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Research

Trade-offs in adapting to changes in climate, land use, and water availability in California

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ABSTRACT. Changes in land use and land cover, water systems, and climate are inextricably linked, and their combined stresses have had severe impacts in many regions worldwide. Integrated adaptation planning can support adaptive capacity by helping institutions manage land and water resources at regional to local scales. Linkages between these stressors mean that planners are often faced with potential trade-offs, and how to couple social and environmental sustainability remains a key question. We explore these questions in California's Central Coast, a region that is already experiencing serious water shortages, housing shortages, rapid expansion of perennial agriculture, and severe droughts that are projected to become worse with climate change. Linked models of land use change (the Land Use and Carbon + Water Simulator [LUCAS-W]), water resources (LUCAS-W), and climate (the Basin Characterization Model [BCM]) produced forecasts of exposure to regional changes at 270-m resolution. We worked with regional stakeholders to develop a matrix of nine vulnerability measures that assessed key sensitivities to these changes. Each vulnerability measure combined one of the three exposure projections with spatial datasets representing one of three sensitivity communities (agricultural, domestic, or ecological). We assessed how five scenarios of land-use and water management strategies under consideration by regional planners could provide institutional, top-down adaptive capacity, and whether there were trade-offs in sustainable development goals for these communities. We found that specific land and water management strategies could greatly reduce regional vulnerability, particularly programs to cap water extractions to sustainable levels. The most dramatic trade-off was between the strategy of water demand caps that increased risk of habitat loss and ecosystem preservation that increased water vulnerability. However, trade-offs were usually limited and spatially localized, suggesting local tailoring of the strategies we assessed could reduce them. Trade-offs were more frequent across exposure classes (land use vs. water vs. climate changes) rather than sensitivity classes (agricultural vs. domestic vs. ecological communities), suggesting win-win opportunities for natural resource management. Our vulnerability maps can inform prioritization efforts for local adaptation planning.

Key Words: *agriculture; California; climate change; critical habitats; groundwater; land-use change; social-ecological system; threatened species; vulnerability; water use*

INTRODUCTION

Changes in land use and land cover (hereafter, "land use"), water systems, and climate are inextricably linked, and understanding the complex coupled interactions of these processes is a central goal of sustainability science (MacDonald 2010, Kramer et al. 2017). Extensive groundwater depletion has been documented in regions worldwide (Wada et al. 2012, Famiglietti 2014), and future development is likely to stress water supplies (Wilson et al. 2016). Future water shortages are expected in turn to alter patterns of development (Biggs et al. 2010, Venot et al. 2010). Climate change is also projected to increase drought frequency and severity in many regions, worsening water shortages (MacDonald 2010). Future land use will likely be a determining factor in regional resilience to climate change (Purkey et al. 2008, MacDonald 2010, Joyce et al. 2011, Mehta et al. 2013, Johannsen et al. 2016); despite being a potentially powerful tool, however, land-use planning has rarely been applied for climate adaptation (Pyke and Andelman 2007). Likewise, experts note that current rates of groundwater depletion are due to inadequate institutional governance (Foster and Garduño 2013). Integrated adaptation planning by institutions at regional to local scales could therefore direct future management of land and water resources, providing regional adaptive capacity to these interconnected stressors.

However, the linkages between land use, water use, and climate change mean that planners are often faced with potential trade-offs (Okamoto et al. 2020), and how to couple environmental sustainability with socioeconomic sustainability remains a central question of sustainability research (Kramer et al. 2017). For example, programs to limit groundwater pumping of aquifers that are in a state of chronic overdraft (where extraction unsustainably exceeds recharge) have been predicted to cause leakage of development pressures into undeveloped groundwater basins, potentially increasing rates of habitat loss (Priess et al. 2011, Liu et al. 2017). Conservation of undeveloped ecosystems could conversely concentrate development in existing agricultural areas already experiencing substantial water shortages (Van Schmidt et al. 2021, 2022). Decision making about sustainable development strategies is localized in nature and requires accurate data (Thiault et al. 2018a). Few studies have assessed vulnerability trade-offs in a spatially explicit manner, in part because vulnerabilities are often spatially heterogeneous and difficult to quantitatively compare (Okamoto et al. 2020). Climate change data at local scales relevant to land-use decision making are incomplete, and projections of land-use change at multi-ecoregion scales have had limited utility at local scales (Sleeter et al. 2015). Differing on-the-ground environmental or social conditions can also dramatically affect local communities' ability to cope with stressors (Turner et al. 2003). Understanding an area's unique exposure to global change processes in conjunction with its social-ecological sensitivity may support establishment of effective adaptation strategies.

Vulnerability assessments are an interdisciplinary subdiscipline of sustainability science focused on understanding patterns of community vulnerability to multiple stressors (Turner et al. 2003). Assessments that synthesize data from different sources are ideal

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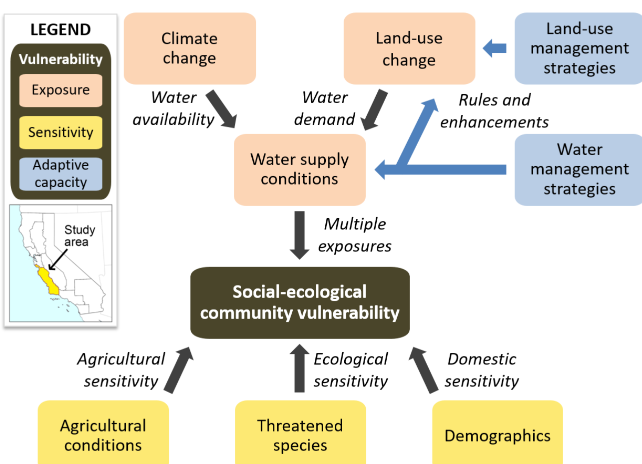
for regional planning because they can directly address priority resources, more comprehensively identify key impacts, and find consensus areas of high vulnerability across measures (Michalak et al. 2022). Vulnerability assessments typically treat vulnerability as having three components (Fig. 1; Thiault et al. 2018a):

1. "Exposure" is the degree of stress experienced by a community. We here focus on projected exposure to (1) land-use change, (2) water shortages, and (3) climate change.
2. "Sensitivity" is determined by the on-the-ground conditions that define how a community will be impacted by a stressor over the short term. We focus on conditions of (1) agriculture, (2) community demographics, and (3) threatened species.
3. "Adaptive capacity" is the degree to which communities are able to anticipate or respond to stress to avoid adverse impacts over the long term. We examine how institutions' land-use and water management strategies can reduce the degree of exposure and its overlap with sensitive areas, thereby providing adaptive capacity.

Fig. 1. A simplified diagram of climate, land use, and water vulnerability for California's Central Coast (inset). Exposure to linked stressors (orange) of climate change, land-use change, and water shortages will combine with on-the-ground sensitivities of agricultural, domestic, and ecological communities (yellow) to determine overall community vulnerability (dark brown). Regional institutions may be able to reduce vulnerability by using integrated development planning for land use and water resources (blue) with new processes (blue arrows) that create adaptive capacity to these stressors.



We conducted a participatory synthesis vulnerability assessment (Glick et al. 2011) to assess impacts of global change processes at a regional scale on vulnerable social-ecological communities in California's Central Coast. This region is facing intense coupled pressures from development, chronic groundwater overdraft, and climate change (Fig. 1, inset; Langridge 2018, Wilson et al. 2020). We worked with stakeholders to produce spatial estimates of future exposure to changes in land use, water demand and supply, and climate from two simulation forecast models, and combined outputs of these models with existing spatial datasets on sensitivities in a geospatial overlay analysis (Okamoto et al. 2020) to create a matrix of nine spatial vulnerability measures. We used these measures to assess changes in vulnerability under five scenarios of land-use and water management strategies under consideration by regional planners, in order to examine (1) whether institutional management could improve sustainability, and (2) whether there were sustainability trade-offs between agricultural, domestic, and ecological communities. We hypothesized that trade-offs would be greatest between human versus ecological communities, but that strategies that relied on reciprocal relationships (i.e., water-development linkages) could be effective at producing win-win solutions (Kramer et al. 2017).

STUDY AREA

Our study region and modeling extent included the five counties of California's Central Coast: Santa Cruz, Monterey, San Benito, San Luis Obispo, and Santa Barbara (Fig. 1, inset). However, we limited our vulnerability assessment to only areas that overlay groundwater basins or were serviced by a water agency. We chose to limit our assessment to these areas because they were the only regions for which water vulnerability could be assessed, and they contained > 90% of all anthropogenic land uses (Van Schmidt et al. 2022).

The Central Coast is a global biodiversity hotspot with nationally important landscapes, such as the Big Sur Coast (Rundel et al. 2016, Hannah 2018), but it also has major agricultural areas and small- to medium-sized cities. There is a disconnect between prosperous coastal communities and inland agricultural areas, which have communities defined by California as disadvantaged communities (DACs; median annual household incomes < 80% of statewide median; California Water Code, section 79505.5(a)). Historical rates of agricultural and urban development have varied dramatically across the five counties (Wilson et al. 2020, Van Schmidt et al. 2022), which could create divergent stressors for local ecosystems and economies. Agricultural expansion presents challenges to habitat conservation. It also may stress water supplies under climate change, especially coupled with shifts in cropping from annual crops to higher-value perennial orchards and vineyards that cannot be fallowed, removing flexibility in irrigation demand during drought (an important consideration given the region's highly variable Mediterranean climate; Wilson et al. 2020). The region also has a housing shortage (Johnson et al. 2004) and is projected to add ~300,000 more people by 2060 (California Department of Finance 2018). From 1990 to 2006, most of California's metropolitan areas adopted policies to limit urban development by restricting housing growth (Alamo and Uhler 2015), and new laws required the demonstration of a sustainable water supply before approval of new housing developments (California Department of Water Resources [CDWR] 2003). Despite the resulting declines in housing construction, water use has continued to grow because of expanding agricultural water usage (Wilson et al. 2020).

Like much of the western United States, the Central Coast is vulnerable to a changing climate, with projected increases in temperatures, extreme droughts, and future water shortages that build on existing over-appropriation of water resources to support substantial development (Barnett et al. 2008, MacDonald 2010, Dettinger et al. 2015, Langridge 2018). Serious water vulnerabilities because of highly variable precipitation are likely to worsen as droughts intensify (Langridge 2018). The Central Coast's expansive cultivated valleys are almost entirely dependent on groundwater (Martin 2014, CDWR 2015, Langridge 2018). Chronic groundwater overdraft has depleted over 40% of regional groundwater basins, a key water supply during drought, resulting in serious water shortages (Barlow and Reichard 2010, Martin 2014, White and Kaplan 2017). This may disproportionately impact DACs that rely on these resources (Brown 2014) or dry groundwater-dependent ecosystems and eliminate their associated fish and wildlife populations (Kløve et al. 2011). During a severe 2012–2016 drought, reduced surface water increased reliance on groundwater, resulting in unprecedented well failures, water shortages, and emergency water restrictions (Leahy 2016). The 2014 Sustainable Groundwater Management Act (SGMA) could dramatically transform water governance (Leahy 2016). SGMA required 127 groundwater basins in overdraft to form Groundwater Sustainability Agencies (GSAs), which must develop groundwater sustainability plans to manage their basins to eliminate overdraft and associated negative impacts, such as seawater intrusion, land subsidence, and surface water depletions (California Water Code 2015). Planned management options include supply-side strategies that increase surface water for consumption and groundwater recharge using desalinated, imported, and/or recycled water, and demand-side interventions to restrict total water pumping (Langridge and Van Schmidt 2020).

METHODS

Vulnerability analysis design

We used a stakeholder-driven scenario development approach to create an evidence-based body of research about the impacts of land-use and water management adaptation strategies (Van Schmidt et al. 2022). This included seven stakeholder meetings (supplemented with individual interviews) from 2019 to 2022 with local government agencies and non-governmental organizations (hereafter, "stakeholders") to identify local priorities and potential adaptations for land and water development (Appendix 1). Meetings were informal discussions, with no quantitative data gathered; we summarize the qualitative feedback we received in this paper and in Van Schmidt et al. (2022). Research partners included the California Climate Change Collaborative (a network of diverse organizations), the City of Salinas (a DAC) and other land-use agencies, and the Elkhorn Slough Foundation (an environmental non-profit). Stakeholders' key water sustainability goals to address were: (1) sufficient water supplies (especially during drought), (2) reducing or halting groundwater level declines, and (3) reducing water pollution (which was determined to be outside the scope of this study). Key land-use goals were: (1) addressing loss of prime farmland, (2) maintaining healthy ecosystems, and (3) sufficient low- and medium-income housing. We then identified development strategies to quantitatively assess their ability to improve the region's adaptive capacity. We selected two water management strategies (demand-side interventions to reduce water-dependent development in overdrafted areas and supply-side interventions to increase water supplies) and two land-use management strategies (preserving prime farmlands and recharge areas and conserving priority habitats).

We next worked with stakeholders to design a matrix of nine vulnerability indicators that could assess trade-offs among these goals. We sought a representative set of vulnerability measures to identify vulnerable social and ecological communities and to assess potential trade-offs among development strategies rather than a comprehensive assessment of future vulnerability (Messina et al. 2008, Quinlan et al. 2015, Angeler and Allen 2016, Allen et al. 2018). Quantifying the general resilience of entire social-ecological systems is prohibitively challenging because of their extreme complexity, making it necessary to assess the vulnerability of specific elements to specific stressors (Quinlan et al. 2015, Angeler and Allen 2016, Allen et al. 2018). Specific vulnerabilities of the Central Coast are qualitatively summarized in Appendix 2, of which we selected a tractable subset to analyze quantitatively. Vulnerability indices commonly integrate exposure and sensitivity into single indices to simplify data, assisting in its application by managers (Thiault et al. 2018a). Following the approach of Okamoto et al. (2020) we created a balanced matrix of nine vulnerability measures that captured the specific sensitivity of three communities (agricultural, domestic, and ecological), and expanded upon their framework by also considering the specific exposure to three distinct stressor classes (land use, water, and climate; Table 1). In this two-step process, exposure to changes was forecast from spatial simulation models and post-processed with spatial datasets of differing sensitivity to estimate vulnerability. Our choice of measures was a priori and designed to capture the goals and adaptations reported by our stakeholders (listed above). In Appendix 1 we describe the justification for and parameterization of each measure in detail, and in the next section we provide a concise summary of our approach.

Exposure and sensitivity models

Exposure to future land-use change and water shortages were jointly modeled with the Land Use and Carbon + Water Simulator (LUCAS-W; Van Schmidt et al. 2022). This is a stochastic, spatially explicit (270-m resolution) state-and-transition simulation model in the program SyncroSim's ST-Sim package (Daniel et al. 2016). Transitions between *developed* (i.e., domestic-industrial), *annual cropland*, and *perennial cropland* (collectively, "development"), as well as natural *rangeland*, are simulated from 2001 to 2061 on the basis of empirical historical rates (1992–2016; Appendix 1.1.1; Wilson et al. 2020). Our design captured trade-offs by making each land-use transition beneficial in some areas and deleterious in others. For example, urbanization and agricultural contraction increases *agricultural land vulnerability* if it occurs on areas designated by the state as important farmland to conserve (California Department of Conservation 2016). However, urbanization reduces *domestic land vulnerability* if it occurs in areas with housing shortages, and agricultural expansion increases *ecological land vulnerability* if it occurs in critical habitats for endangered species. Outputs included probability of different transitions by, or final land-use state in, 2061 (Table 1).

LUCAS-W estimates total water use in each groundwater basin on the basis of historical data and therefore can project land use–driven water shortages based on conditions of long-term overdraft (Van Schmidt et al. 2022). Importantly, LUCAS-W implicitly incorporates impacts of climate change on water sustainability via a key parameter (*total sustainable supply* of

Table 1. Matrix of nine vulnerability measures that were the product of an exposure and a sensitivity measure. To avoid overall vulnerability being skewed by outlier values in any one variable, measures that did not naturally range 0 to 1 (labeled N) were capped to this range after normalization to the range 0 to the 90th percentile, except for domestic land sensitivity, which was normalized for the range 75% to 100%. Data sources were Van Schmidt et al. (2022) for land and water exposure, Flint and Flint (2014) for climate exposure, California Department of Conservation (2016) and Van Schmidt et al. (2022) for agricultural sensitivity, U.S. Census Bureau (2017) for domestic sensitivity, and Thorne et al. (2019) for ecological sensitivity; see Appendix 1 for details.

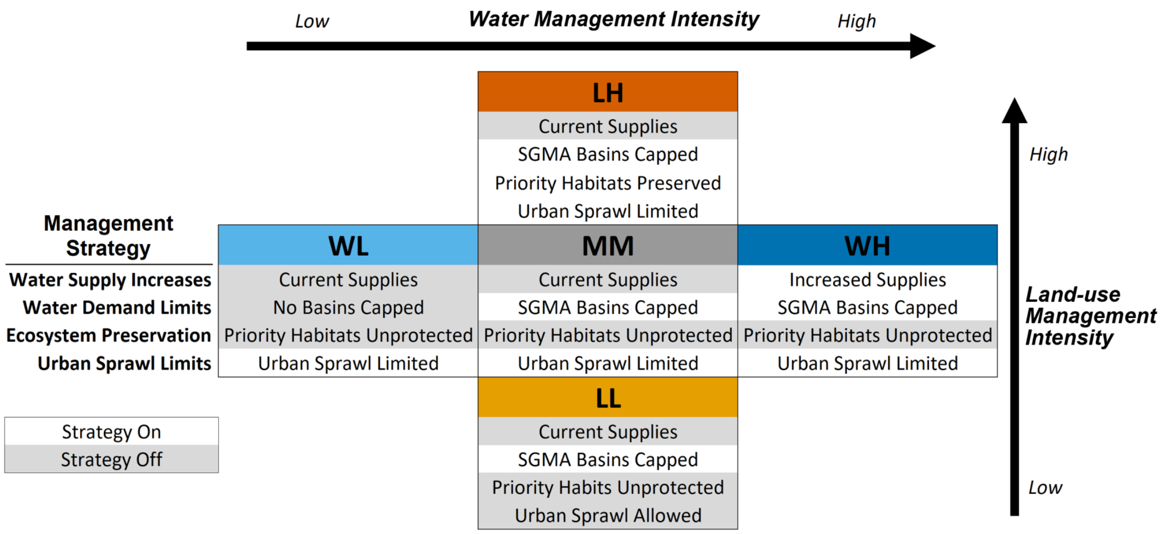
Exposure type	Sensitivity type	Vulnerability assessed	Exposure measure	Sensitivity measure
Land	Agricultural	Loss of important farmland	**Max** (Probability of developed land use 2061, probability of ag. contraction 2001–2061)	Important farmland ranking (ordinal)
	Domestic	Lack of new development in areas with housing needs	1 - probability of new developed land use 2061	Percent of housing units occupied within development zone[N]
	Ecological	Loss of critical habitats for endangered species	Probability of cropland or developed land use 2061	Critical habitat of at least one species (yes/no)
Water	Agricultural	Increased water demand that cannot be fallowed (orchards/vineyards)	Percent overdraft 2061 OR ½ the percent increase in total water use 2001–2061[N]	Percent of water use from perennial cropland in 2061
	Domestic	Household vulnerability to increased water inaffordability	Percent overdraft 2061 OR ½ the percent increase in total water use 2001–2061[N]	Percent of population at risk of future water affordability within developed land use
	Ecological	Drying of groundwater-dependent habitats for endangered species	Percent overdraft 2061 OR ½ the percent increase in total water use 2001–2061[N]	Percent of endangered freshwater species vulnerable to overdraft[N]
Climate	Agricultural	Increased irrigation water needs of crops	Change in climatic water deficit 1981–2010 to 2040–2069[N]	Cropland water use (per-cell) in 2061[N]
	Domestic	Household vulnerability to heat-related health impacts	Change in mean max temperature (June–August), 1981–2010 to 2040–2069[N]	Percent of population elderly within developed land use in 2061[N]
	Ecological	Loss of runoff and recharge that keeps streams, ponds, and vernal pools wet	Decrease in runoff and recharge 1981–2010 to 2040–2069[N]	Percent of endangered freshwater species vulnerable to drought

water in each water agency's management area) that is derived from local water agency modeling studies that incorporated projected effects of climate change (see Van Schmidt et al. 2022 for details). Although the Central Coast chiefly uses groundwater, some areas also utilize surface water and imported water (Table A2.1), so *total sustainable supply* included non-groundwater water supplies. We used estimated overdraft (for basins where *total sustainable supply* was known) as our primary exposure measure; for basins where this was unknown, we estimated it on the basis of percent increase from 2001 levels (Appendix 1.1.2). We paired this single estimate of exposure with all three sensitivity measures to model the degree of overdraft in groundwater basins with sensitive water-intensive crops, DACs, and groundwater-dependent threatened species that were particularly vulnerable to water shortages.

