which were spatial (maps, geotiff raster files) or nonspatial tabular data summaries for multiple geographic zones (Byrd et al., 2021; Wilson et al., 2021). The USFWS decision maker, the Partners for Fish and Wildlife Program (Partners Program), required more tailored information to implement a use case, which led to additional work to inform a strategic prioritization effort.

The Partners Program is the USFWS habitat restoration cost-sharing program for private landowners. Because it was represented by a decision maker with authority to sign budgetary agreements and the technical knowledge to understand the research products being developed, the program became an early adopter of these research products. The Partners Program was also motivated to develop new data-driven approaches for prioritizing where to implement wetland restoration on private land. After the applications workshop, focused relationship building (Bojovic et al., 2021) created the opportunity to apply the science products to the Partners Program strategic planning. Continued engagement helped understanding of the stakeholders' decision context, information need, and how to tailor model outputs to meet this need. Ultimately, model outputs on

FIGURE 4 For the Central Valley of California, relative percent difference in change in (a) all flooded waterbird habitat and (b) highly ranked flooded waterbird habitat (i.e., high conservation priority) for good-management scenarios relative to poor-management scenarios from present day to the 2072–2101 climate period. Relative percent difference values, for example, (EEM – dust)/dust × 100 or (dream – BBAU/BBAU) × 100 (abbreviations defined in Table 1), are summarized by water evaluation and planning model (WEAP) zone and month for each water availability scenario (blue, positive values [i.e., greater preservation of flooded habitat in the good-management scenario relative to the poor-management scenario]; red, negative values [less preservation of flooded habitat in the good-management scenario relative to the poor-management scenario]; tiles on the horizontal axis, WEAP zones scaled to their area of baseline flooded habitat plotted by average latitude [vertical axis]). The WEAP zones are defined by a combination of water management systems, surface and groundwater basin boundaries, and conservation planning basin boundaries (Matchett & Fleskes, 2017). Habitat area change was calculated from an initial baseline flooded-area map generated from the HBAU scenario (the historical climate) (Wilson et al., 2022).

future flooding and land use were combined with recent historical spatial data to produce wetland-restoration prioritization maps.

Influence of management decisions in a changing climate

Analysis of our flooded habitat change product shows where and when prioritizing good management (EEM and dream scenarios) can make a difference to habitat outcomes. This management influence varied by month, latitude, and habitat rank, but was similar for dry and wet–variable climates. In January, a time of peak migratory waterbird populations, prioritization of water for habitat and wetland restoration had a positive effect on all habitats in the drier southern Central Valley. Here, close to double the habitat area was preserved per WEAP zone relative to poor management (dust and BBAU scenarios) (Figure 4; Appendix S4). The EEM and dream scenarios had a stronger positive effect on highly ranked habitats in January. In October near the beginning of the migratory season and when most crop fields are not yet flooded, good management benefited highly ranked habitats throughout the Central Valley and all habitats more so in the southern Valley. The greatest influence of management decisions was seen in March, when crops are no longer flooded and waterbird habitat is limited predominantly to managed wetlands. In March, for all and highly ranked habitats, good management increased habitat preservation by approximately 200% relative to poor management in both dry and wet–variable climates. However, the effect of management varied substantially across zones (Figure 4; Appendix S4).

When considering all flooded habitat in January, in the northern Central Valley, climate-driven water availability affected the best-case scenario, with either the dream or BBAU wet–variable climate scenario leading to the least habitat loss. However, in most other cases, in the southern Central Valley in January, and throughout the Central Valley in October and March, for both all and highly ranked flooded habitats, it did not matter if projected water supply was high or low—it was the EEM or dream scenario that led to higher conservation, with good management in wet and dry climates leading to similar outcomes for habitat availability (Figure 5; Appendices S5 & S6). During