Projected exposure to climate changes was estimated via the Basin Characterization Model (BCM; Flint and Flint 2014), which spatially downscales global climate model projections of temperature and precipitation to 270-m resolution (following methods in Flint and Flint 2012). It develops a rigorous energy balance and integrates spatial data on soils, geology, and monthly climate to estimate change in *runoff* as surface water, potential *recharge* to groundwater aquifers, and *climatic water deficit* (an indicator of drought stress on plants and therefore irrigation water demand), among other variables (Tables A2.2, A2.3). We calculated model-averaged outputs from the BCM across five global climate models (Appendix 1.1.3) for Representative Concentration Pathway (RCP) 8.5, a high-greenhouse gas emissions climate change scenario (Riahi et al. 2011). We focused on RCP 8.5 because we sought to assess potential vulnerability and this represented the worst-case emissions scenario. We assessed how land-use patterns could interact with patterns of sensitivity by potentially placing *developed* land use with at-risk elderly populations in areas of greater increases in heat stress or placing water-intensive crops in areas exposed to increases in climatic water deficit (a proxy for increasing irrigation water needs; Table 1). Our selected measure of ecological climate vulnerability (imperiled freshwater species experiencing surface water declines) was only tenuously linked to land-use change patterns. We elected to not force a linkage to the land use–driven management scenarios and left this measure static across scenarios. We modeled exposure as change in these three metrics between two 30-year windows, historical (1981–2010) and projected (2040–2069).

Sensitivity measures (Table 1) were obtained from diverse datasets (Appendix 1.2). Agricultural sensitivity data were derived from cropland projections from LUCAS-W (Van Schmidt et al. 2022), crop water demand data (CDWR 2014), and farmland importance rankings (California Department of Conservation 2016). Demographic sensitivity maps were derived from 2017 census data (U.S. Census Bureau 2017). Ecological sensitivity data were based on range maps for imperiled species and subspecies (Howard et al. 2015, Thorne et al. 2019). We reviewed species accounts and conservation plans from government agencies to create a supplementary ecological vulnerability report (Appendix 2.5 and citations therein) that classified each of the region's 25 threatened freshwater-dependent (sub)species according to whether they were endangered because of their habitats drying out (as a result of groundwater overdraft and/or drought; Table 2.4).

Fig. 2. 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, whereas gray indicates it was inactive. Scenarios ranged from water (W-) and land-use (L-) management intensity low (-L) to high (-H), with a central scenario that was moderate and moderate intensity (MM) for both water and land-use management. Adapted from Van Schmidt et al. (2022).



Scenario-driven adaptive capacity assessment

The LUCAS-W model was used to assess five scenarios of water and land-use management to estimate adaptive capacity based on regional sustainable development strategies developed with stakeholders. Importantly, each scenario only altered the spatial pattern of where coupled land use and water use changes occurred, whereas overall rates of changes were kept constant. We grouped four policies along two axes: (1) land-use management intensity low (LL) to high (LH), and (2) water management intensity low (WL) to high (WH). A central moderate management scenario (MM) served as the intersection of these axes (Fig. 2). We varied one management axis at a time while the other axis was held constant at the "moderate" policy level, allowing us to assess a tractable subset of the most relevant policy combinations and examine the influence of each by turning each strategy on or off separately. The two "moderate" central strategies were set on the basis of feedback from stakeholders on their current management strategies (Van Schmidt et al. 2022).

For land-use management, the LL scenario had no new land-use strategies implemented (but existing protected areas were included). The MM scenario added the first land management strategy, "urban sprawl limits" that prevented *urbanization* on any land designated by the county or state as important farmland (California Department of Conservation 2016) or a recharge area (Van Schmidt et al. 2022). Urban sprawl limits were "moderate" management intensity because stakeholders reported such strategies are already usually incorporated into land-use planning. The LH scenario added a more intensive strategy, "ecosystem preservation," which prevented urbanization and agricultural expansion on federally-listed critical habitats for threatened species or prioritized by the key core areas or corridors for wildlands by the California Essential Habitat Connectivity prioritization effort (Thorne et al. 2019).

For water management, the WL scenario was a continuation of pre-SGMA "business-as-usual" management with no water demand limits. We assessed two water management strategies: (1) demand-side interventions to reduce development in overdrafted areas by adding water demand caps, and (2) supply-side interventions to increase water supplies. The MM scenario added a "water demand caps" strategy that limited new development if total water use overlying an agency's jurisdictional boundaries exceeded the current *total sustainable supply*. This strategy simulated a water pumping allocation system, which was included as the moderate management intensity level because this is planned by virtually all GSAs if water sustainability is not reached, whereas only a subset of them propose water supply enhancements. We did not assess water supply enhancements without demand caps in this study because our previous study found this to be ineffective at achieving water sustainability (Van Schmidt et al. 2022). When a water agency's management area is in overdraft, new development is prohibited if it would increase water demand and fallowing is prioritized (Van Schmidt et al. 2022). This strategy is potentially transformative of system behavior (Walker et al. 2006) because it creates a novel feedback with water demand (i.e., adding the new blue linkage from water supply conditions to land-use change in Fig. 1). In the WH scenario the second strategy, "water supply enhancement," increased the *total sustainable supply* value by adding water from projects that GSAs were planning to implement.

Calculating and reporting vulnerability

Each measure of exposure and sensitivity (Table 1) was masked, rescaled 0–1, and resampled to a 270-m resolution raster to allow comparison (Appendix 1; Okamoto et al. 2020). Final measures of each vulnerability were the product of exposure and sensitivity, calculated via raster math. We created maps of *overall vulnerability* by summing all nine specific vulnerability measures for each cell. We report trends in regional-wide specific vulnerabilities based on mean per-cell values to capture the average vulnerability, and the 75th (land and climate) or 95th (water, due to a very skewed distribution) percentile to capture changes in the number of high-vulnerability areas.

We report spatial patterns in *land vulnerability* for the LL scenario, treating this as a baseline because it had the least land protections. We report baseline water and climate vulnerability using the WL scenario because this approximated a pre-SGMA trajectory for the region and this strategy had the greatest impact on development patterns (Van Schmidt et al. 2022). We assessed the adaptive capacity of localities and the region overall by determining whether any of the management scenarios were effective at reducing social and ecological vulnerabilities.

RESULTS

Land-use change vulnerability

We first summarize major trends in exposure to projected 2021–2061 land-use change; for a more comprehensive description see Van Schmidt et al. (2022). Region-wide *perennial cropland* and *developed* land expanded, outpacing a decline in *annual cropland* and resulting in a mean net loss of 417 km² (range −167 to −581 km²) of natural areas. Agricultural intensification (*annual cropland* replaced with *perennial cropland*) was widespread in all five counties. All five management scenarios assumed these same rates (Van Schmidt et al. 2022).

Without urban sprawl limits protecting prime farmland and groundwater recharge areas from urbanization, new *developed* land use was most likely to occur around edges of major cities, which resulted in high vulnerability of loss of farmland in these areas (Fig. 3a). This was particularly the case in Santa Cruz, where open land for alternative urban expansion was very limited. San Benito had projected long-term agricultural contraction, which drove high agricultural vulnerability there (Fig. 3a). Agricultural vulnerability was higher where projected water supply shortfalls forced agricultural contraction under water demand caps (Fig. 3a).

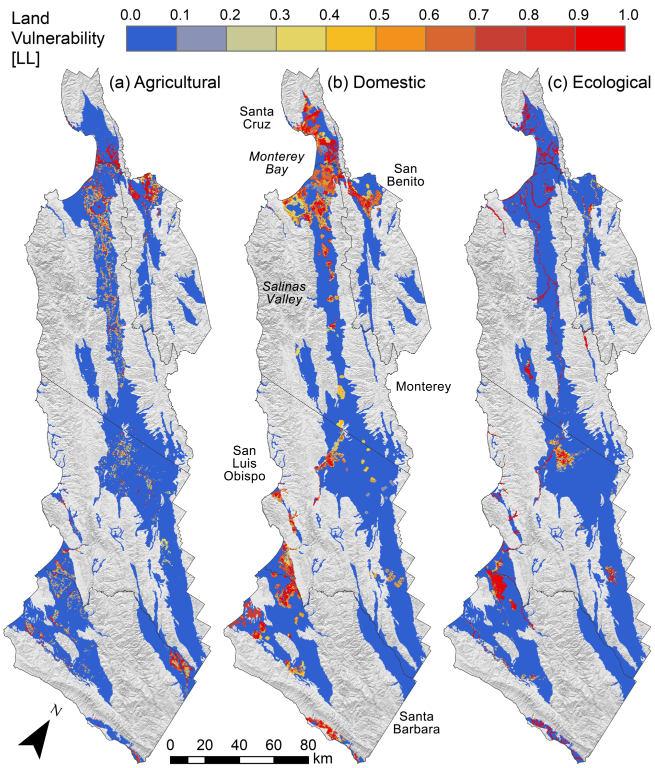
Projected domestic vulnerability (the likelihood of no new housing in areas with most housing filled) was high around most cities (Fig. 3b), but particularly in the Monterey Bay region and Santa Barbara. Our stakeholder working group reported that many of these cities are facing serious housing shortages.

Major hotspots of ecological vulnerability (probability of development in or adjacent to critical habitats) were riparian habitats around the Monterey Bay as well as around cities in the southern half of the region (Fig. 3c). Critical habitats of outlying rangelands and forests were low risk.

Water vulnerability

Despite the overall spread of *developed* land and *perennial cropland*, region-wide water use was projected to stay the same from 2021 to 2061 (mean +8916 acre-feet/year, range across simulation replicates −66,354 to +70,563 acre-feet/year) because increased water demand from these land uses was offset by the loss of more water-intensive *annual cropland* (Van Schmidt et al. 2022). Without water demand caps the Central Coast had widespread water vulnerability projected by 2061 (Fig. 4): nine

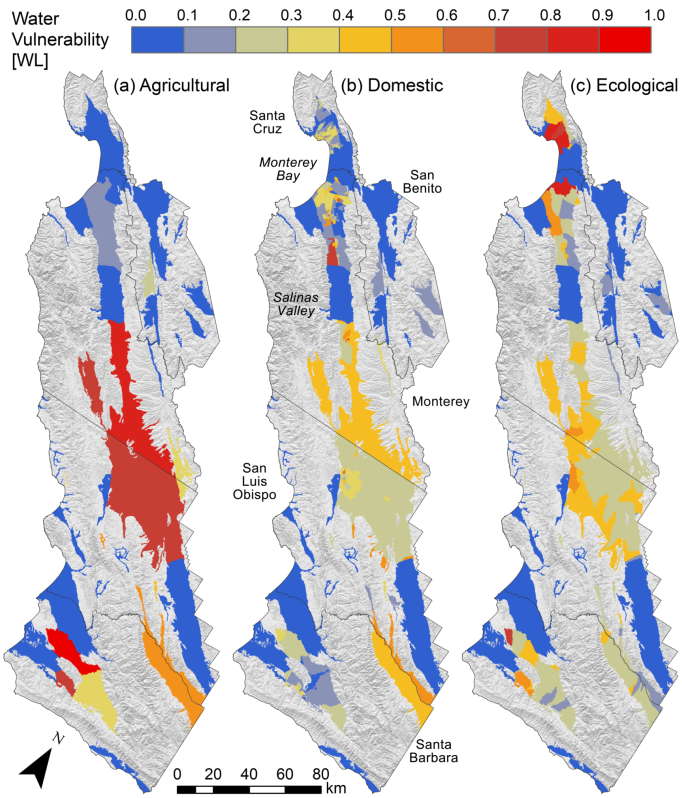
Fig. 3. Vulnerability to (a) loss of important farmland, (b) lack of new development in areas with housing needs, and (c) loss of critical habitats for endangered species under land-use projections to 2061 in California's Central Coast under a land-use management low intensity [LL] scenario (water demand caps, no urban sprawl limits or new ecosystem preservation). Red indicates high vulnerability, blue low vulnerability. Gray areas are topography outside of groundwater basins that were excluded. See Table 1 for description of vulnerability measures and Appendix 3 for maps of other scenarios. Data accessible in Van Schmidt et al. (2023).



groundwater agencies were in unsustainable long-term overdraft and an additional four basins for which overdraft could not be calculated roughly doubled their water use (range +93.6% to +141.8%). Several areas with current overdraft issues had low vulnerability across measures because they did not have overdraft with projected 2061 land uses (Table A2.2). Despite all water vulnerability measures sharing this measure of exposure to water shortages, different sensitivities drove divergent patterns of water vulnerability across the region.

Agricultural vulnerability, which represented drought sensitivity as the percent of agriculture that was perennial and therefore could not be fallowed during dry years, was very high in the southern Salinas Valley (Fig. 4a). These areas have experienced recent explosive growth of perennial agricultural that was projected to continue (Van Schmidt et al. 2022). Other vulnerable areas included a basin in southern Salinas Valley that was relatively undeveloped but projected to see significant agricultural expansion (Fig. 4a).

Fig. 4. Vulnerability to basin-wide water shortages (driven by development projected by 2061) coupled with (a) increased demand for perennial agriculture that cannot be fallowed, (b) households vulnerable to increased water unaffordability, and (c) groundwater-dependent habitats for endangered species, in California's Central Coast for the water management low intensity [WL] scenario (no water demand caps, urban sprawl limits). Red indicates high vulnerability, blue low vulnerability. Gray areas are topography outside of groundwater basins that were excluded. See Table 1 for description of vulnerability measures and Appendix 3 for maps from other scenarios. Data accessible in Van Schmidt et al. (2023).



Domestic vulnerability (potential water shortages in DACs) had localized hotspots in cities, many of which were small, urban parcel-block units that represent important higher population density despite their limited spatial extent (Fig. 4b). In some of these communities, up to 100% of households were at risk of future water unaffordability. San Benito County and Santa Barbara County had lower vulnerability (Fig. 4b).

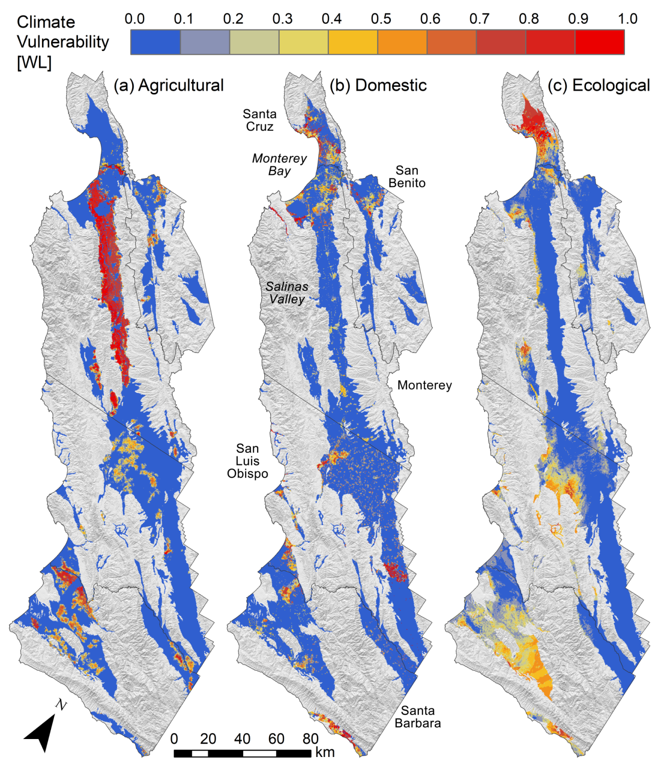
Region-wide there were 980 known freshwater-dependent bird, amphibian, fish, invertebrate, and plant species and subspecies (Howard et al. 2015). Of these, 143 (15%) are species of conservation concern, including 25 federally- or state-listed as threatened. Of these 25 species and subspecies, 18 were threatened by falling water tables drying out their groundwater-dependent habitats (Appendix 2.5 and citations therein; Table A2.4). Up to seven threatened groundwater-dependent species overlapped in the most vulnerable areas (vulnerability = 1.0; Fig. 4c). Around the Monterey Bay, species are currently threatened by high levels of habitat conversion because of urbanization (Appendix 2.5), leading to co-occurrence of high domestic and ecological vulnerability (Fig. 4b, c).

Climate change vulnerability

All five counties are projected to become hotter and to receive increased precipitation on average by the end of the century (Flint and Flint 2014, Langridge 2018). Crucially, although there will be more water on average, individual precipitation events will be more variable and concentrated with worse droughts (Table A2.2). Even with higher rainfall, increased warming will likely increase evaporative losses and subsequent irrigation demand (Langridge 2018).

All areas experienced increases in climatic water deficit (range +44.12 to +156.33) that would likely increase cropland water needs. Agricultural vulnerability was highest in the northern Salinas Valley (Fig. 5a), where major increases in climatic water deficit overlapped areas of annual cropland with higher applied water demand (Van Schmidt et al. 2022). In areas where less water-intensive perennial crops dominated, such as in southern Salinas Valley (Van Schmidt et al. 2022), there was reduced vulnerability to this measure (Fig. 5a).

Fig. 5. Vulnerability to Representative Concentration Pathway (RCP) 8.5 climate changes coupled with land-use change by 2061 resulting in hotspots of (a) increased irrigation water needs of crops, (b) household vulnerability to heat-related health impacts, and (c) loss of runoff and recharge that keep freshwater ecosystems wet, in California's Central Coast for the water management low intensity [WL] scenario (no water demand caps, urban sprawl limits). Red indicates high vulnerability, blue low vulnerability. Gray areas are topography outside of groundwater basins that were excluded. See Table 1 for description of vulnerability measures and Appendix 1 for maps from other scenarios. Data accessible in Van Schmidt et al. (2023).



Maximum summer temperature also increased in all areas (+0.702 to +4.75 °C). Coastal cities were the greatest hotspots of domestic vulnerability to climate change, which we modeled as increases in maximum temperature in areas with elderly populations that are more at risk of heat-related health impacts (Fig. 5b). The agricultural cities and towns of inland areas tended to have lower vulnerability.

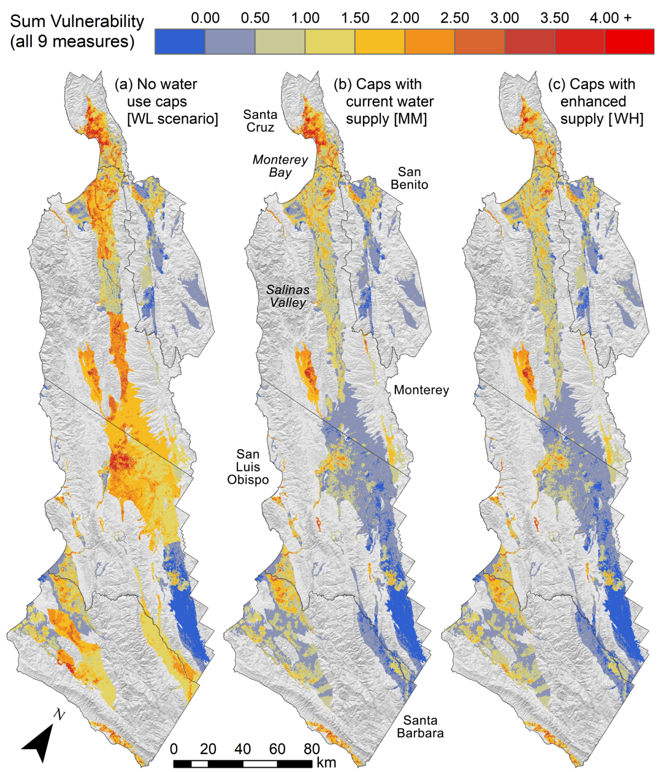
There were 17 threatened freshwater species in the study area that were imperiled by their habitats drying during drought (Appendix 2.5 and citations therein; Table A2.4), which could worsen as recharge and runoff declined under climate change. Declines in water inputs to ecosystems (runoff plus recharge) were highest at high elevations (maximum −88.47 mm), whereas many lowland areas experienced no declines. Santa Cruz County was the area at greatest risk of this, with up to seven species concurrently threatened in some areas (Fig. 5c). Other major at-risk areas were southern Monterey County and southern Santa Barbara County (Fig. 5c). Some areas overlapped where declining groundwater levels also threatened species (Fig. 4b); we identified 14 species as imperiled by both droughts and declining groundwater levels (Appendix 2.5; Table A2.4).

Cumulative vulnerability and adaptive capacity

Water demand caps impacted vulnerability more dramatically than any other measure, significantly decreasing region-wide water vulnerability (Figs. 6 and 7). Mean overall region-wide sum vulnerability was 1.32 (95th percentile = 2.61) without water demand caps (LL scenario; Fig. 6a). Vulnerability was reduced when each water agency capped water demand at current sustainable water supplies (MM scenario mean = 0.69, 95th percentile = 2.14). Reductions were widespread, completely eliminating overdraft in seven of the nine agencies projected to otherwise be in overdraft in 2061; the only exception was in Santa Cruz County, where limited land availability prevented water demand caps from shifting development to less water-stressed basins (Fig. 6a, b). Pairing water demand caps with proposed water supply enhancements resulted in the lowest overall vulnerability (WH scenario mean = 0.68, 95th percentile = 2.03) largely because of reducing overdraft in Santa Cruz County, which could not meet sustainability criteria with water demand caps alone (Fig. 6c, d). Protecting prime farmland and recharge areas from urbanization had little impact (Fig. 7a, b), with regional sum vulnerability close to that in the MM (LL scenario mean = 0.70, 95th percentile = 2.17). Compared to the MM scenario, preserving priority ecosystems resulted in slightly greater average vulnerability (mean = 0.75), but reduced the number of high vulnerability areas (95th percentile = 2.06). This was because the strategy reduced vulnerability in Lockwood Valley (the southeastern-most valley in Monterey County) but increased vulnerability in central Santa Barbara County (Fig. 7b, c).

The areas surrounding cities (i.e., yellow-to-red areas in Fig. 5b) were generally the greatest hotspots of cumulative vulnerability (Figs. 6 and 7) because domestic, agricultural, and ecological communities relied on the same limited land and water resources and experienced significant climate impacts (Figs. 3–5). Santa Cruz County and the southern coast of Santa Barbara County were particularly vulnerable across scenarios, both of which are surrounded by forested mountains that provide little flexibility for alternative development patterns. Agricultural cities were also major hotspots, particularly without water demand caps (Fig. 7a). Although Lockwood Valley is currently sparsely developed and unregulated by SGMA (CDWR 2020), it was projected to be a major vulnerability hotspot because of significant expansion of *perennial cropland* (Figs. 6 and 7).

Fig. 6. Impact of increasing intensity of water management on spatial patterns of overall vulnerability (sum of nine measures of exposure and sensitivity; Table 1) by 2061 for California's Central Coast. (a) Water management low intensity (WL) scenario, with water use uncapped. (b) Water management moderate intensity (MM) adds demand caps within groundwater agency management areas that prevent total water use from exceeding current total sustainable supply. (c) Water management high intensity (WH) increases this total sustainable supply cap with new supply enhancement measures described as likely to be implemented by agency staff (Van Schmidt et al. 2022).

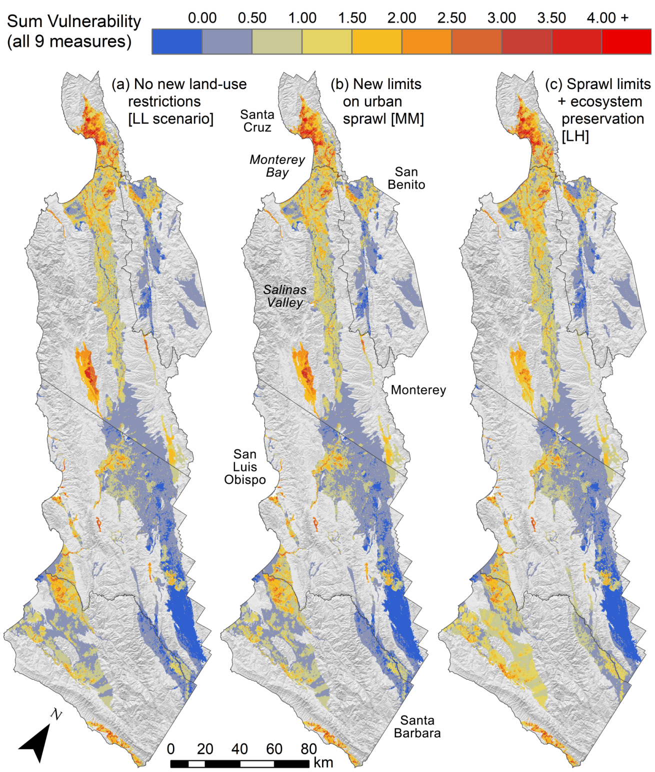


Vulnerability trade-offs

Table 2 summarizes region-wide trade-offs in specific vulnerability driven by each management strategy. Appendix 3 maps specific vulnerability (i.e., Figs. 3–5) for all five scenarios.

Capping water demand at current sustainable water supplies resulted in six- to ten-fold reductions in average agricultural (0.35 to 0.03), domestic (0.18 to 0.03), and ecological (0.21 to 0.04) water vulnerability (Fig. 8; compare WL to MM). All other management strategies reduced mean vulnerability by relatively

Fig. 7. Impact of increasing intensity of land-use management on spatial patterns of overall vulnerability (sum of nine measures of exposure and sensitivity; Table 1) by 2061 for California's Central Coast. (a) Land-use management low intensity (LL) scenario, which allows development in areas designated important for agriculture, groundwater recharge, and conservation priorities. (b) Land-use management moderate intensity (MM) adds prevention of urban expansion on areas designated important for agriculture or groundwater recharge (Van Schmidt et al. 2022). (c) Land-use management high intensity (LH) additionally adds prevention of urban expansion or agricultural expansion on critical habitats or priority conservation areas designated by the state or federal governments (Thorne et al. 2019).



modest amounts in comparison (≤ 0.07). Caps caused leakage of agricultural expansion from major agricultural areas reliant on overdrafted aquifers into unregulated basins that are currently relatively undeveloped (Van Schmidt et al. 2022). This resulted in some trade-offs at local scales, but these were minor compared to the dramatic reduction in water vulnerability. Caps caused slight increases in the number of areas at high vulnerability for agricultural contraction on prime farmland (agricultural land vulnerability; +0.02 mean, +0.07 75th percentile) and development of critical habitats (ecological land vulnerability; +0.01 mean, +0.10 75th percentile; Fig. 8a-c). It did not appear to alter climate change vulnerability, with negligible decreases for agriculture (−0.01 mean, −0.01 75th percentile) and increases for domestic (+0.00 mean, +0.01 75th percentile; Fig. 8g, h) areas.

Water supply enhancement raised the water demand caps, which decreased high-risk areas for domestic (−0.00 mean, −0.08 95th percentile) and ecological (−0.01 mean, −0.05 95th percentile) water vulnerability, but increased agricultural water vulnerability (+0.00 mean, +0.11 95th percentile; Fig. 8d-f, compare MM to WH). This was because they allowed for more development on basins that were at risk (i.e., currently overdrafted). They also slightly increased agricultural (+0.03 mean, +0.02 75th percentile) and domestic (+0.02 mean, +0.02 75th percentile) climate vulnerability by re-concentrating agricultural expansion in areas such as the Salinas Valley (Van Schmidt et al. 2022) that had high climate vulnerability (Fig. 5a, b).

Preventing urbanization of important farmland and areas important for groundwater recharge successfully reduced regional agricultural land vulnerability (−0.03 mean, −0.07 75th percentile; Fig. 8a, compare LL to MM). Although it did not have apparent impacts on water vulnerability (Fig. 8d-f, all changes ≤ 0.01), this may underestimate water sustainability benefits because we could not model increased groundwater recharge from preventing paving of recharge areas. Despite lowering urbanization rates around agricultural cities (Van Schmidt et al. 2022), this strategy had surprisingly minimal impacts on domestic vulnerability to housing shortages (domestic land; +0.01 mean, +0.00 75th percentile; Fig. 8b). However, it did slightly elevate potential health impacts from heat stress under climate change (+0.02 mean, +0.03 75th percentile; Fig. 8h).

Preserving priority ecosystems had some of the most notable trade-offs region-wide (Fig. 8, compare MM to LH). It greatly decreased development of critical habitats (−0.06 mean, −0.30 75th percentile; Fig. 8c), in part by reversing the leakage of development into undeveloped basins caused by water demand caps (Van Schmidt et al. 2022). However, this markedly increased agricultural water vulnerability (+0.03 mean, +0.25 95th percentile), in addition to slight increases in ecological (+0.02 mean, +0.01 95th percentile) and domestic (+0.02 mean, −0.01 95th percentile) water vulnerability. This was because it once again concentrated development in current major agricultural regions where water supplies are more stressed (e.g., in the Salinas Valley; Van Schmidt et al. 2022), which also slightly increased agricultural climate vulnerability (+0.04 mean, +0.02 75th percentile; Fig. 2g).

DISCUSSION

Trade-offs of development planning strategies

We created a novel coupled approach to modeling land use, water demand, and climate scenarios to assess management trade-offs between nine stakeholder-defined, potentially competing vulnerabilities of agricultural, domestic, and ecological communities in California's Central Coast. We expanded on the approach of Okamoto et al. (2020) by balancing not only three classes of sensitivities (as they did) but also three classes of exposures. This allows the comparison of which axis—exposure or sensitivity—was more likely to drive trade-offs. Contrary to our hypotheses, we found that trade-offs were more frequent across exposure classes (land use vs. water vs. climate changes) than sensitivity classes (agricultural vs. domestic vs. ecological communities). Water demand caps benefitted all water vulnerability measures for all sensitivity classes (Fig. 8d-f) while increasing land vulnerability for both agriculture and ecosystems

Table 2. Summary of trade-offs among management strategy assessed via simulated scenarios of coupled land-use change, water demand, and climate change within California's Central Coast (data in Fig. 8).

Management strategy	Benefits	Drawbacks
Capping water demand at current sustainable water supply	Major reduction in agricultural, domestic, and ecological water vulnerability	Increased agricultural contraction on prime farmland and development of critical habitats
Water supply enhancement (with demand caps)	Reduced domestic and ecological water vulnerability	Increased agricultural water vulnerability, and agricultural and domestic climate vulnerability
Urban sprawl limits	Reduced loss of prime farmland	Increased domestic climate vulnerability
Ecosystem preservation	Major reduction in loss of critical habitats	Major increase in agricultural water vulnerability, increase in agricultural climate vulnerability

(Fig. 8a-c). Conversely, ecosystem preservation policies that reduced ecological land vulnerability did not increase agricultural or domestic land vulnerability (Fig. 8a-c), but increased all three kinds of water vulnerability (Fig. 8d-f). This suggests that trade-offs in social-ecological systems among resource categories (i.e., land vs. water resources) may be more common than trade-offs between social versus ecological communities, which may co-benefit. Future studies should test this hypothesis in other systems.

We found that sustainable development strategies could jointly meet multiple goals with limited trade-offs, which were often spatially localized. This suggests a one-size-fits-all approach to managing land and water resources of the Central Coast may not be optimal, echoing findings of Okamoto et al. (2020). Water supply enhancement increased agricultural water vulnerability (Fig. 8d) by encouraging additional development in overdrafted areas (Van Schmidt et al. 2022), but was necessary to achieve groundwater sustainability in Santa Cruz County (Figs. 6b, c, 8e). Ecosystem preservation decreased vulnerability in Monterey County but increased it in Santa Barbara County (Fig 7b-c). Trade-offs could therefore be reduced by applying management strategies strategically to fit local conditions.

The most notable trade-offs were for demand-based water management interventions, which have been found to be necessary to achieve water sustainability in many semi-arid regions (Purkey et al. 2008, MacDonald 2010, Joyce et al. 2011, Mehta et al. 2013, Johannsen et al. 2016) but have also been predicted to cause leakage of development into undeveloped groundwater basins (Priess et al. 2011, Liu et al. 2017). Previous studies with LUCAS-W likewise showed that water sustainability could be achieved simply by shifting new development outside of overdrafted areas, but speculated this leakage could introduce trade-offs by developing natural regions with high ecological sensitivity (Van Schmidt et al. 2022). In this study, we accounted for differing sensitivities and confirmed that although trade-offs did exist, they appeared minor at broader scales by only slightly increasing the proportion of high-vulnerability ecological and agricultural lands (Fig. 8a-c).

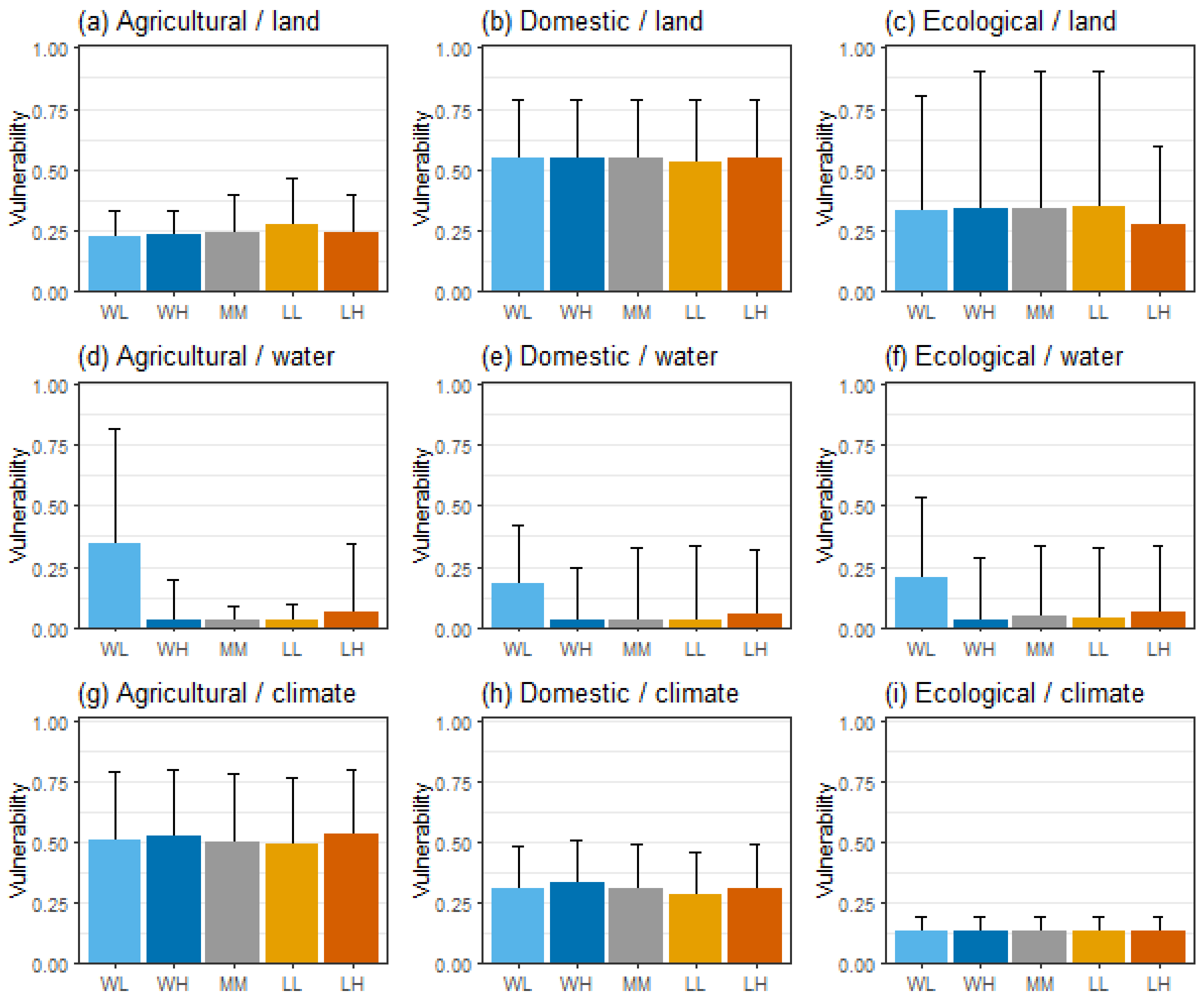
The dramatic benefits of water demand caps on adaptation to climate-mediated water shortages (Fig. 8d-f; Langridge 2018, Van Schmidt et al. 2022) illustrate the importance of development planning for adapting to climate change. Water demand caps co-benefitted all three measures of water vulnerability (agricultural, domestic, and ecological), whereas water supply enhancement increased agricultural water vulnerability. This may be because demand caps transformed the behavior of this socio-ecological system at a fundamental level by adding new feedbacks between development and water sustainability (Fig. 1), rather than simply trying to treat the problem by increasing water supplies in currently overdrafted areas (Van Schmidt et al. 2022). This supports a hypothesis in social-ecological systems research that adding reciprocal couplings between social and ecological processes can help couple environmental sustainability to socio-economic sustainability (Kramer et al. 2017).

Vulnerability hotspots

Vulnerability assessments can be valuable tools for conservation and climate adaptation planning, and our maps (Van Schmidt et al. 2023) could help local agencies prioritize efforts (Thiault et al. 2018a). Projecting future land-use scenarios allows land managers to visualize alternative futures to optimize best management strategies (Alcamo et al. 2006). Areas where multiple vulnerabilities overlap tended to be in and around major cities (Figs. 6 and 7). Hotspots of vulnerability were otherwise frequently in different areas for different types of vulnerability (Figs. 3–5), in agreement with other assessments (Thiault et al. 2018b).

Complementary patterns of vulnerability resulted from distinct differences between prosperous coastal communities (vulnerable areas in Fig. 5b) and inland agricultural areas with many low-income workers (vulnerable areas in Fig. 6b). Groundwater depletion could drive the drying of wells during drought, which disproportionately impacts DACs (Gleeson et al. 2020). Inland agricultural communities had higher water unaffordability indicators coupled with risk of groundwater depletion (Fig. 4b), and these at-risk areas could be targeted for water affordability programs. Conversely, coastal tourism-based communities with older residents (often retirees) had higher risk of heat-related health impacts among the elderly (Fig. 5b). Programs to improve access to climate-control for low-income elderly residents could be targeted to these communities. Agricultural livelihoods may be at risk in the northern counties (Fig. 3a) as development pressures from major urban centers like the San Francisco Bay Area expand their urban footprint, a concern reported to us by a stakeholder representative for indigenous farmworkers in San Benito County. Lastly, water demand varies significantly across crops (Allan et al. 1998) and was higher for annual cropland in the Central Coast (Van Schmidt et al. 2022). Crop water efficiency programs could be targeted toward water-intensive agricultural areas at risk of increased water demand under climate change (Fig. 5a). Continuation of recent shifts from annual crops to perennial orchards and vineyards, which cannot be fallowed, removes flexibility in irrigation demand during drought (Wilson et al. 2020) that may be useful to account for in drought preparedness strategies in these areas (Fig. 4a).

Fig. 8. Projected mean vulnerability (y-axis) across California's Central Coast by 2061 for nine measures of sensitivity (titles, left of slash) and exposure (titles, right of slash) under five management scenarios (x-axis). To illustrate changes in the number of high-vulnerability areas, error bars show 75th percentile values for land (a–c) vulnerabilities, 95th percentile values for water (d–f) vulnerabilities, and 75th percentile for climate vulnerabilities (g–i). See Table 1 for a description of each vulnerability measure. Scenarios ranged water (W-) and land-use (L-) management intensity low (-L) to high (-H), with a central scenario that was moderate intensity (MM) for both water and land-use management; see Figure 2 for scenario design and descriptions.