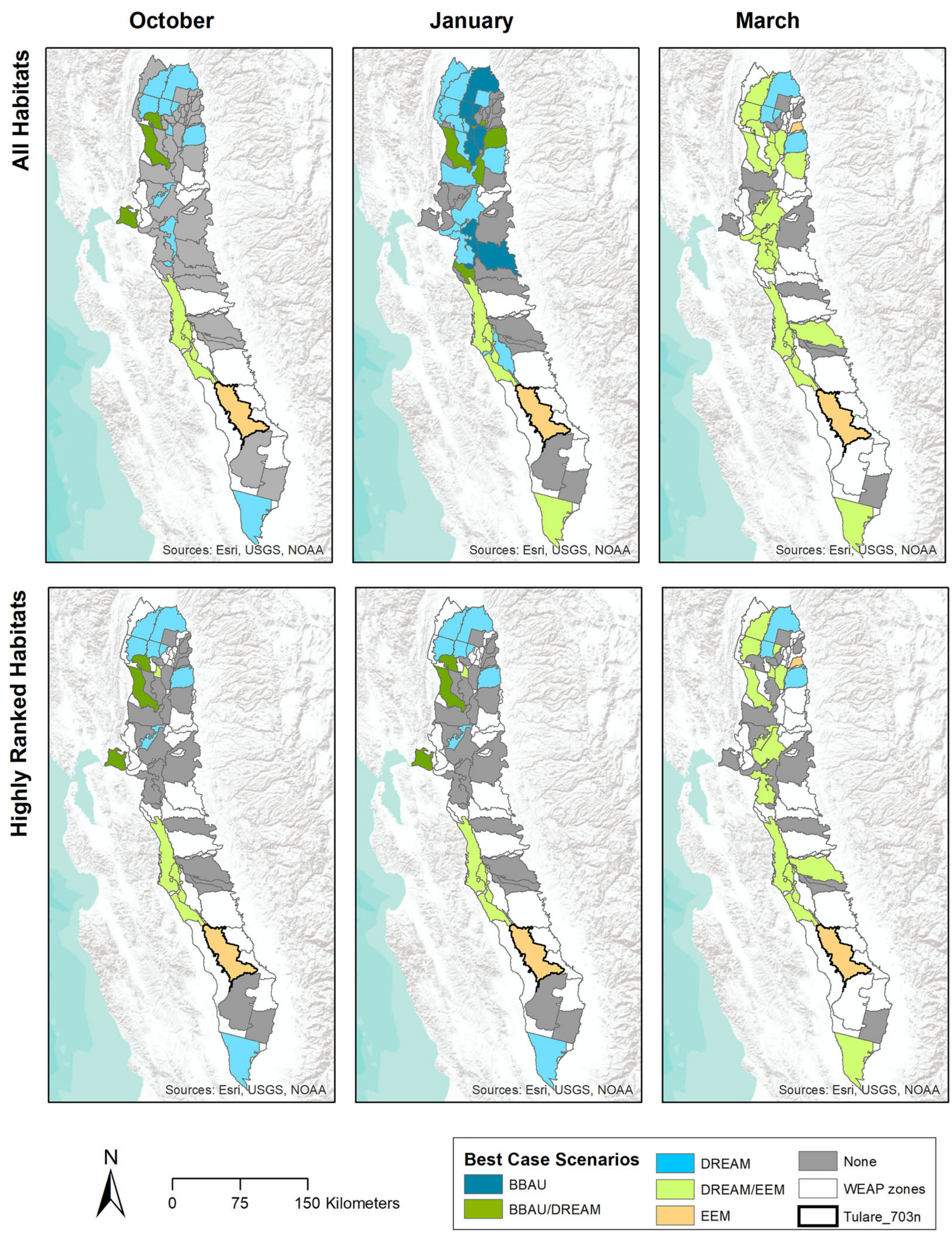

FIGURE 5 Best-case scenarios for habitat preservation for all and highly ranked (i.e., high conservation priority) flooded habitats in the 2072–2101 period for each water evaluation and planning model (WEAP) zone for October, January, and March (white, <1 km^2 baseline flooded habitat in a given month; gray, no best-case scenario identified; abbreviations defined in Table 1). The Tulare_703n zone is a case where the good management and dry climate scenario (everyone equally miserable) was the best case for every month and habitat type.

March, all zones with EEM or dream best-case scenarios contained wetland restoration, and in 18 out of 24 of these zones, the area of flooded habitat increased over baseline levels. We observed some unexpected outcomes. In zone Tulare_703n, the EEM dry climate, good management scenario was the best case in each month (Figure 5) because more cropland habitat was converted to high-water-demand orchards and vineyards in the wet–variable climates.

DISCUSSION

Stakeholder roles in coproducing usable knowledge

We found the need to balance the depth and breadth of stakeholder engagement to coproduce usable products tailored to specific decision contexts (van der Graaf et al., 2018). Although engaging with all relevant stakeholders is essential to capture broad perspectives, we also acknowledged that individuals varied in their capacity to engage and use information. We aimed to reach a large stakeholder community to ensure breadth of knowledge, but ultimately we recognized that a single set of models and products often cannot satisfy all needs. Thus, we consider development of 4 use cases and early adoption of products a positive outcome representing the depth of iterative knowledge coproduction and engagement that occurred.