Ecosystems are also affected by land-use change, climate change, and indirectly by both via reductions in groundwater levels, which often are the main source of water for vegetation in drier regions. Groundwater-dependent ecosystems provide important ecosystem services and support disproportionate amounts of regional biodiversity (Kløve et al. 2014), and their drying can eliminate fish and wildlife populations that depend on them (Kløve et al. 2011). Of the 25 threatened species in the Central Coast, all but three were described as imperiled by either groundwater declines or drought, and over half were imperiled by both (Appendix 2.5 and citations therein; Table A2.4). Investments in wetland hydrology restoration and management could be targeted toward these at-risk ecosystems (Figs. 4c and 5c). We found ecosystem preservation policies could cause trade-offs with agricultural vulnerabilities (Fig. 3a), but our models protected very extensive tracts of land marked as broad habitat conservation priorities (Van Schmidt et al. 2022). More targeted investments in habitat protection in the areas identified as high-risk (Fig. 3c) may preserve key habitats without these trade-offs.

Model uncertainty and limitations

Forecast models have substantial uncertainties, but if uncertainty is taken into account when weighing decisions they can still provide useful information for adaptation planning (Miller et al. 2022). It is difficult to quantify uncertainty for synthesis vulnerability assessments because uncertainty arises from numerous sources, including scenarios, design choices, data collection, and errors in modeling of both the original and the synthesis studies (Evans 2012, Miller et al. 2022). Uncertainty in climate projections is particularly high, arising from choice of global climate model, socioeconomic development scenarios, natural stochasticity and annual variability, and statistical downscaling approaches (Reilly et al. 2001, Gao et al. 2020). Although methods for quantifying uncertainty in synthesis vulnerability assessments are limited, there are guidelines for identifying areas of greater confidence: projections based on different methodologies can identify areas consistently at risk under multiple models (i.e., agreement across Fig. 5a-c), projections that incorporate multiple scenarios can identify areas of agreement (we used a model-averaging approach), and larger areas of consistent high or low vulnerability (i.e., municipalities or counties) are less likely to suffer from random spatial error than individual pixels (Glick et al. 2011, Pacifici et al. 2015, Michalak et al. 2022). In lieu of the impossibility of validating integrated forecast models, researchers have suggested that participatory science can serve as pseudo-validation by having stakeholders "ground-truth" forecasts (Messina et al. 2008, Moss 2008). We followed this tactic, presenting our interim results to regional stakeholders and experts at multiple stages throughout development prior to final results to ensure our effort reasonably captured regional dynamics. Areas that are high risk across scenarios and measures (i.e., the overall vulnerability maps; Figs. 6 and 7) likely have increased confidence because they are more robust to the idiosyncrasies of any one scenario or measure (Michalak et al. 2022).

Our approach may underestimate vulnerability. Our study focused on adaptive capacity derived from institutional decision making about land-use and water management. LUCAS-W is one of the only models that represents top-down institutional feedbacks between land-use change and water resources, but it does not yet have the capacity to model bottom-up feedbacks and synergies from climate (Van Schmidt et al. 2022). In reality, complex linkages between climate change with land use and water are likely to further alter patterns of vulnerability (Michalak et al. 2022). For example, areas of increasing climatic water deficit (Fig. 4a) are likely to increase irrigation water demand (Hayhoe et al. 2004), which could worsen water overdraft (Fig. 3a). Future models could incorporate these and other feedbacks.

The vulnerabilities we assessed can be difficult to quantitatively compare and are not comprehensive. Although we reprocessed, masked, and normalized our data to allow for comparisons of different measures (Appendix 1; Okamoto et al. 2020), quantitative comparison of vulnerability measures could still be affected by measure design choices that might alter the scale of responses (Evans 2012). Notably, water vulnerability had a very skewed distribution in our study, which may complicate comparisons of it with other measures. Similar studies have found scaling and weighting decisions had only limited effects on spatial patterns of social and ecological vulnerability (Thiault et al. 2018a). Nevertheless, when comparing among different measures, the existence of changes in vulnerability (i.e., co-benefits and trade-offs in Table 2) is more reliable than their relative magnitude (i.e., Fig. 8). Vulnerabilities are also value-driven; some impacts could be viewed as categorically unacceptable despite small spatial extents (e.g., the extinction of a rare species; Okamoto et al. 2020).

Last, we sought to create a representative set of measures for representing stakeholder-defined concerns and testing key trade-offs, but we could not comprehensively assess all vulnerabilities. For example, stakeholders ranked water quality as a key concern, but we were unable to model it with our available tools. Many groundwater basins have water quality impairments that we did not account for, including nitrate, arsenic, chloride, and fecal coliform concentrations that exceed regulatory maximum contaminant levels (Table A2.2; CDWR 2003). These contaminants arise from both nonpoint and point sources, including septic systems, former disposal sites, orphaned sites, and stormwater runoff. A critical issue is seawater intrusion into coastal aquifers, which could make groundwater unusable for agriculture (Martin 2014). Our vulnerability measure treated percent overdraft of groundwater as posing an equal threat across areas, but seawater intrusion could arguably make coastal areas more sensitive to overdraft than inland areas.

We therefore stress the importance of holistically viewing our results and map products as "one tool in the toolbox." Adaptation decision making is more likely to be successful when done in conjunction with local knowledge, stakeholder engagement, and collaboration (Bakker and Morinville 2013, Dobbin et al. 2015). To this end, Appendix 2 provides a complementary qualitative review of additional social and ecological sensitivities for the Central Coast that we compiled in the process of developing our model with stakeholders.

CONCLUSIONS

As land use, water systems, and climate feedbacks change over the coming decades, institutions will be challenged to balance the needs of multiple social-ecological communities. There is a substantial need for integrative vulnerability assessments in many regions; however, to be most successful they will need to be intentionally designed to address specific management goals (Michalak et al. 2022). Our approach highlights a way to design vulnerability analyses for systematically identifying benefits and trade-offs to multiple diverse groups. Our results indicate that integrated adaptation planning by institutions could simultaneously achieve multiple goals. The dramatic influence of water demand caps on reducing vulnerability of agricultural systems, human communities, and ecosystems highlights opportunities that potentially transformative laws like SGMA have to transition systems from unsustainable configurations into resilient ones (Walker et al. 2006, Van Schmidt et al. 2022). Our approach was also able to identify trade-offs, which tended to be localized. Spatially explicit vulnerability studies like ours can provide maps to planners that highlight where these trade-offs occur so that managers may better tailor strategies to local conditions and considerations, while still providing consistent regional-scale planning tools.

Author Contributions:

Nathan D. Van Schmidt: conceptualization, methodology, software (LUCAS-W, 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 and editing. Lorraine E. Flint: funding acquisition, conceptualization, methodology, software (BCM), writing – review and editing. Ruth Langridge: supervision, project administration, funding acquisition, conceptualization, methodology, workshop and meeting organization, stakeholder interviews, resources, writing – review and editing.

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All exposure, sensitivity, and vulnerability maps are available as a data release in the U.S. Geological Survey's ScienceBase catalog (Van Schmidt et al. 2023; https://doi.org/10.5066/P9XQVEL4). The LUCAS-W model is freely available from ScienceBase (Van Schmidt et al. 2021; https://doi.org/10.5066/P9209XW4); modeling was done using the ST-SIM software application which can be downloaded, free of charge, from APEX Resource Management Solutions (http://apexrms.com). The Basin Characterization Model projections are freely available from the USGS (Flint and Flint 2014; https://doi.org/10.5066/F76T0JPB). 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 (Grant #CCRP0023) and the U.S. Geological Survey's Ecosystems Land Change Science Program. We thank Paul Selmants and Michelle Stern for additional assistance with exposure models, and our peer reviewers for their feedback.

Data Availability:

The data/code that support the findings of this study are openly available in the U.S. Geological Survey's ScienceBase catalog at https://doi.org/10.5066/P9XQVEL4. The LUCAS-W model is also openly available from ScienceBase at https://doi.org/10.5066/P9209XW4. BCM projections are available from the USGS at https://ca.water.usgs.gov/projects/reg_hydro/basin-characterization-model.html.

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Appendix 1: Exposure and sensitivity parameterization methods

Appendix for "Trade-offs of development strategies for adapting to coupled changes in climate, land-use, and water for social and ecological communities in California"

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A1.1 Exposure parameterization

We used two simulation models to forecast exposure to global change processes in a 270-m grid. The Land Use and Carbon + Water Simulator (LUCAS-W; Van Schmidt et al. 2021, 2022) was used to jointly forecast future land-use change and resulting impact on water supplies in a fully coupled model. The Basin Characterization Model (BCM; Flint & Flint 2014) provided climate projections.

A1.1.1 Exposure to land-use stress

In this and the following section we briefly summarize our coupled modeling of LULC and water use. For a more comprehensive description of the design process, parameterization, and model behavior, see Van Schmidt et al. (2022). See Main Text section 3.3 for management scenario modeling.

Spatially explicit land-use/land-cover (LULC) and water use projections from 2001–2061 were created by the LUCAS-W model (Van Schmidt et al. 2022). This model is a variant of the LUCAS model (Wilson et al. 2016, 2017, 2020, Sleeter et al. 2017), a stochastic state-and transition simulation model developed in the program SyncroSim's ST-Sim package (Daniel et al. 2016). The model divides the landscape into 270 x 270-m cells, each with one of the following LULC classes: *rangeland*, *forest*, *wetland*, *water*, *barren*, *transportation*, *perennial cropland*, *annual cropland*, and *developed* (i.e., residential or industrial). LULC change occurs by simulating the following transitions based on historic (1992–2016) rates: urban expansion, *agricultural expansion* (*rangeland* converting into either *annual cropland* or *perennial cropland*), *agricultural contraction* (*cropland* converting back to *rangeland*), and *agricultural intensification* (*annual cropland* converting into *perennial cropland*).

All models were run for 10 Monte Carlo iterations, following previous work which found this number of replicates was sufficient to capture the range of stochastic variability (Sleeter et al. 2017, Wilson et al. 2020). We used the mean annual or cumulative probability of change in LULC from 2001–2061 (mean across the 10 iterations) as our measure of exposure to LULC change stress. Different types of land-use changes may be beneficial or detrimental for different regional vulnerabilities. Table 1 (*Exposure Metric* column) describes the specific LULC transitions used for each type of vulnerability.

A1.1.2 Exposure to water stress

LUCAS-W updated LUCAS with a linkage to program *R* (v3.4.3; R Core Team 2017) via the package *rsyncrosim* (v1.2.4) that creates feedbacks between groundwater sustainability and development rates. Water use per cell was estimated by attributing *perennial cropland*, *annual cropland*, and *developed* with an empirical historic water use estimate in acre-feet/year (AFY), allowing joint estimation of changing LULC and water use (Wilson et al. 2016).

Water supply for each groundwater agency within the Central Coast was modeled as a parameter called *total sustainable supply*, defined as the long-term average sustainable yield (in AFY) of groundwater plus other current or in-progress water supplies (e.g., surface water in reservoirs). We estimated this parameter for each agency by reviewing published GSA and other water agency documents, and estimates were subsequently confirmed or corrected via interviews with agency staff (Van Schmidt et al. 2022).

We used percent groundwater overdraft in 2061 as our primary measure of exposure to water stress for agricultural, domestic, and ecological vulnerability. Overdraft was calculated as the acre-feet/year of water use for each groundwater agency (i.e., the sum of per-cell water use across the agency's management area) that exceeded the *total sustainable supply,* divided by the *total sustainable supply*. Because the low-priority basins were generally unstudied and unregulated by SGMA, they did not have *total sustainable supply* determinations and thus we could not calculate overdraft in these basins. We instead used the % change in water use ((2061 – 2001) / 2001) as an alternative measure of exposure to water stress within these basins. To check that this was a viable proxy, we fit a simple linear model: *Pct Overdraft ~ Pct Change in Total Water Use*. We used the medium- and low-priority basins whose *total sustainable supply* was known (n = 19) using the data from 2001–2061 from the uncapped scenario ("WL"; see main text section 3.3). We found good agreement (*Pct Overdraft* = 0.49 * *Pct Change in Total Water Use*, $p < 0.001$, $R^2_{adj} = 0.55$). This indicated the measure was a reasonable proxy, with *Pct Change in Total Water Use* approximating half of the overdraft. We therefore defined "groundwater stress" as either *% overdraft 2061* (for basins where this was known) or *0.5 × % change in total water use 2001–2061*. We normalized this measure capped at the 90th percentile (19.4%); the maximum projected overdrafted (184.0%) was for the very small *Salinas Valley Basin GSA – Langley Area*, an outlier.

A1.1.3 Exposure to climate stress

We used the Basin Characterization Model (BCM) v6.5 to estimate exposure to climate stress (Flint and Flint 2014). This model downscales global climate model (GCMs) projections of temperature and precipitation to 270-m and integrates spatial data on soils, geology, and monthly climate to estimate change in *runoff* as surface water, *recharge* to groundwater aquifers, *climatic water deficit* (CWD), and other variables. We model-averaged BCM outputs derived from five GCMs (CCSM4, CNRM, Fgoals, IPSL, and MIROC; Flint and Flint 2014) for the Representative Concentration Pathway (RCP) 8.5 greenhouse gas emissions scenario (Riahi et al. 2011). We chose to focus exclusively on RCP 8.5 because we were mapping *potential vulnerability* and this represented the worst-case high emissions scenario, corresponding to more severe warming within our study area (Flint and Flint 2014). We assessed the change in the average of each of three measures (Main Text, Table 1) between two 30-year windows, historic (1981-2010) and projected (2040-2069). Water bodies were masked out of the original layers and had missing values, which we filled with the *Nibble* function in ArcMap (v10.7.1; Esri 2011). The "Exposure measure" column in Main Text Table 1 describes the specific BCM outputs variables we model-averaged; our choices are described in more detail in the next section, where we discuss their corresponding sensitivities. Each measure had outlier high values and was therefore normalized to their 90th percentile: 3.07 for Maximum June/July/August temperature (max observed 4.75), 92.27 for increasing climatic water deficit (max 209.34), and 28.73 for decreasing runoff + recharge (max 156.33).

A1.2. Modeling sensitivity

We used previously published spatial datasets on social demographics and ecosystems (listed below), in conjunction with some outputs from the LUCAS-W model, to model the Central Coast's existing sensitivities to LULC, water, and climate stress. Many sensitivities covered a small portion of the full study area, and contained many areas of zero vulnerability because the sensitive community was absent there. For land sensitivities these included areas without any important farmland ranking, areas outside the development zone, and areas that were not critical habitat; for climate sensitivities these included areas that were not cropland and areas that were not developed. When calculating summary statistics for the nine *specific vulnerability* layers, including these areas zero-inflated the data and more reflected the proportion of total areas at-risk, rather than reflecting changes in vulnerability within the areas occupied by the relevant communities. Therefore when calculating these summary statistics we masked these "not relevant to this sensitivity" areas to NA in each of their respective maps.

A1.2.1 Agricultural sensitivity

Agricultural land sensitivity was modeled as the loss of important farmland, which was delineated based on Farmland Mapping and Monitoring Program farmland rankings; these rankings combine considerations of land, climate, water, and history of cultivation to estimate the overall value of the farmland for conservation (California Dept. of Conservation 2016). We ranked this sensitivity measure ordinally as: 1 = prime farmland, 0.75 = farmland of statewide importance, 0.5 = unique farmland, 0.25 = farmland of local importance, and 0 = all other lands.

Groundwater is a key backup water supply during drought (Langridge and Van Schmidt 2020), so exposure to overdraft can represent a significant drought vulnerability for cropland.

Perennial cropland crops cannot be readily fallowed and live for decades (Johnson & Cody, 2015), which may create an inflexible water demand during drought that increases agricultural vulnerability. We therefore combined these, modeling *agricultural water sensitivity* based on LUCAS-W's 2061 projected percent of the total water use within each agency or basin that was from perennial cropland (i.e., the percent that was inflexible).

The water use estimates produced by LUCAS-W are based on climatic conditions for average crops calculated over the recent historic period, and do not take into account potential future changes in water demand due to climate change. We used the projected 2061 agricultural water demand per-cell as our *agricultural climate sensitivity* measure to overlay with increases in CWD, which can be used to quantify the supplemental amount of water needed to maintain current vegetation cover (Stephenson 1998). It is defined as the amount of additional water that would have evaporated or transpired if present given the projected temperature. We chose to focus on this metric of agricultural climate vulnerability because of the serious water shortages facing the Central Coast, but we note that perennial crops are also sensitive to increasing temperature and are predicted to experience yield declines under climate change (Kerr et al. 2018). This was normalized 0–517.6 (90^{th} percentile, maximum value 791).

A1.2.2 Demographic sensitivity

We created spatial maps of demographic sensitivity based on the 2017 American Community Survey block-group level data from the U.S. census (U.S. Census Bureau 2017), which was the finest scale available for our layers of interest. Because block-groups vary in size based on population density, data were thus finer-scale for urban areas and coarser-scale over rural areas. While our exposure models used forecasts, most of our sensitivity models were a snapshot of on-the-ground current conditions. This introduces a potential spatial mismatch between spatial patterns of current census data and future land-uses, which may influence interpretation of results.

A central concern of Central Coast is addressing an affordable housing shortage, as in many regions of California (Johnson et al. 2004). There is a perception that addressing the housing shortage conflicts with water sustainability, such as the so-called "show me the water" law that mandates housing developments cannot be built without a demonstrated sustainable source of water (California DWR 2003). To capture this potential tradeoff, we estimated *domestic land sensitivity* as the percentage of housing units that were filled within a census-block (i.e., areas where there is a lack of available housing). It was rare for census blocks to have fewer than a third of housing vacant, and it would be dubious to consider any areas with more than a quarter of housing vacant as experiencing a housing shortage. Therefore, rather than normalizing we rescaled this variable to range from 1 = 100% filled (maximum sensitivity) and to 0 = ≤75% filled (minimum sensitivity). Exposure was modeled as a lack of new urban development (1 – *Urbanization probability*). Across scenarios, >95% of raster cells that experienced the *urbanization* transition were within 540 m (2 cells) of initial 2001 *developed* areas. Furthermore, many small isolated groups of *developed* pixels were scattered throughout rangeland that aerial imagery revealed were generally just single farms or roads. We therefore defined a "development zone” as areas ≤540 m from 2001 *developed* areas of >3 contiguous pixels. We then set *domestic land sensitivity* = 0 outside of the development zone, to avoid artificially inflating vulnerability by treating the extensive outlying agricultural or natural areas as “high vulnerability” for housing shortages.

Poverty often correlates with lower access to necessary resources to prepare for, or to invest in, actions required to adapt to water shortages (Morrow 1999). During past droughts those on low or fixed incomes in California have struggled with the rising cost of water (Cooley et al. 2016). On the Central Coast, there is a large divide between more affluent coastal communities, and low-income communities concentrated in inland urban centers and low-wage farm labor in rural towns. Mack & Wrase (2017) modeled that based on projected increases in water prices, households with income of $45,120 or less were at risk of future water unaffordability (based on U.S. Environmental Protection Agency criteria). For our model of *demographic water sensitivity*, we applied this cutoff to census-block data on “household income in the past 12 months” to estimate the percentage of households within each-census block that were at risk of future water unaffordability.

Lastly, we quantified *demographic climate sensitivity* as mortality and morbidity risk from more severe extreme heat events, quantified as exposure to change in annual maximum temperature. Our demographic sensitivity to this exposure was the percent of the population that was elderly, because numerous studies have found this demographic group is far more at-risk for health impacts during heat waves, particularly within developed regions (Oudin Åström et al. 2011). This was multiplied by the 2061 probability of *developed* land-use and normalized 0–0.31 elderly population (90^{th} percentile, maximum value 0.81). A hotspot of vulnerability was identified in southwestern San Luis Obispo County for an area that was a solar farm, so the spatial extent of vulnerability in this area is likely overestimated (Fig. 5b).

A1.2.3 Ecological sensitivity

For our measures of ecosystem vulnerability, we assessed potential impacts on state- and/or federally-listed threatened and endangered species. We obtained spatial data on critical habitat designations from the Central Coast Greenprint (Thorne et al. 2019), a state-funded compendium of data on ecosystems within the region, and on freshwater species ranges from Howard et al. (2015). We converted these polygon data to categorical 270-m raster maps for our analysis.

Further development of natural lands will cause habitat loss, directly threatening the Central Coast’s distinctive coastal, grassland, and shrubland ecosystems. These are habitats which face the steepest declines in North American birds, and contain high priority areas for native plant range movements (Langridge 2018; North American Birds Conservation Initiative, 2016). We modeled *ecological land sensitivity* as any habitats which were designated as critical habitats for one or more threatened species. Note that while critical habitats have some legal protections, development of critical habitats is possible with permitted incidental take (e.g., via compensatory mitigation measures; Wilhere 2009).

For the remaining two sensitivity measures we focused on vulnerability to drying within key freshwater ecosystems, which contain the vast majority of threatened species within the Central Coast (Thorne et al. 2019). Of the 980 known species and subspecies, 26 (3%) are listed as endangered or threatened under the U.S. or California Endangered Species Acts, and an additional 117 (12%) have been identified as warranting special conservation concern (Howard et al. 2015). Freshwater ecosystems are affected by climate change directly via changing precipitation patterns and worsening droughts (Langridge 2018), and via climate and LULC indirectly via reductions in groundwater levels that threaten groundwater dependent ecosystems (GDEs). GDEs include springs, deep-rooted plant communities, and emergent, riparian, and estuarine wetlands that depend on groundwater for persistence; they provide important ecosystem services and support disproportionate amounts of regional biodiversity (Kløve et al. 2011). In drier regions, groundwater is often the main source of water for vegetation. GDEs provide important ecosystem services and support disproportionate amounts of regional biodiversity (Kløve et al. 2014). They support numerous endemic species within the Central Coast (Howard et al. 2015) and are critical habitat for federally endangered amphibians that are at risk of extirpation due to climate change (Sinervo 2018). Overexploitation of groundwater can have severe consequences including the drying of GDEs and elimination of fish and wildlife populations that depend on them (Kløve et al. 2011).

We reviewed species accounts and conservation plans from the U.S. Fish and Wildlife Service, California Dept. of Fish and Wildlife, and Riparian Habitat Joint Venture (RHJV) Riparian Bird Conservation Plan (RHJV & California Partners in Flight, 2004). A list of reviewed documents is provided in the text of Appendix A2.5. Based on these documents we classified whether each threatened species was endangered by their habitats drying out due to (1) falling groundwater tables due to groundwater overdraft, and/or (2) drought (Appendix A2.5). *Ecological water sensitivity* was the per-cell count of species with habitats threatened by groundwater overdraft, and was multiplied with the measure of groundwater stress. *Ecological climate sensitivity* was the per-cell count of species with habitats threatened by drought, and was multiplied with decreases in the sum of runoff and recharge. Ranges were taken from Howard et al. (2015).

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Appendix 2: Review of social and ecological sensitivities related to land-use, water resources, and climate change for California's Central Coast

Appendix for "Trade-offs of development strategies for adapting to coupled changes in climate, land-use, and water for social and ecological communities in California"

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A2.1 Overview and approach

This appendix reviews current conditions and sensitivities at the nexus of land-use, water resources, and climate change for the California Central Coast. It is intended to highlight key considerations derived from interactions between stakeholders and our research team. A premise of this work was that the review process would contribute to a better understanding of the abilities (and the limitations) of available information and modeling to inform management. Our goals for this assessment were: 1) to gather feedback on how to improve our science to make it as useful as possible to regional decision-makers; and 2) inform our scenario and vulnerability analysis to provide options that can meet regional sustainable development goals. We compiled this report as part of that process and present it here for scientific transparency and to help inform adaptation. For complementary detailed reports on exposure aspects of vulnerability, see Langridge et al. (2018) for a review of the Central Coast's exposure to climate change, and Wilson et al. (2020) and Van Schmidt et al. (2022) for projected exposure to development and water shortages.

The five-county region faces a variety of risks. Climate change may increase the frequency and severity of extreme weather events, including droughts and heat waves (Langridge et al., 2018). Land-use shifts from undeveloped to developed land, from agricultural to municipal uses, and from annual to perennial crops, will exacerbate drought impacts on water supplies and consequently on local communities (Wilson et al. 2020). Water insecurity is already an issue, and serious water shortages occurred during the 2012–2016 drought (Medellín-Azuara et al. 2016, Leahy 2016). Economically disadvantaged communities may face disproportionate risks or be less able to cope with changes (Brown 2014). Projections of potential future trends in the context of current social and environmental conditions may support fuller understanding of what exposure to the coupled stressors of climate and land-use changes will mean for the region as a whole.

Table A2.1. County-wide reliance on different water sources in an average water year. Data are from agency reports; percentages were calculated based on raw acre-feet/year values.

Water Sources	**Santa Cruz**[1]	**Monterey**[2]	**San Benito**[3]	**San Luis Obispo**[4]	**Santa Barbara**[5]
Groundwater	78%	95%	55%	90%	34%
Surface water	18%	1%	<1%	8%	15%
Imported water	<1%	0%	44%	2%	47%
Recycled water	4%	4%	1%	<1%	3%
Desalinated water	0%	0%	0%	<1%	1%

[1] County of Santa Cruz (2017)

[2] Monterey County Water Resources Agency (2019)

[3] Todd Groundwater (2018)

[4] Cannon Consulting et al. (2014); San Luis Obispo County Flood Control and Water Conservation District (2012)

[5] Santa Barbara County Water Agency (2017)

A2.2 Current water supply conditions

There are numerous key existing challenges to water quantity and quality. The Central Coast Region is heavily reliant on groundwater (Table A2.1). Groundwater overdraft occurs in multiple basins, and causes seawater intrusion in multiple basins along the coast (Langridge et al. 2018). Groundwater usage exceeds recharge in many basins with over 40 percent of regional groundwater basins already in unsustainable overdraft (Martin 2013). Falling groundwater levels have resulted in the drying of wells and water supply shortages are already a serious problem in many areas (California Dept. of Water Resources 2020). Saltwater intrusion into overdrafted groundwater aquifers is an especially significant issue near the coast. In the Pajaro Valley, aquifers have been subject to overdraft and resulting seawater intrusion since the 1940s (Hanson 2003), and while the rate of intrusion has been reduced it has not been halted. In the Salinas Valley, seawater intrusion has advanced since it was first measured in 1944, migrating over 8 miles into the Salinas Valley aquifer system (Monterey County Water Resources Agency 2017). Surface water supplies also face challenges. State Water Project (SWP) water deliveries will fluctuate related to climate change and regulatory constraints (Langridge et al. 2018). Furthermore, sediment accumulation in reservoirs that reduces storage capacity and threatens reservoir releases (Mahoney 2018).

Water quality impairment occurs in many basins from both point and nonpoint sources including nitrate groundwater contamination, and arsenic problems, which exceed some enforceable maximum contaminant levels (MCLs; California Dept. of Water Resources 2003, Langridge et al. 2018). The extensive use of water for irrigation in the major agricultural production areas led to nitrate pollution of drinking water supplies—a critical problem throughout the region. Hundreds of drinking water wells serving thousands of people throughout the region have nitrate levels exceeding the drinking water standard (Harter et al. 2012, RWQCB Central Coast Region 2012). The nutrients in agricultural runoff significantly impact downstream estuaries, and eutrophication decreases salt marsh resilience through proliferation of algal mats (Wasson et al. 2017). Low-lying coastal wastewater treatment plants are threatened by flooding and sea-level rise (Langridge et al. 2018). There are also shallow groundwater contamination issues at orphaned contaminated industrial sites (California Dept. of Toxic Substances Control 2021). Lastly, several aquifers in the region have mineral impairments from their soils (e.g., chromium-6 or brackish water), which limits their utility; in some cases these can be treated (e.g., iron and manganese), but these impairments may make other aquifers unusable (California Dept. of Resources 2003).

There are several social dimensions of water vulnerability. Older infrastructure that constrains system operability (Langridge et al. 2018). Regional collaboration may support conjunctive groundwater management, such as in Paso Robles, which formed a cooperative GSA across several jurisdictions (Montgomery & Associates 2020). Ensuring adequate supply and water quality for all users may benefit from additional groundwater monitoring and management (Salinas Valley Basin GSA 2020).

Water quantity and water quality issues are spelled out in more detail in Table A2.2, grouping them by groundwater basin because communities in this region rely extensively on groundwater.

More extreme droughts and higher temperatures projected under climate change will alter the natural recharge of groundwater and potentially exacerbate groundwater overdraft (Langridge 2018). Importantly, reduced groundwater storage may limit the use of groundwater as a backup supply during drought (Langridge and Van Schmidt 2020). Fewer but more severe rainfall events are also projected (Swain et al. 2018) that will result in intense run-off that may overwhelm sewer and treatment facilities and potentially negatively affect stream and coastal water quality. Potential impacts to Central Coast water resources from these projected climate changes include (Langridge et al. 2018):

- Agricultural water use and domestic landscaping water demand are likely to increase
- Groundwater extraction may increase exacerbating the rate of seawater intrusion
- Lower seasonal surface flows will affect nitrate inputs, soil processes, and agricultural productivity
- Changes in rainfall patterns will affect the release of surface water from reservoirs

Table A2.2. Summary by Central Coast groundwater basin(s) of current water conditions including average well yield, total dissolved solids (TDS), and water quantity and quality issues. Data are compiled from California Dept. of Resources (2003). Salinas Valley (SV) is reported at the subbasin level due to its size. "Critically overdrafted" basins are those listed by the California Dept. of Water Resources, which excludes adjudicated basins ([A]); basins described only as "overdrafted" have declining groundwater levels, but do not yet have substantial adverse impacts from this. Basins with little development often had no data (ND).

Basin(s)	Yield	TDS	Water quantity issues	Water quality issues
County of Santa Cruz				
N. Coastal Aquifers (3 Basins)	179	ND	None known (agricultural development, but little data)	None known
West Santa Cruz Terrace	200	480	Highly variable and unreliable aquifers	Seawater intrusion near coast
Santa Margarita	244	360	Overdrafted but decline is slowing	TDS, iron, manganese
Santa Cruz Mid-County	665	482	Critically overdrafted; some confined aquifers have partially recovered	Seawater intrusion, iron, manganese, chromium-6, arsenic
Corralitos	500	580 – 910	Critically overdrafted	Nitrate
County of Monterey				
Carmel Valley	600	260 – 670	Overdrafted; mandated 60% cuts to protect threatened species' habitat	Iron & manganese; septic tank nitrates but levels appear safe
SV Seaside Area[A]	1,000	200 – 900	Overdrafted; mandated 60% cuts to protect threatened species' habitat	Seawater intrusion, hydrogen sulfide, iron
SV Monterey Area	450	355 – 679	None known (developed-little data)	High water hardness
SV 180/400 Foot Aquifer	ND	478	Critically overdrafted	Seawater intrusion, nitrate
SV East Side Aquifer	ND	450	Overdrafted; water table is depressed	Nitrate
SV Langley Area	450	ND	Stable	Nitrate

SV Forebay Aquifer	ND	624	Slightly overdrafted	Nitrate; Deep Aquifer may be unusable due to sodium
SV Upper Valley Aquifer	ND	443	Stable	Nitrate, sulfate, boron, TDS; east side conductivity issues
Peach Tree, Lockwood, and Cholame Valleys	84 - 1,000	ND	None known (relatively undeveloped, little data)	None known
County of San Luis Obispo				
SV Paso Robles Area	ND	614	Critically overdrafted (recent – due to growth in vineyards)	TDS, nitrate, on occasion; scattered patches of hydrogen sulfide
SV Atascadero Area	ND	ND	Stable (Rinconada fault restricts flow from overdrafted Paso Robles)	TDS, chloride
Los Osos Valley	230	354	Critically overdrafted (Los Osos Area)	Seawater intrusion
San Luis Obispo Valley	300	768	Overdrafted in Edna Valley, stable in San Luis Valley; subsidence	TDS, nitrate, chloride
Santa Maria River Valley[A]	1,000	598	Overdrafted; withdrawals set by adjudication, except for fringe	Notably high nitrates; TDS, sulfate & chloride in some areas
Carrizo Plain	500	161 - 94,750	None known (relatively undeveloped, little data)	Water in Morales Formation is too brackish to use; very mineralized near Soda Lake
Coastal Streams (10 basins)	0 – 400	413 - 1,150	Little data-evidence of seawater intrusion suggests potential overdraft	Chloride levels in basins may indicate seawater intrusion
Southern Interior Valleys (5 basins)	0 – 100	ND	None known (relatively undeveloped, little data)	None known

County of San Benito				
Gilroy-Holister Valley (North San Benito)	400	ND	Overdrafted until 1976; water table rose when reservoirs & imports began- still depressed in areas	Salinity, nitrate, boron, and trace elements occasionally exceeds drinking water standards
Santa Ana, Upper Santa Ana, and Quien Sabe Valleys	122	ND	None known (relatively undeveloped, little data)	Naturally poor in the Santa Ana & Upper Santa Ana Valleys
San Benito River, Dry Lake, & Bitter Water Valleys	ND	ND	Dry Lake Valley aquifer is naturally dry; no other issues known (undeveloped, little data)	None known
Hernandez Valley	58	ND	Groundwater not usable (Hernandez Reservoir occupies most of basin)	None known
County of Santa Barbara				
Cuyama Valley	1,100	858	Critically overdrafted; central area is fairly shallow	High salinity and nitrates due to evaporation of irrigation in basin
San Antonio Creek Valley	400	415	Overdrafted	TDS (mainly in west); seawater intrusion prevented by bedrock
Santa Ynez River Valley	750	507	Water levels declining in some areas – stable in others	Nitrate; some evidence of seawater intrusion near ocean
Goleta[A]	500	755	Overdrafted; declining again after recovering from lows in 1990s	Seawater intrusion prevented by bedrock
Foothill	ND	828	Overdrafted	Nitrate, sulfate
Santa Barbara	560	ND	Stable; historical overdraft remedied with water imports	Seawater intrusion at southern end
Montecito	750	700	Overdrafted	Offshore fault prevents seawater intrusion; chloride, iron, manganese
Carpinteria	300	557	Stable; historical overdraft remedied with water imports	Elevated nitrates in west

For those counties that receive imported water, SWP deliveries are projected to decrease by 5.6% due to climate change and environmental concerns in the delta, unless major improvements to delta infrastructure are pursued (Kerckhoff et al. 2013). Moreover, reduced imported water and declining spring and summer streamflows may shift reliance to already overdrafted groundwater resources (Hayhoe et al. 2004, Langridge et al. 2016). Land-use change to more water-intensive development may pose additional stress on already overdrafted water supplies (Van Schmidt et al. 2022), and agricultural expansion could also worsen preexisting nitrate pollution problems.

The Central Coast is projected to become slightly wetter, especially northward, but individual precipitation events will be more variable and concentrated, making it harder to capture the increased runoff during winter storms (Langridge 2018). Crucially, the projected increased precipitation variability may lead to significantly worse droughts. Table A2.3 summarizes changes in three hydrologic variables during historic and projected droughts using the Basin Characterization Model (v8; Flint and Flint 2014), a regional water balance model that combines projected temperature and precipitation with data on topography, soils, and historical hydrology to calculate *recharge* to groundwater aquifers and *runoff* to surface waters (per 270 m^2 area of land). To calculate future droughts under climate change, we took each projection from Flint and Flint (2014) and calculated a running annual 5-year mean for each variable. We entered this value into an overall average "projected drought" if it was equal to or less than the average for that variable during the 2012–2016 drought (Table A2.3). In both the high-emissions RCP 8.5 scenario and the moderate-emissions RCP 4.5 scenario (Van Vuuren et al. 2011), a significantly worse drought is projected to occur by the end of the century, with less than half of the previous drought's precipitation. Projections predicted no recharge or runoff in three counties. Surprisingly, the moderate RCP4.5 scenario of emission stabilization (Van Vuuren et al. 2011) predicted the worst drought.

Finally, while the Central Coast relies primarily on groundwater as a water source, several areas do receive imported water from the SWP. Under end-of-century RCP 8.5 warming (Van Vuuren et al. 2011), projections show that in a wet year like 2016–2017 it will lose two-thirds of its snow, while in a drought period like 2011–2016, the Sierra Nevada will lose 85% of its snow (Reich et al. 2018).

In line with these projections, the DWR predicts that SWP deliveries will decrease by 5.6% due to climate change and delta environmental concerns, depending on adaptation strategies (Kerckhoff et al. 2013). Additionally, SWP water will likely cost more in the future (Harou et al. 2010, Tanaka et al. 2015).

Table A2.3. Impacts of historic and two climate change scenarios on drought water supplies, the Representative Concentration Pathway (RCP) 4.5 (moderate greenhouse gas emissions) and 8.5 (high greenhouse gas emissions; Van Vuuren et al. 2011). Values (mm) are for the severe historic 2012–2016 drought compared to the most severe droughts calculated as the mean five-year running minimums averaged across 11 Global Climate Models assessed by the Basin Characterization Model v8 (Flint et al. 2021).

	Historic 2012–2016			**RCP 8.5**			**RCP 4.5**		
County	**Precip.**	**Runoff**	**Recharge**	**Precip.**	**Runoff**	**Recharge**	**Precip.**	**Runoff**	**Recharge**
Santa Cruz	688.9	67.2	119.2	324.2	51.9	88.8	383.2	52.2	85.7
Monterey	351.4	15.7	47.9	131.9	12.3	24.7	199.9	9.9	25.1
San Benito	264.3	2.6	2.6	74.8	0.0	0.0	101.5	0.0	0.0
San Luis Obispo	259.1	2.3	4.4	72.5	0.0	0.0	99.1	0.0	0.0
Santa Barbara	273.9	3.1	2.6	74.2	0.0	0.0	103.8	0.0	0.0

A2.3 Agricultural sensitivities

Agriculture is a major industry in the region, with high on-farm employment. It is facilitated by the combination of flat land, well-textured alluvial soils, groundwater irrigation technology, long rain-free periods, and the air-conditioning effect of coastal fog. A large variety of crops are grown, with truck nursery, berry, and vineyard crops dominating (Tourte et al. 2016). Viticulture is present in several areas and continues to grow today, particularly in the Paso Robles area. The fresh market berry industry in Santa Cruz and Monterey counties has seen dramatic growth in strawberry (the dominant berry crop), raspberry, and blackberry production over the last 50 years, and most notably since the 1980s (Tourte et al. 2016).

Agricultural production is highly sensitive to climate change including changes in temperatures, precipitation patterns, and increased frequency and intensity of climate extremes. Alterations in the amount, form, and distribution of precipitation along with more extreme droughts will decrease water availability and potentially reduce crop areas and yields (Tanaka et al. 2015). This will influence crop selection and acreage allocation decisions, technology adoption, water demand, and the diversity of crops planted, potentially reducing agricultural biodiversity as well as future food security (Bertone Oehninger et al. 2016).

Recent research on the temperature sensitivity of California specialty crops to future climate projections shows high sensitivity to changing temperature in the Central Coast (Kerr et al. 2018). Specifically, wine grapes, strawberries, and lettuce—dominant crops in the Central Coast—had higher relative magnitude of negative impacts from increased temperatures of the top 14 value-ranked specialty crops in the state (Kerr et al. 2018). Yield declines have also been predicted with warmer winters and hotter summers (Lobell and Field 2011). Plant diseases, insects and invasive weeds are also affected by temperature related climate factors (Pathak et al. 2018).

Perennial crops such as orchards and vineyards are among the most profitable, but may be more sensitive to climate change. They require several years to reach maturity and profitable production, cannot be fallowed and are therefore more vulnerable to droughts, and can be negatively impacted by relatively small temperature changes during critical development stages and near harvest (Pathak et al. 2018). Threshold temperature impacts can affect wine grape quality. For example, the yields for wine grapes and strawberries may be reduced due to warm winters. Given the 20–30 year lifespan of most specialty perennial crops, their resilience to a changing climate and shifting water availability is limited (Lobell and Field 2011). However, agricultural intensification also has many benefits. It often leads to 1) a higher investment and return per acre, 2) the creation of more jobs and demand for related support industry and housing, 3) the creation of more land-use conflicts at the agriculture/urban interface, 4) technological innovation, and 5) improvements in irrigation efficiency (County of San Luis Obispo 2010).