The coproduction inputs, or the knowledge and experience of different individuals and their time spent participating in the project (Djenontin & Meadow, 2018), influenced final outcomes. Namely, different groups played key roles to reduce the gap between knowledge and practice or action (Kadykalo et al., 2021). To facilitate engagement, we relied on boundary-spanning organization members from the USFWS Science Applications Program; members served as "evidence bridges" who synthesized the research, maintained networks, and filled a role that neither scientists nor practitioners are typically equipped to provide due to skill sets and time (Kadykalo et al., 2021). Boundary spanners led the scenario planning workshop and applications workshop and maintained dialogue with partners. They contributed facilitation skills and the capacity to convene people from across a large landscape and a diverse set of institutions. Boundary spanners also played an essential role in creating an in-depth understanding of the needs of decision makers.

We also engaged with early adopters, namely, the USFWS Partners Program, who had the signing authority and technical knowledge that facilitated information uptake, which helped build credibility in the technical study. Focused discussion between scientists and the early adopters allowed us to tailor the use of products for decision-making (Bojovic et al., 2021). The application of research may not always be evident to decision makers. Yet early adoption provides opportunity to build trust among decision makers and show how to integrate science in decision-making. Early adopters can demonstrate this trust by initially using science products to inform a near-term decision, and this helps reduce the knowledge-to-action gap.

Influence of management decisions in a changing climate

Through analysis of our coproduced data products, we gained insights into the potential role of management in sustaining waterbird habitat given a changing climate. First, the influence of management decisions can vary over a year. Analysis of the modeled scenario outcomes, particularly maps of projected flooded habitat loss, revealed that management decisions, not climate, are the primary drivers influencing the extent of future habitat availability in certain situations. Management was particularly influential in the migratory shoulder seasons of October and March (i.e., beginning and end of the migratory season). At these times, surface water availability is typically limited due to lack of flooded cropland, and the need to enhance waterbird habitat is most critical (Reynolds et al., 2017; Reiter et al., 2018). Scenario outcomes for EEM and dream, the 2 different climate futures prioritizing flooded habitat, were similar across the valley in October and March (Appendix S6), and managed wetland restoration drives these patterns.

Second, protected area status can magnify the impact of management. The subcategory of highly ranked flooded habitats was more likely to persist in January with good management decisions than all habitats combined. This outcome was independent of water availability scenario, indicating that highly ranked habitats were more resilient to a dry climate. This may be because a greater proportion of highly ranked habitat was protected (47.4%) than the full extent of all flooded habitat (20.4%) (California Protected Areas Database and the California Conservation Easement Database [https://www.calands.org/]).

Third, managing early creates more opportunities. Our comparison of management scenarios agreed with other modeling efforts that show that taking actions earlier maximizes the chance of achieving conservation targets, whereas delaying implementation leads to more lost opportunities and fewer options (Naujokaitis-Lewis et al., 2018). Our models simulated 90% of restoration by 2051, a period when wet and dry climate model precipitation projections were similar. This provided the opportunity to secure water for wetlands when more was available.

Finally, multiple factors influenced the capacity to prioritize management. Surrounding land use and reliance on voluntary water deliveries were 2 factors that stood out. Model results indicated that on average, water was available for wetlands when prioritized in both wet and dry climates. Surprisingly, we found unexpected consequences of dry future climates. In some cases, the good management and dry climate scenario (everyone equally miserable) represented the best case for habitat. This was because there was less orchard and vineyard expansion into wildlife-friendly cropland and associated water use than in the good management and wetter climate scenario.

Our results were based on modeled 30-year climate averages and showed the potential to address longer term projected climate conditions. However, securing water for wetlands in the Central Valley is already challenging given present-day recurring drought. During the 2020–2021 water year, average California precipitation dropped to 282 mm, which is the lowest ever recorded (L. Flint, unpublished data) and among the lowest values projected in our hot and dry climate model. The Refuge Water Supply Program, created by the 1992 Central Valley Project Improvement Act, supplies water to 19 federal, state, and private wetland reserves. Despite obligations to provide baseline water supplies to these refuges, contract amounts can be reduced in drought years. Drought and reduced water supply can lead to reduced open water habitat, which was observed in the recent extreme drought of 2013–2015 (Reiter et al., 2018).