The degree to which long-term droughts or climate change will impact farmers may depend on several factors (Howden et al. 2007, Massawe et al. 2016, Kerr et al. 2018, Peterson et al. 2020):

- Location (e.g., distance to coast, soils; Kerr et al. 2018);
- Types and diversity of crops and other activities (Kerr et al. 2018, Peterson et al. 2020);
- Current farming practices (e.g., soil and water conservation, organic/conventional farming; Howden et al. 2007);
- Access to water resources and existing stresses on water resources (e.g., groundwater overdraft; Langridge et al. 2018);
- Financial resources to invest in technologies and dependence on income solely from farming vs. several income sources (Howden et al. 2007);
- Access to flood and drought insurance and use of climate-related information for planning (Howden et al. 2007);
- Market, policy-related, or legal constraints on farming and participation in farming cooperatives (Howden et al. 2007);

Longer-term adaptation options to shift varieties or locations of production can require significant time and capital investment. In general, smaller farmers with fewer financial, technological, and water resources, fewer (or less flexible) response options, limited crop diversity, fewer risk sharing opportunities, and greater dependence on farm income tend to be more vulnerable to climate change (Howden et al. 2007, Massawe et al. 2016, Kerr et al. 2018, Peterson et al. 2020).

A2.4 Domestic sensitivities

The characteristics of county populations influence the vulnerability of local communities to water shortages under future climate and land-use change. Extreme weather events (such as drought) and increases in peak temperatures both stress water supplies and can threaten public health. Different population segments can experience greater vulnerability to the threat of water shortages under changing climate and land-use shifts.

Water shortages and increased temperatures under climate change may increase mortality and morbidity, especially for those most vulnerable (Moser and Ekstrom 2012). Segments of population that will be the most at risk include those who are elderly, infants, have chronic heart disease, lung disease, or mental disabilities, are socially or economically disadvantaged, and those that work outdoors (California Natural Resources Agency 2009). The implications of demographics for the vulnerability of particular populations, and their ability to adapt to water shortages include:

Elderly populations are most at risk for health-related adverse impacts from heat waves that are projected to increase under climate change, particularly in developed regions (Haines et al. 2006).

Lower income and poverty level often correlate with lower access to necessary resources to prepare for, or to invest in actions required to adapt to water shortages under climate and land-use changes (Morrow 1999). Income is one of the most important indicators of lower adaptive capacity. The differential incomes and the level of poverty in some cities indicate that particular populations are likely to experience such increased vulnerabilities. During past droughts those on low or fixed incomes have struggled with the rising cost of water (Cooley et al. 2016). On the Central Coast, there is a large divide between communities with more affluent populations and low income communities. The highest concentration of low income and poverty is found in inland urban centers, and low-wage farm labor in the more rural inland towns. The price of water is projected to increase four-fold over the coming century, and 68 regional census tracts have been identified as having median incomes that would be unable to afford these rate increases (Mack and Wrase 2017).

Minority populations, notably Hispanic migrant workers, tend to have lower capacity for responding to disasters and adapting to climate change than non-Hispanic whites (Morrow 1999). Where individuals are not fluent in English, it may be difficult to access or receive important information for preparing for and responding to weather- and climate-related emergencies.

Lower educational attainment correlates with lower adaptive capacity to deal with extreme events such as drought or water supply shortages (Striessnig et al. 2013). The possible connection between education and the ability to deal with disasters and change may also involve a lack of insurance and lower capacity to obtain emergency preparedness and response information (Hoffmann and Muttarak 2017).

A2.5 Ecosystem sensitivities

Climate change may push some species (particularly herpetofauna and plants) beyond their eco-physiological limits, causing extirpations or extinctions. However, high elevations within mountain ranges and coastal fog belts may provide climate refugia for herpetofauna if these areas are protected (Sinervo 2018). Extensive natural areas dominate outside of the agricultural valleys and coastal cities, but land-use change models project significant expansions of agricultural and urban areas (Van Schmidt et al. 2022). These developments threaten species via habitat loss, and imperil the corridors necessary for herpetofauna species to disperse to climate refugia (Sinervo 2018).

Development will also make preserving aquifers even more challenging, especially when coupled with warmer temperatures and increased variability in precipitation under climate change, posing a synergistic threat to GDEs. Overexploitation of groundwater can have severe consequences including the drying of GDEs and elimination of fish and wildlife populations that depend on them (Kløve et al. 2011). The extent to which freshwater ecosystems depend on groundwater versus surface water will vary locally, and local knowledge about the water sources of habitats may improve decision making. In this section we focus on species of conservation concern as indicators for overall ecosystem health, and assess their water availability needs. However, water quality also directly affects the functioning of healthy ecosystems.

We obtained range ata from the California Freshwater Species Database, a comprehensive collection of hundreds of different sources of data on species' distributions that was compiled collaboratively by NGOs, government agencies, and academics (Howard et al. 2015). We then trimmed this dataset to the Central Coast five-county region. We removed from these lists any species which were only found on the very fringes of the region or counties, and two plant species (*Eryngium aristulatum* var. *parishii* and *Navarretia fossalis*) and one bird (*Laterallus jamaicensis coturniculus*) that do not generally occur within the Central Coast based on contemporary critical habitat definitions and range maps (Bauder et al. 1998, Richmond et al. 2008)Richmond et al. 2008). In total there are 980 known species and subspecies that are dependent on freshwater habitats within the Central Coast region. Of these species, 26 (3%) are listed are as endangered or threatened under the U.S. or California Endangered Species Acts, and an additional 117 (12%) have been identified as warranting special conservation concern (Howard et al. 2015). We reviewed species accounts and conservation plans from the U.S. Fish and Wildlife Services, California Dept. of Fish and Wildlife, and Riparian Habitat Joint Venture Riparian Bird Conservation Plan (Riparian Habitat Joint Venture & California Partners in Flight, 2004) for all of the freshwater-dependent species that were federally- or state-listed as threatened and identified whether they were imperiled either by groundwater overdraft lowering water tables, reduced surface water inflows (i.e., drought), both, or neither.

We report the results of the review for those species below. The main threats for species identified as being most at risk in each county from the synergistic impacts of land-use change and climate change on water resources are summarized below and in Table A2.4. Species and subspecies with smaller local ranges are at more risk of regional extinction, as small disturbances to their existing ranges may remove the populations altogether (Stacey and Taper 1992). Species with wide ranges that cross multiple jurisdictional boundaries may benefit from coordinated management (Miller et al. 2019).

The Willow Flycatcher (*Empidonax traillii*) is an insectivorous bird that is state-listed as threatened and lives in woody vegetation along streams throughout the Central Coast (Craig and Williams 1998). The Southwestern Willow Flycatcher (*Empidonax traillii extimus*) subspecies is federally listed and found within the Central Coast only along the Santa Ynez River (U.S. Fish and Wildlife Service 2018). The Least Bell's Vireo (*Vireo bellii pusillus*) is an ecologically similar endangered species (Kus 2002). These species help maintain healthy riparian forests by controlling insect populations, but have declined due to habitat loss from groundwater pumping, overgrazing, and impounding of stream areas. Nest parasitism by Brown-headed Cowbird (*Molothrus ater*), which have expanded into these fragmented habitats and replace the species' eggs with their own, has exacerbated their declines (Kus 2002, U.S. Fish and Wildlife Service 2018).

Table A2.4. Federally- and state-listed threatened freshwater-dependent species of the Central Coast. Each was classified based on the literature reviewed as threatened by groundwater (G), surface water (S), both (GS), or neither (N). Listing is hierarchical: endangered (E-) > threatened (T-); federally listed (-F) > state listed (-S). SCr=Santa Cruz, SBe=San Benito, Mon=Monterey, SLO=San Luis Obispo, SBa=Santa Barbara. Salmonids are listed by ESU designation. Range and listing information from Howard et al. (2015); the citations used to determine threat categorization for each species are provided in the text of Appendix A2.5.

Common name (*Scientific name*)	Threat	Top listing	Local range (km^2)	Found within county?				
				SCr	SBe	Mon	SLO	SBa
Southwestern Willow Flycatcher (*Empidonax traillii extimus)*	GS	E-F	259					X
Least Bell's Vireo (*Vireo bellii pusillus)*	GS	E-F	2716		X	X	X	X
Willow Flycatcher (*Empidonax traillii)*	GS	E-S	282				X	X
Bald Eagle (*Haliaeetus leucocephalus)*	N	E-S	10206	X	X	X	X	X
Bank Swallow (*Riparia riparia)*	N	T-S	3466	X	X	X	X	X
Santa Cruz Long-toed Salamander (*Ambystoma macrodactylum croceum)*	GS	E-F	444	X	X	X		
Arroyo Toad (*Anaxyrus californicus)*	GS	E-F	8653			X	X	X
California Tiger Salamander (*Ambystoma californiense californiense)*	S	T-F	24419	X	X	X	X	X
California Red-legged Frog (*Rana draytonii)*	GS	T-F	32010	X	X	X	X	X
Tidewater Goby (*Eucyclogobius newberryi)*	GS	E-F	4357	X		X	X	X
Unarmored Threespine Stickleback (*Gasterosteus aculeatus williamsoni)*	GS	E-F	279					X
Central Coast Coho Salmon (*Oncorhynchus kisutch* – CCC ESU)	GS	E-F	1401	X		X		
Southern California Steelhead (*Oncorhynchus mykiss* – SC ESU)	GS	E-F	6012				X	X
Central California Coast Winter Steelhead (*Oncorhynchus mykiss* – CCCW ESU)	GS	T-F	1205	X				
South Central California Coast Steelhead (*Oncorhynchus mykiss* – SCCC ESU)	GS	T-F	18107	X	X	X	X	X
Longfin smelt (*Spirinchus thaleichthys)*	GS	T-S	59			X		
Longhorn Fairy Shrimp (*Branchinecta longiantenna)*	S	E-F	427				X	
Vernal Pool Fairy Shrimp (*Branchinecta lynchi)*	S	T-F	5598		X	X	X	X
Marsh Sandwort (*Arenaria paludicola)*	G	E-F	446	X			X	
Salt Marsh Bird's-beak (*Chloropyron maritimum* var. *maritimum)*	G	E-F	265				X	X
Chorro Creek Bog Thistle (*Cirsium fontinale* var. *obispoense)*	G	E-F	639				X	X
La Graciosa Thistle (*Cirsium scariosum* var. *loncholepis)*	GS	E-F	733				X	X
Contra Costa Goldfields (*Lasthenia conjugens)*	S	E-F	473			X		X
Gambel's Yellowcress (*Nasturtium gambelii)*	G	E-F	150				X	X
California Sea-blite (*Suaeda californica)*	N	E-F	669			X	X	

Amphibians that live in upland habitats often rely on freshwater habitats for breeding, and species are threatened by both development and drought. Santa Cruz Long-toed Salamander (*Ambystoma macrodactylum croceum*) breeds in just 19 ephemeral freshwater ponds around the Santa Cruz-Monterey county border, and are threatened by development in this area (U.S. Fish and Wildlife Service 2009a). Water stress is also a significant threat, and ponds may dry prematurely during drought years, causing the death of all juveniles (California Dept. of Fish and Wildlife 2015). While populations can persist through single dry years, prolonged drought could extirpate them. Seawater intrusion into aquifers that feed these ponds can also negatively impact reproductive success (U.S. Fish and Wildlife Service 2009a). Arroyo Toad (*Anaxyrus californicus*) requires slow-moving streams with sandy terraces for breeding. It is threatened by habitat loss due to development, and human modifications of streams that affect non-flood and flood streamflow quantity and timing, water quality, or plant communities can all negatively impact the species. Small population sizes make it particularly susceptible to severe drought, which could cause extinction (U.S. Fish and Wildlife Service 2014). California Tiger Salamander (*Ambystoma californiense californiense*) depends on vernal pools and is threatened throughout its range, but the Santa Barbara population is distinct and endangered (Davidson 2017a). It has declined due to loss of vernal pools to development, negative impacts from small mammal burrow control, and invasive species. Extended droughts under climate change could dry the ponds enough to cause breeding failures (Davidson 2017a). California Red-legged Frogs (*Rana draytonii*) live in ponds and slow-moving streams throughout the region, and use uplands for sheltering over summer. They are threatened by habitat fragmentation due to urbanization, and non-native plants and predators (Davidson 2017b). Maintaining habitat for this species was a factor in mandated reductions in pumping and dam removal within the Carmel River Basin (Langridge et al. 2016).

Pacific salmonids (*Oncorhynchus* spp.) are listed as evolutionary significant units (ESUs), distinct population segments that are reproductively isolated and represent an important component of the species' evolutionary legacy (Waples 1995). Steelhead trout (*Oncorhynchus mykiss*) have three endangered ESUs within the Central Coast: the southern California, central California coast winter, and south central California coast (SCCC) steelhead. Steelhead are anadromous fish hatching in freshwater, spending most of their life in the ocean, then migrating back up rivers to spawn. Their most crucial need is to maintain stream connectivity, which requires minimum adequate streamflows and managing dams. They were a reason for state-mandated 60%reductions in pumping from the Carmel River Basin, and the determination of minimum water levels for MPWMD's Aquifer Storage and Recovery program that withdraws surplus water from this basin to inject into the Salinas Valley Seaside subbasin (Langridge et al. 2016). The Coho salmon (*Oncorhynchus kisutch*) Central Coast ESU, listed as endangered under ESA in the 1990s, continues to decline due to the loss of freshwater habitat from development and river regulation, overfishing, interaction with hatchery fish, and unfavorable climatic changes (Swales 2019). The Tidewater Goby (*Eucyclogobius newberryi*) is a small endangered fish endemic to lagoons and brackish estuaries along the coast, and the Unarmored Threespine Stickleback (*Gasterosteus aculeatus williamsoni*) lives in slow-moving, densely vegetated portions of San Antonio Creek within Vandenberg Air Force Base (U.S. Fish and Wildlife Service 2005, 2009b). Both species had populations extirpated from other rivers due to dewatering streams from water diversions, groundwater overdraft, and drought. Dewatering of streams and seawater intrusion into aquifers has also raised salinity in lagoons, imperiling the Tidewater Goby (U.S. Fish and Wildlife Service 2005). Catastrophic die-offs of Threespine Sticklebacks during drought have been observed; persistence depends on the upper reaches of streams that are at risk of drying under climate change (U.S. Fish and Wildlife Service 2009b).

There are two endangered invertebrates that live within vernal pools in the Central Coast: Longhorn Fairy Shrimp (*Branchinecta longiantenna*) and Vernal Pool Fairy Shrimp (*Branchinecta lynchi*). Urban and agricultural development eliminating vernal pools are the greatest threat to these species (U.S. Fish and Wildlife Service 2007a, 2012). Longhorn Fairy Shrimp have a restricted range and are found in only 20 pools around Carrizo Plain National Monument, with 8 of these on unprotected private lands. They can lay dormant to persist through dry years, but prolonged droughts under climate change could extirpate populations (U.S. Fish and Wildlife Service 2012). Vernal Pool Fairy Shrimp are more widely distributed but require cool-water pools, and will die off not only during low-precipitation years but also if water temperatures exceed 75ºF. Thus, they are also vulnerable to the warmer winters projected under climate change, and maintaining connectivity will be important for enabling this species to adapt to climate change by dispersing to cooler pools (U.S. Fish and Wildlife Service 2007a). Because vernal pools in this region generally fill from winter precipitation and are underlain by impermeable clay, groundwater overdraft is unlikely to threaten these species.

Plant species frequently have very small ranges, narrow eco-physiological tolerances, and depend directly on accessing the water table within their range of rooting depths, leaving them particularly susceptible to the joint threats of development, climate change, and groundwater overdraft. Chorro Creek Bog Thistle (*Cirsium fontinale* var. *obispoense*) only occurs in spring areas in serpentine soils that receive summer fog, and is endemic to 13 sites within San Luis Obispo County. It requires year-round wetness, and is threatened by groundwater pumping and upstream water diversions. High projected population growth within the area will increase water demands and may cause springs to dry (U.S. Fish and Wildlife Service 2007b). Marsh Sandwort (*Arenaria paludicola*) is a freshwater marsh plant that is naturally found only at Oso Flaco Lake in San Luis Obispo county, and is threatened by development, loss of groundwater, and invasive species (California Dept. of Fish and Wildlife 2013). La Graciosa Thistle (*Cirsium scariosum* var. *loncholepis*) is endemic to wetlands within the Callender Dunes and Guadalupe Dunes. Development was a major factor in its decline and it remains at only 5 of 21 historically inhabited sites. Seasonal fluctuations in water level are critical to this species because it depends on colonizing recently disturbed habitats near the edges of groundwater-dependent coastal dune wetlands. Groundwater overdraft in Santa Maria and Arroyo Grande are the biggest threat (U.S. Fish and Wildlife Service 2019). Gambel's Yellowcress (*Nasturtium gambelii*) is a perennial herb that is endemic to perennial freshwater wetlands on the coastward side of the mountains south of San Luis Obispo. It has declined due to habitat loss from development, nutrient water pollution causing excessive growth of competitors, and genetic hybridization with an introduced crop. The only two remaining genetically pure populations are on federally protected lands, but water tables within them are dropping due to groundwater overdraft and the marsh habitat is declining (U.S. Fish and Wildlife Service 2011).

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Appendix S3: Comprehensive specific vulnerability maps

Appendix for “Trade-offs of development strategies for adapting to coupled changes in climate, land-use, and water for social and ecological communities in California”

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A3.1 Description of appendix

This appendix contains comprehensive maps of all nine specific vulnerabilities (Main Text, Table 1) under all five scenarios (Main Text, Figure 2). It complements Main Text Figs. 3–5, which are not replicated here, to illustrate shifts in specific vulnerabilities under different management scenarios.

Data sources used as inputs to these maps included Van Schmidt et al. (2022) for land and water exposure, Flint and Flint (2014) for climate exposure, California Dept. of Conservation (2016) and Van Schmidt et al. (2022) for agricultural sensitivity, U.S. Census Bureau (2017) for domestic sensitivity, and Thorne et al. (2019) for ecological sensitivity. See Appendix S1 for full details of how data sources were reprocessed to produce these maps.

ACKNOWLEDGEMENTS

All exposure, sensitivity, and vulnerability maps are available as a data release in the U.S. Geological Survey’s ScienceBase catalog (Van Schmidt et al. 2023; https://doi.org/10.5066/P9XQVEL4). The LUCAS-W model is freely available from ScienceBase (Van Schmidt et al. 2021; https://doi.org/10.5066/P9209XW4); modeling was done using the ST-SIM software application which can be downloaded, free of charge, from APEX Resource Management Solutions (http://apexrms.com). The Basin Characterization Model projections are freely available from the USGS (Flint and Flint 2014; https://doi.org/10.5066/F76T0JPB). 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 (Grant #CCRP0023) and the U.S. Geological Survey’s Ecosystems Land Change Science Program. We thank Paul Selmants and Michelle Stern for additional assistance with exposure models.

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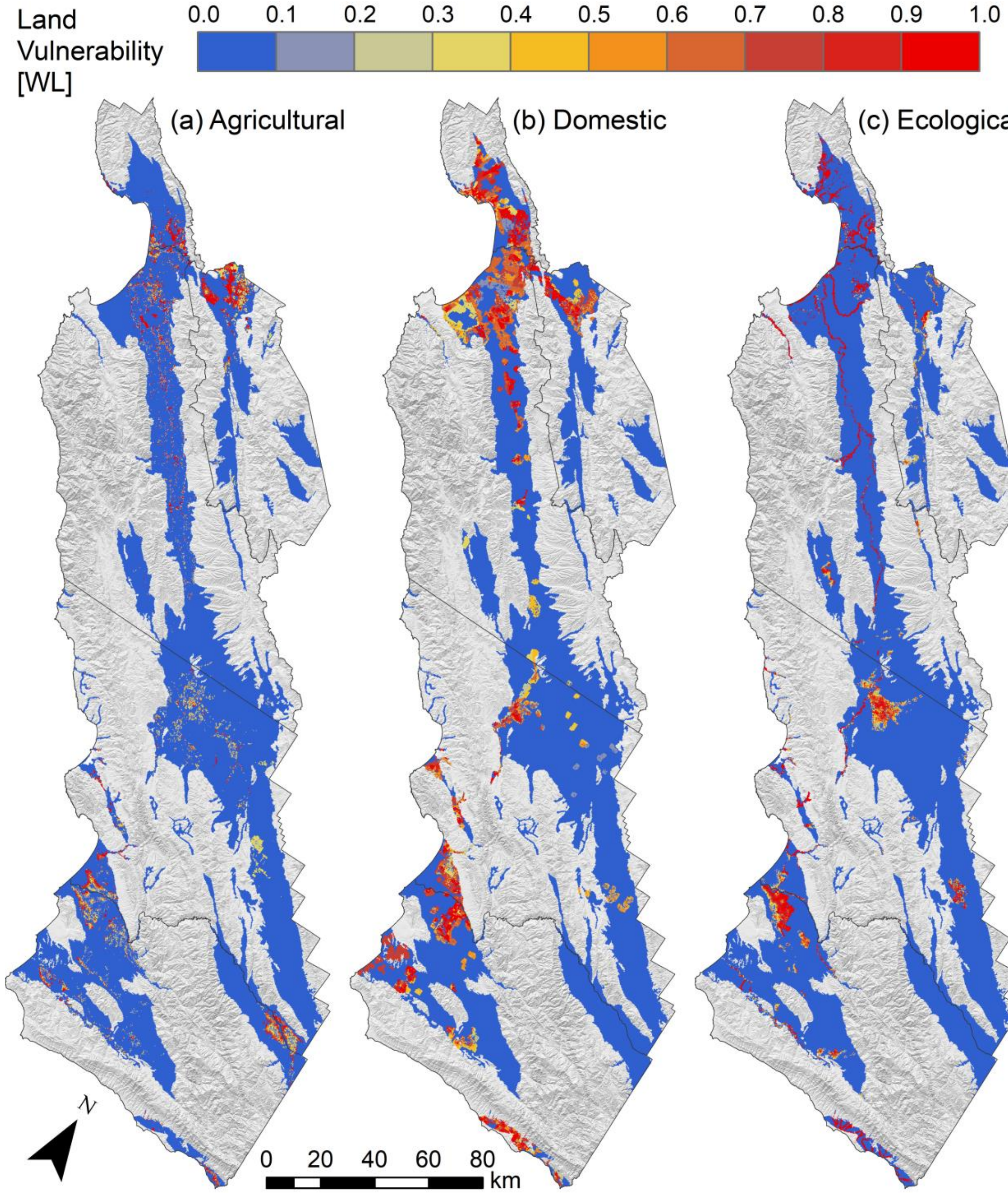

Figure A3.1. Spatial patterns of (a) loss of important farmland, (b) lack of new development in areas with housing needs, and (c) loss of critical habitats for endangered species under land-use projections to 2061 in California's Central Coast. The Water management Low intensity [WL] scenario (no water demand caps, urban sprawl limits) is shown.

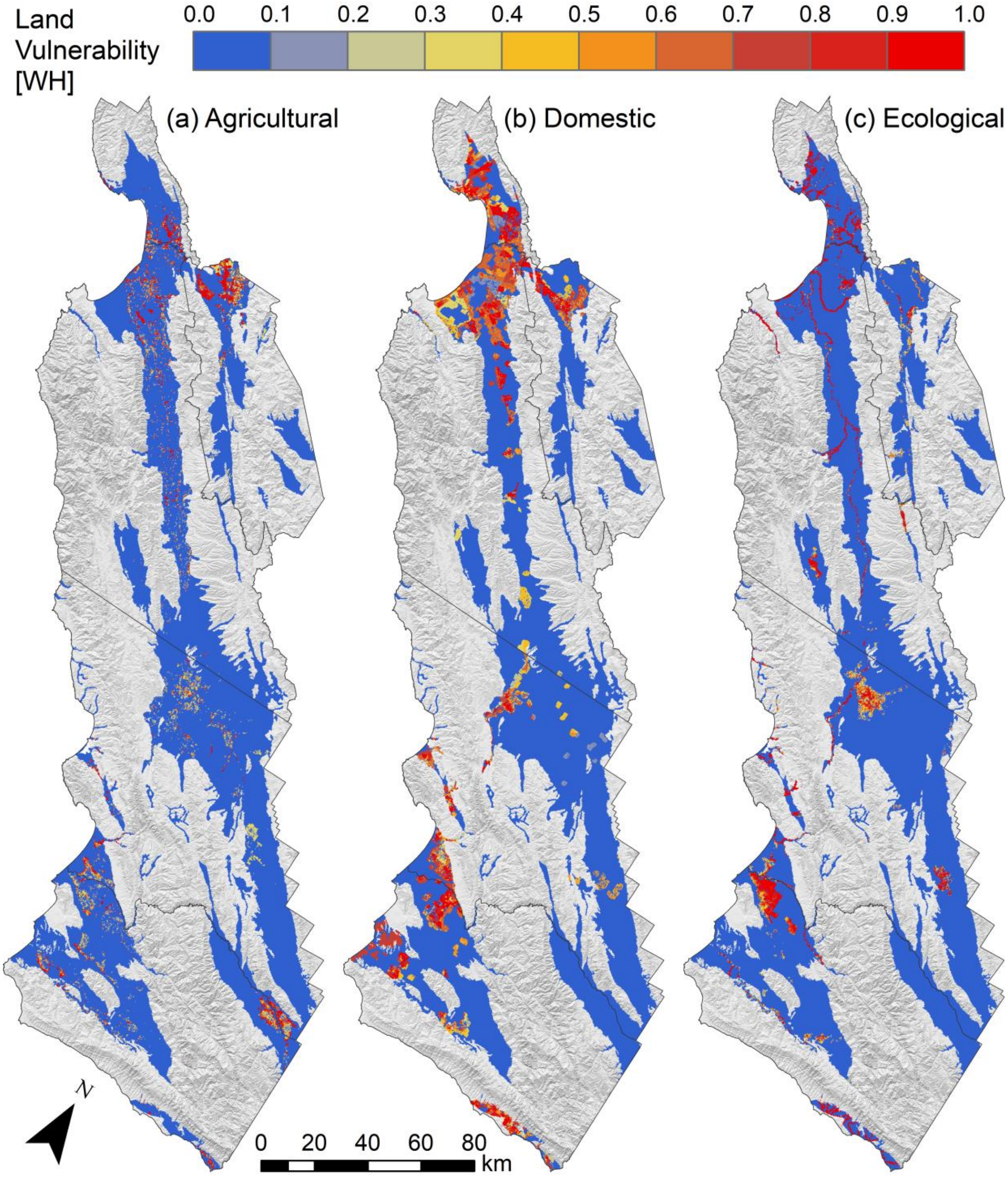

Figure A3.2. Spatial patterns of (a) loss of important farmland, (b) lack of new development in areas with housing needs, and (c) loss of critical habitats for endangered species under land-use projections to 2061 in California's Central Coast. The Water management High intensity [WH] scenario (water demand caps with enhanced supplies, urban sprawl limits) is shown.

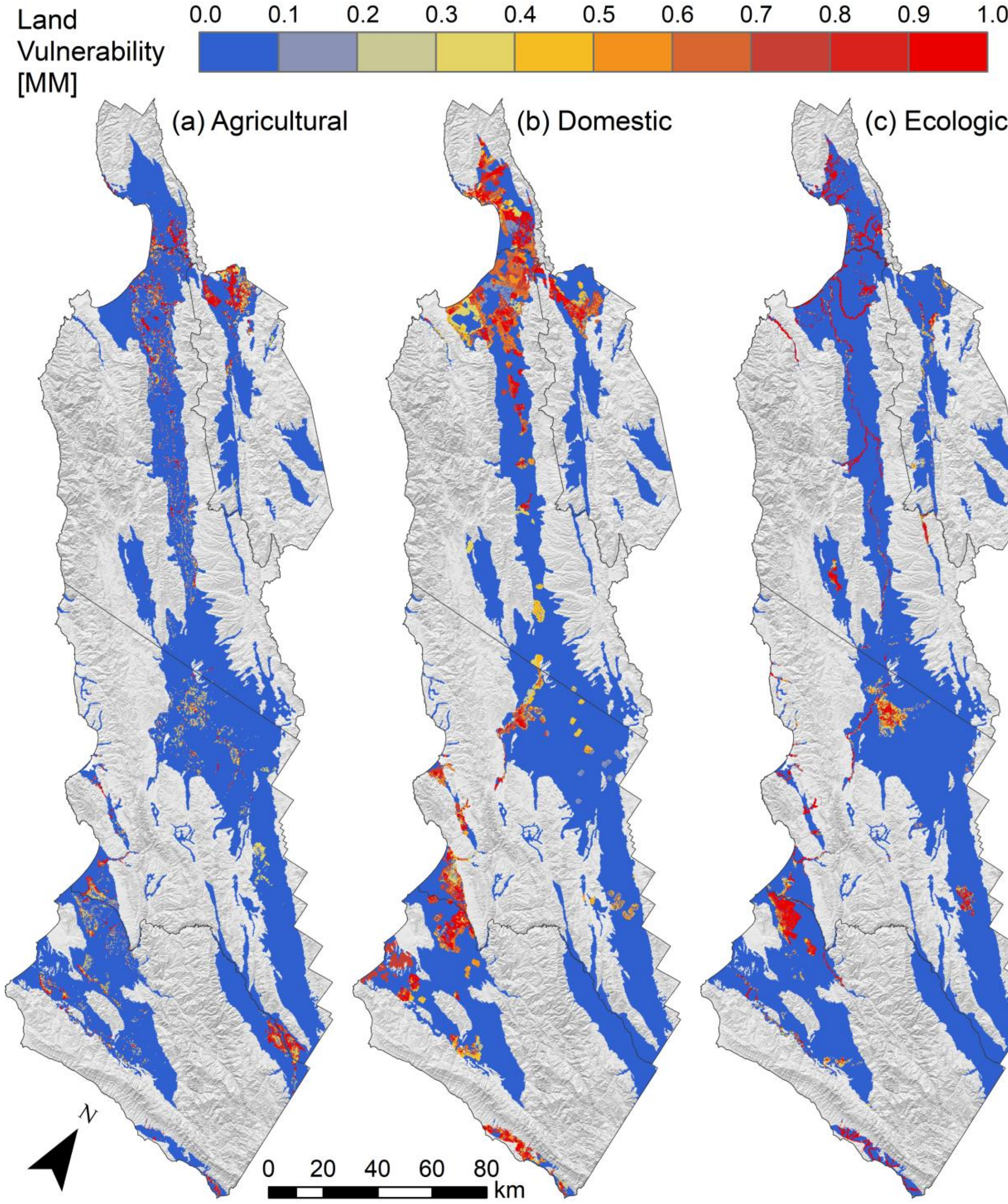

Figure A3.3. Spatial patterns of (a) loss of important farmland, (b) lack of new development in areas with housing needs, and (c) loss of critical habitats for endangered species under land-use projections to 2061 in California's Central Coast. The land management Medium intensity and water management Medium intensity [MM] scenario (water demand caps with current supplies, urban sprawl limits) is shown.

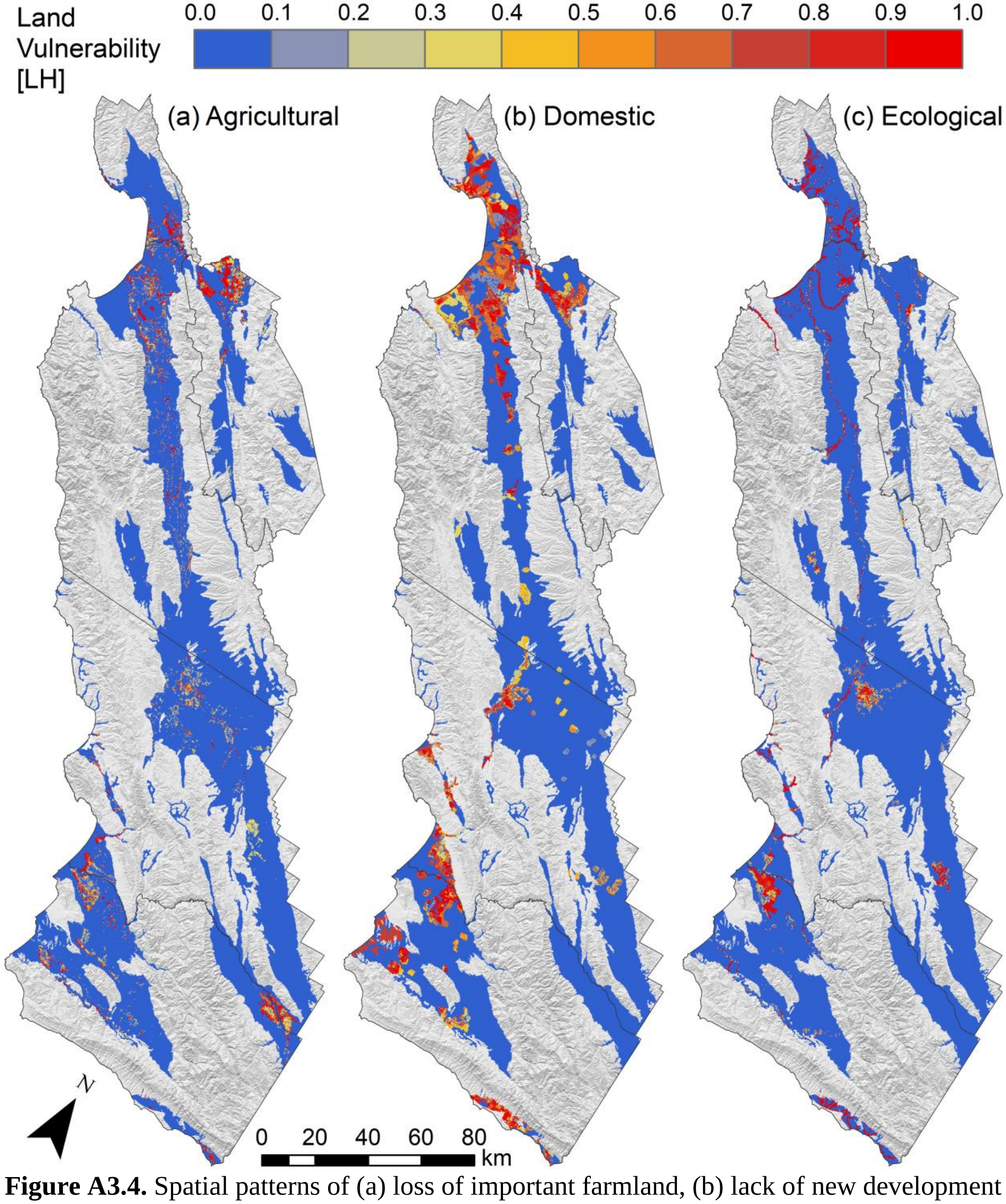

Figure A3.4. Spatial patterns of (a) loss of important farmland, (b) lack of new development in areas with housing needs, and (c) loss of critical habitats for endangered species under land-use projections to 2061 in California's Central Coast. The Land management High intensity [LH] scenario (water demand caps with current supplies, urban sprawl limits and new ecosystem preservation) is shown.

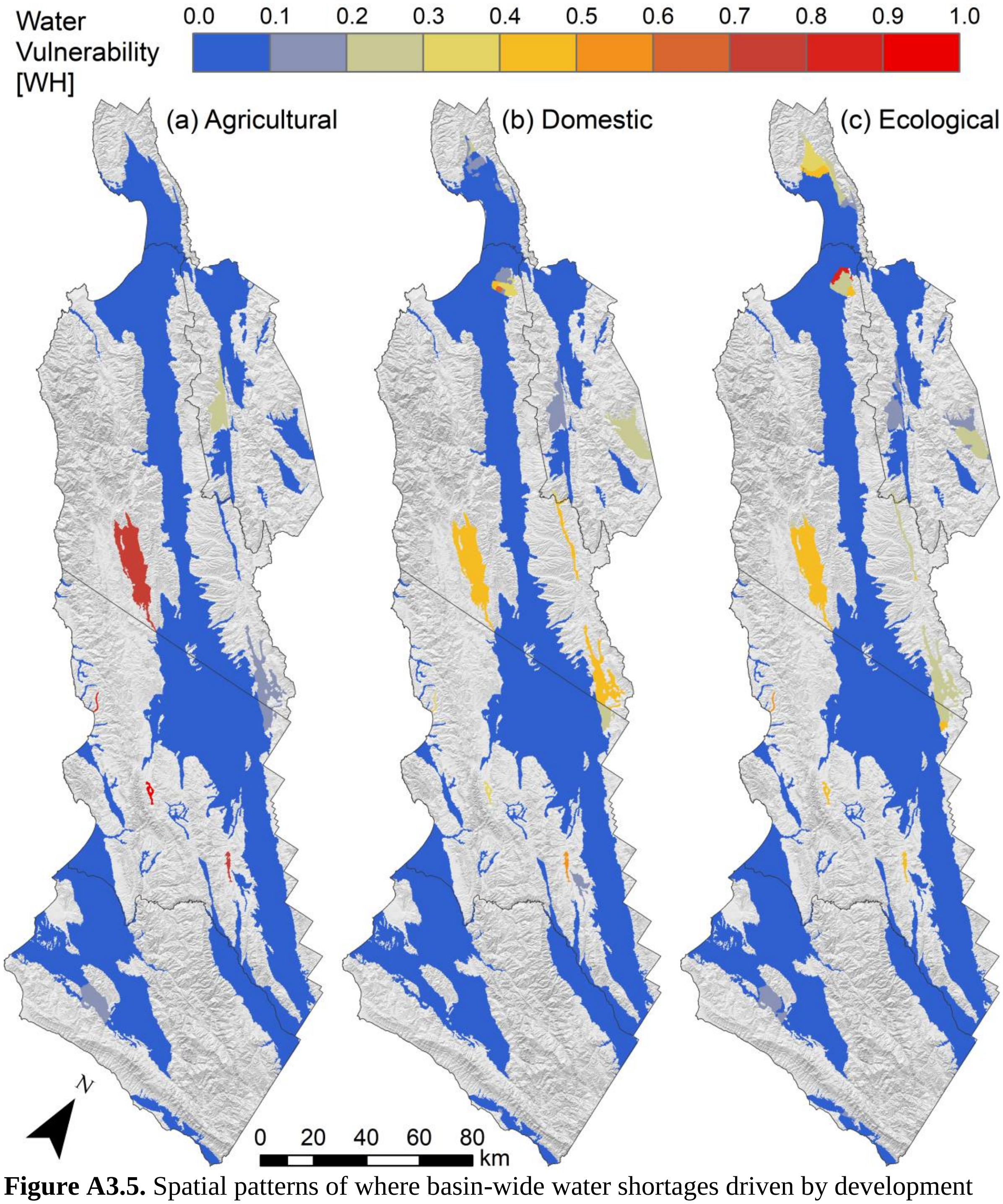

Figure A3.5. Spatial patterns of where basin-wide water shortages driven by development projections to 2061 overlap with (a) increased perennial demand for perennial agriculture that cannot be fallowed, (b) households vulnerable to increased water unaffordability, and (c) groundwater-dependent habitats for endangered species in California's Central Coast. The Water management High intensity [WH] scenario (water demand caps with enhanced supplies, urban sprawl limits) is shown.