Our study built on past WEAP modeling efforts, which identified the greatest habitat loss associated with a warmer, drier climate and reduced prioritization and delivery of water for waterbird habitats (Matchett & Fleskes, 2017). Our scenarios with beneficial habitat outcomes (EEM and dream) prioritized water for managed wetlands to a greater extent than nearly all other water uses (Wilson et al., 2022). Despite model assumptions that many public and some private wetlands have higher priority water supplies than agriculture, some agricultural areas are currently supported by equal or more senior water rights or have the financial resources to obtain water in drought years, whereas some wetlands do not (Matchett & Fleskes, 2017). The WEAP model might also overestimate actual wetland reuse of runoff from precipitation and crop irrigation drainage, creating an overestimate of the area of wetlands flooded during severe drought.

Additional needs for information uptake

The gap between knowledge and practice in conservation can be caused by multiple factors, such as 1-way interactions with practitioners or poor communication of uncertainty (Bertuol-Garcia et al., 2018). We found that the environment in which the project took place and other external factors, considered "context" (Djenontin & Meadow, 2018), posed the greatest barriers to information uptake.

There are limits to wetland restoration. Socioeconomic variables with limited data, like landowner willingness to sell, can be difficult to accurately model long-term, which can lead to inappropriate interpretation and use of model outputs (Allison et al., 2018). As a result, we modeled spatial allocation of wetland restoration according to biophysical and landscape variables with adequate empirical data. However, many additional variables such as water rights, cost, financial resources of water users, land ownership, and landowner willingness all influence restoration siting. For example, in a WEAP zone in the Sacramento Valley with high modeled restoration rates, low-cost water, and prevalence of high-value rice crops made land acquisition competitive and restoration less feasible (M. Hamman, USFWS, personal communication).

The regulatory environment shifts. Regulations that are shifting more quickly than the research process can alter the relevance of the final information products. A shift in regulatory environment occurred during our process when the 2014 California Sustainable Groundwater Management Act (SGMA) was implemented. The law requires managers of groundwater basins to develop and implement groundwater sustainability plans (GSPs) to mitigate overdraft within 20 years. Although GSPs could influence water supply to waterbird habitats, information on plans that could be incorporated into scenarios was not available for the project. As such, our scenarios did not directly address this potential regulatory impact on water supply. We produced spatially explicit outputs summarized by groundwater basins to help shine an SGMA light on results, at the request of stakeholders. This analysis identified critically overdrafted basins, revealed where wetland management may have greater impact, and informed the need for conservation projects (S. Arthur, Audubon California).

Discrepancies in decision-making time frames exist. Institutional factors, particularly discrepancies in time frames for decision-making, also limited uptake of new information. Many workshop participants expressed interest in considering climate on 50- to 100-year time horizons. However, it was challenging to integrate long-term projections into shorter, 1- to 2-year decision time frames of most managers, who are primarily responsible for developing and following 5- to 10-year planning documents. The recent extreme droughts in California exacerbated this challenge, and this crisis came to dominate decision-making activities compared with longer term challenges. Uniquely though, our scenario modeling was part of a larger coproduction project that also modeled and delivered near-term forecasts (seasonal to interannual planning horizons). We found that codevelopment of research products designed for near-term planning built trust in a user community, which created a possible path to incorporate future scenario products into longer term planning when the opportunity arises.

In summary, we found that a landscape with highly managed water creates climate adaptation opportunities because infrastructure may be in place to manipulate wetland habitats in a way that can overcome climate uncertainty in some situations. Our coproduction process was developed to create usable information, yet the uptake and use of this information was influenced by the roles of different stakeholders plus external influences like decision-making time frames and shifting regulations. On a large scale, wetland conservation and restoration in the Central Valley may hinge on policy reforms and funding mechanisms that increase flexibility in providing water to wetlands (King et al., 2021). As a result, broadscale use of climate adaptation knowledge may depend on engagement with decision makers who have legislative and budgetary authority in the region. Planning activities will also be strengthened by considering the potential for more frequent and exceptional droughts, while balancing shorter term management needs and shifting water policy.

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CONFLICT OF INTEREST STATEMENT

The authors declare no conflicts of interest.

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SUPPORTING INFORMATION

Additional supporting information can be found online in the Supporting Information section at the end of this article.

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