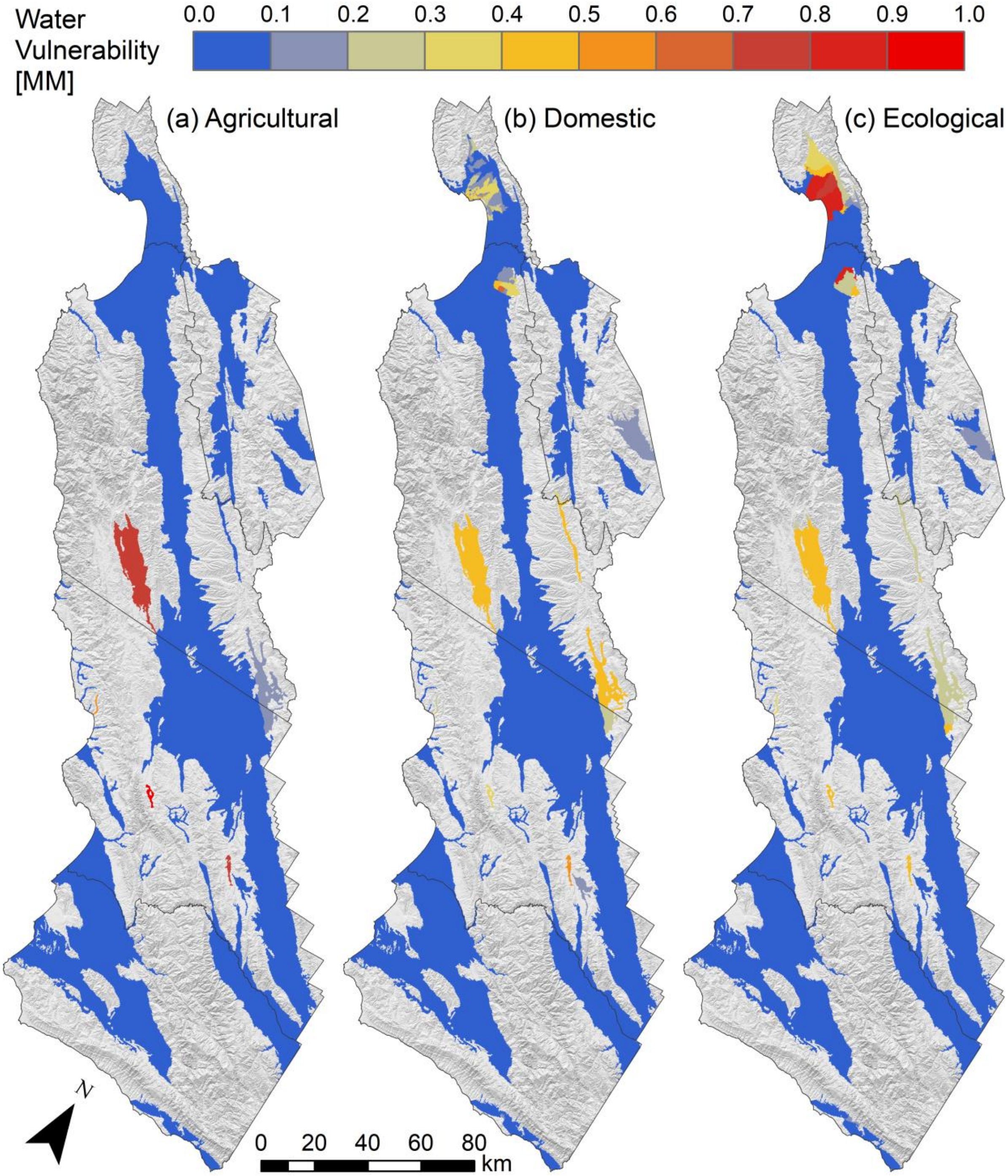

Figure A3.6. Spatial patterns of where basin-wide water shortages driven by development projections to 2061 overlap with (a) increased perennial demand for perennial agriculture that cannot be fallowed, (b) households vulnerable to increased water unaffordability, and (c) groundwater-dependent habitats for endangered species in California's Central Coast. The land management Medium intensity and water management Medium intensity [MM] scenario (water demand caps with current supplies, urban sprawl limits) is shown.

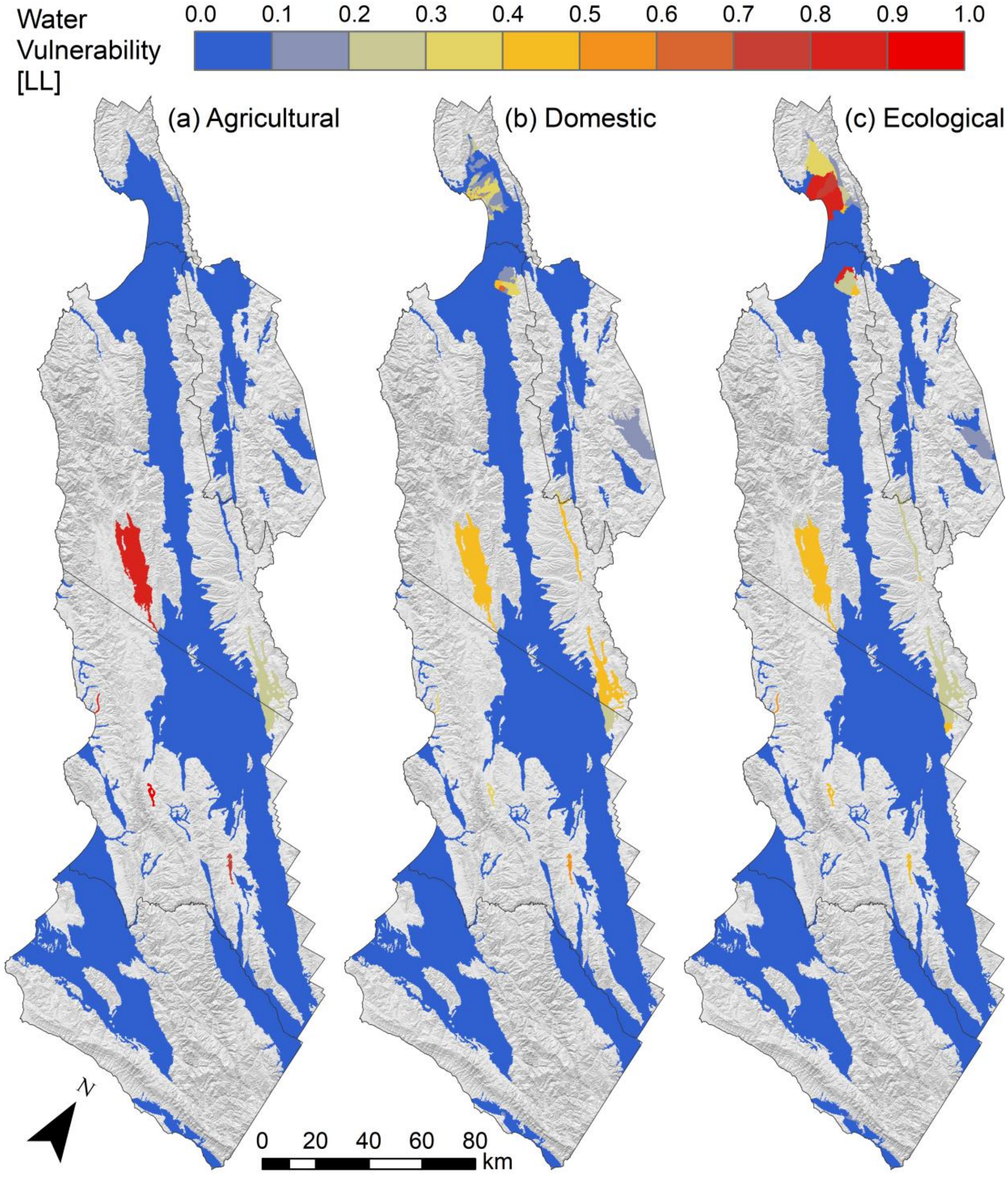

Figure A3.7. Spatial patterns of where basin-wide water shortages driven by development projections to 2061 overlap with (a) increased perennial demand for perennial agriculture that cannot be fallowed, (b) households vulnerable to increased water unaffordability, and (c) groundwater-dependent habitats for endangered species in California's Central Coast. The Land management Low intensity [LL] scenario (water demand caps with current supplies, no urban sprawl limits or new ecosystem preservation) is shown.

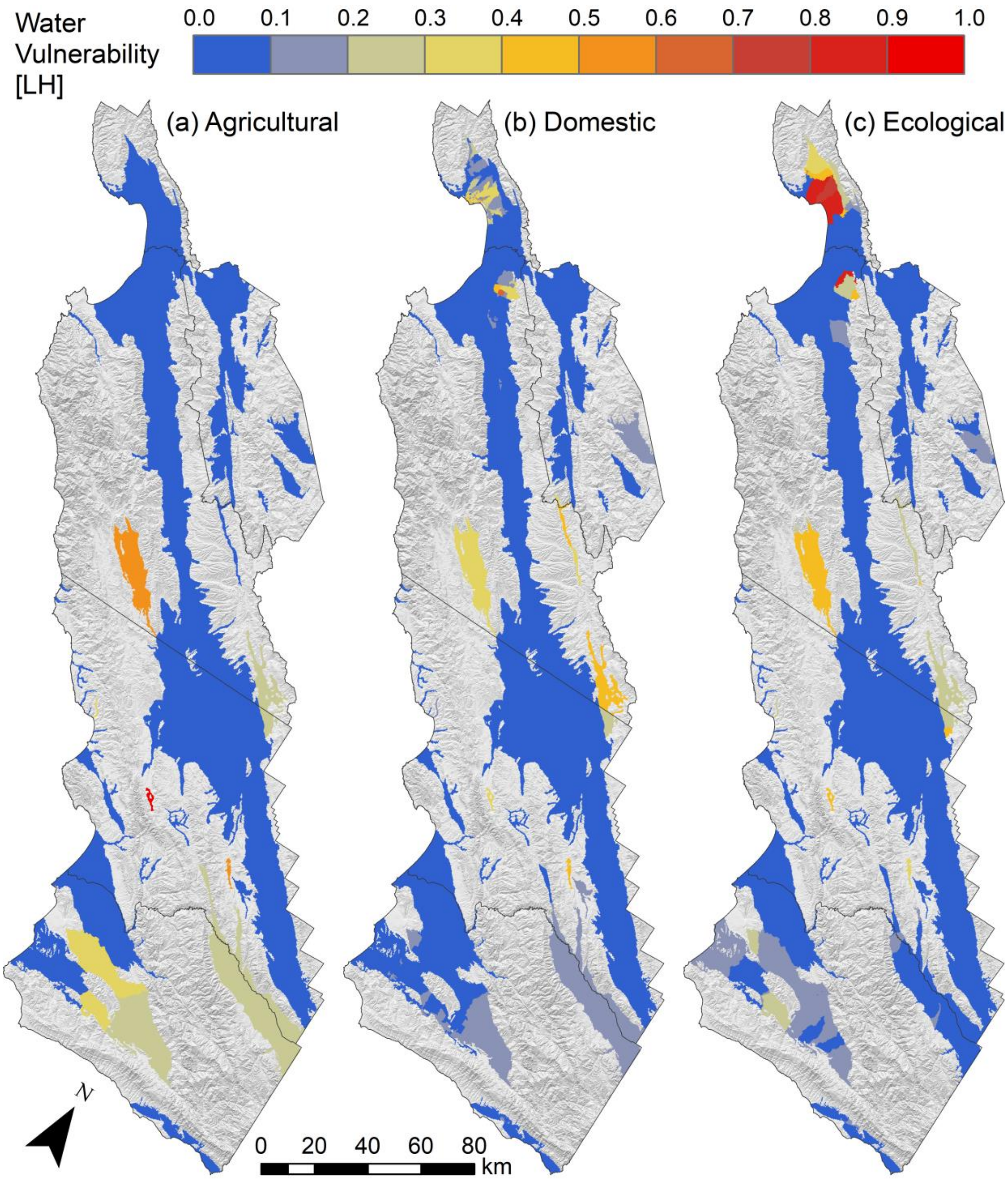

Figure A3.8. Spatial patterns of where basin-wide water shortages driven by development projections to 2061 overlap with (a) increased perennial demand for perennial agriculture that cannot be fallowed, (b) households vulnerable to increased water unaffordability, and (c) groundwater-dependent habitats for endangered species in California's Central Coast. The Land management High intensity [LH] scenario (water demand caps with current supplies, urban sprawl limits and new ecosystem preservation) is shown.

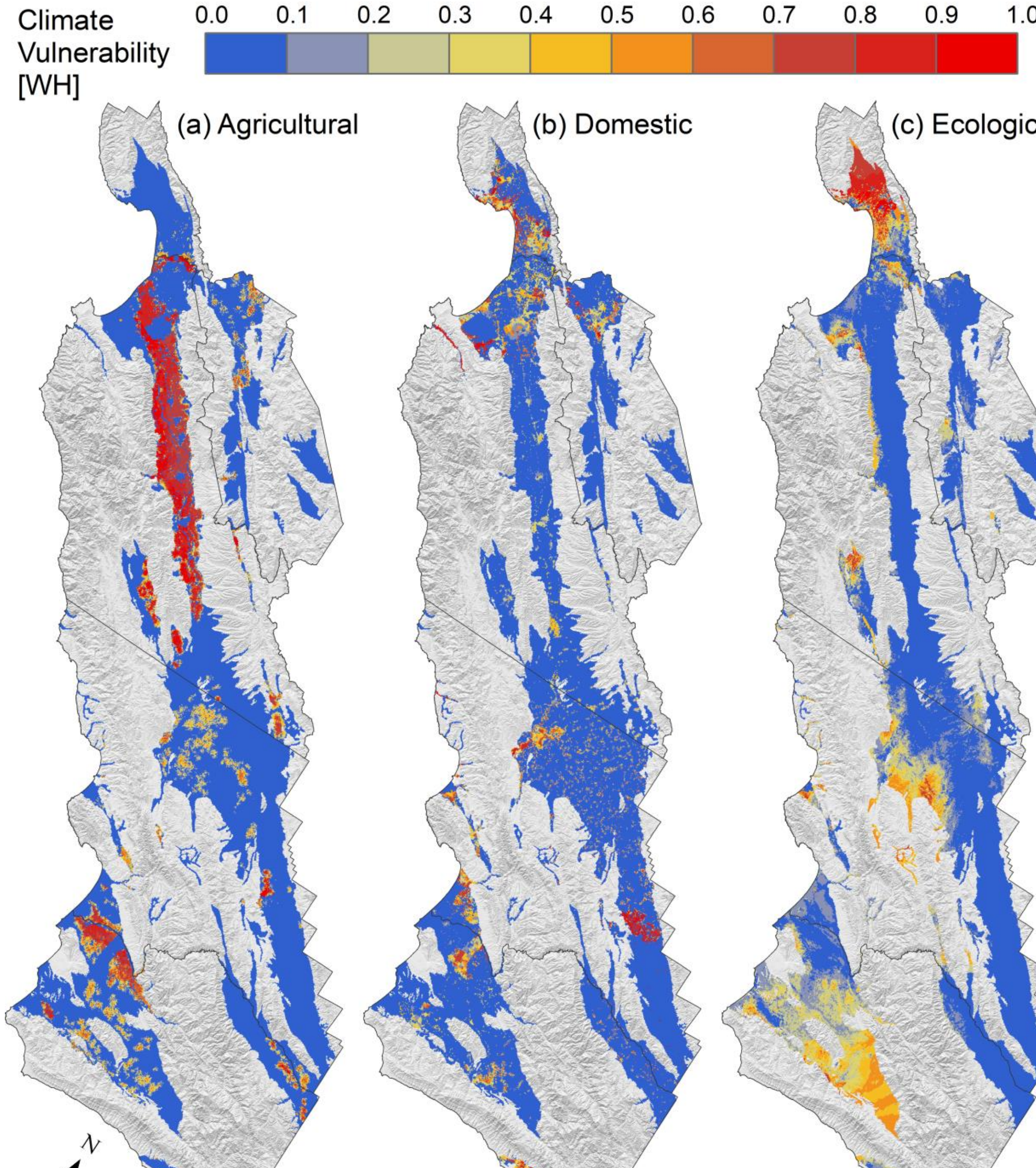

Figure A3.9. Spatial patterns of where RCP 8.5 climate changes will overlap with land-use change by 2061 to create hotspots of (a) increased irrigation water needs of crops, (b) household vulnerability to heat-related health impacts, and (c) loss of runoff and recharge that keeps freshwater ecosystems wet in California's Central Coast. The Water management High intensity [WL] scenario (water demand caps with enhanced supplies, urban sprawl limits) is shown.

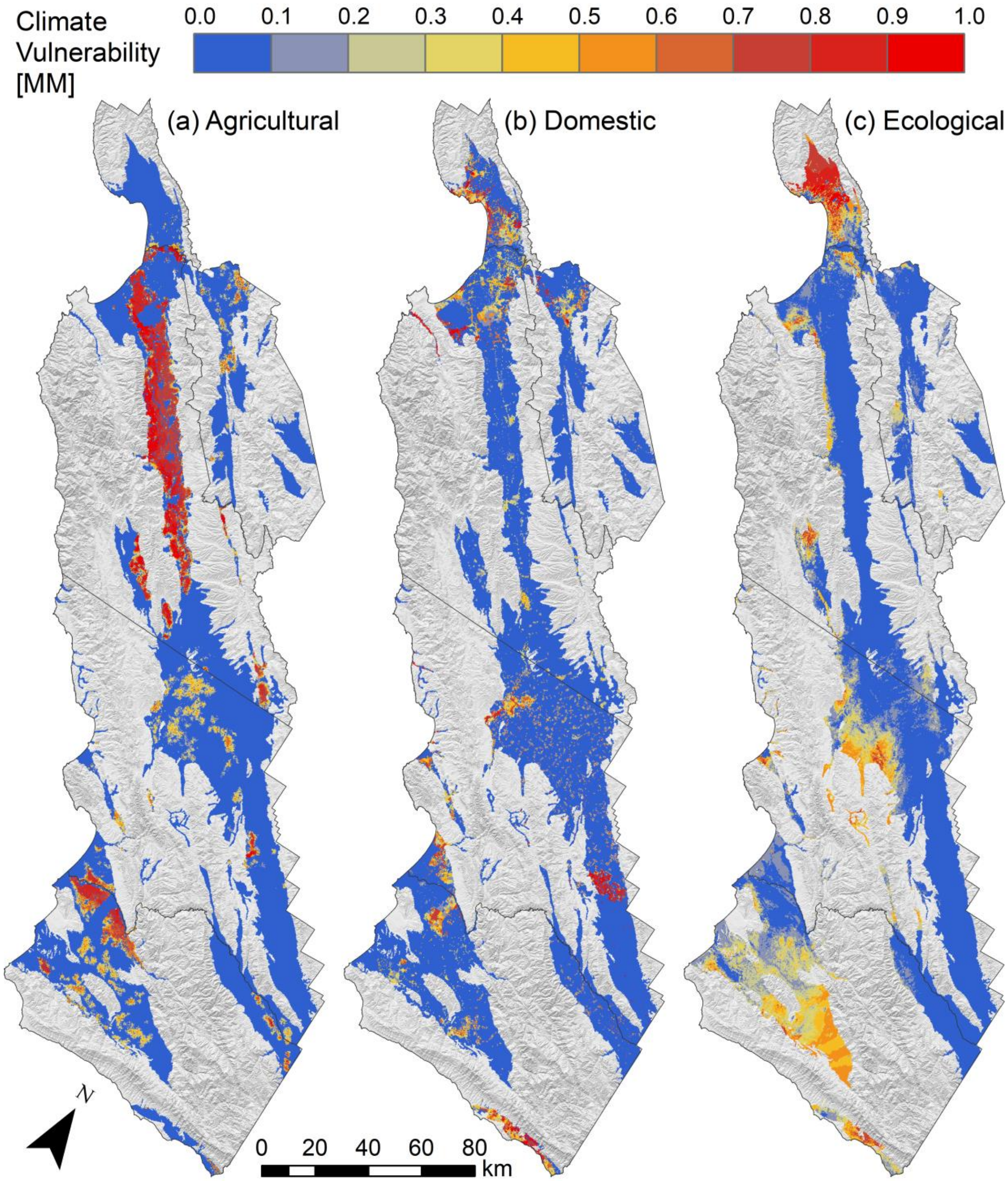

Figure A3.10. Spatial patterns of where RCP 8.5 climate changes will overlap with land-use change by 2061 to create hotspots of (a) increased irrigation water needs of crops, (b) household vulnerability to heat-related health impacts, and (c) loss of runoff and recharge that keeps freshwater ecosystems wet in California's Central Coast. The land management Medium intensity and water management Medium intensity [MM] scenario (water demand caps with current supplies, urban sprawl limits) is shown.

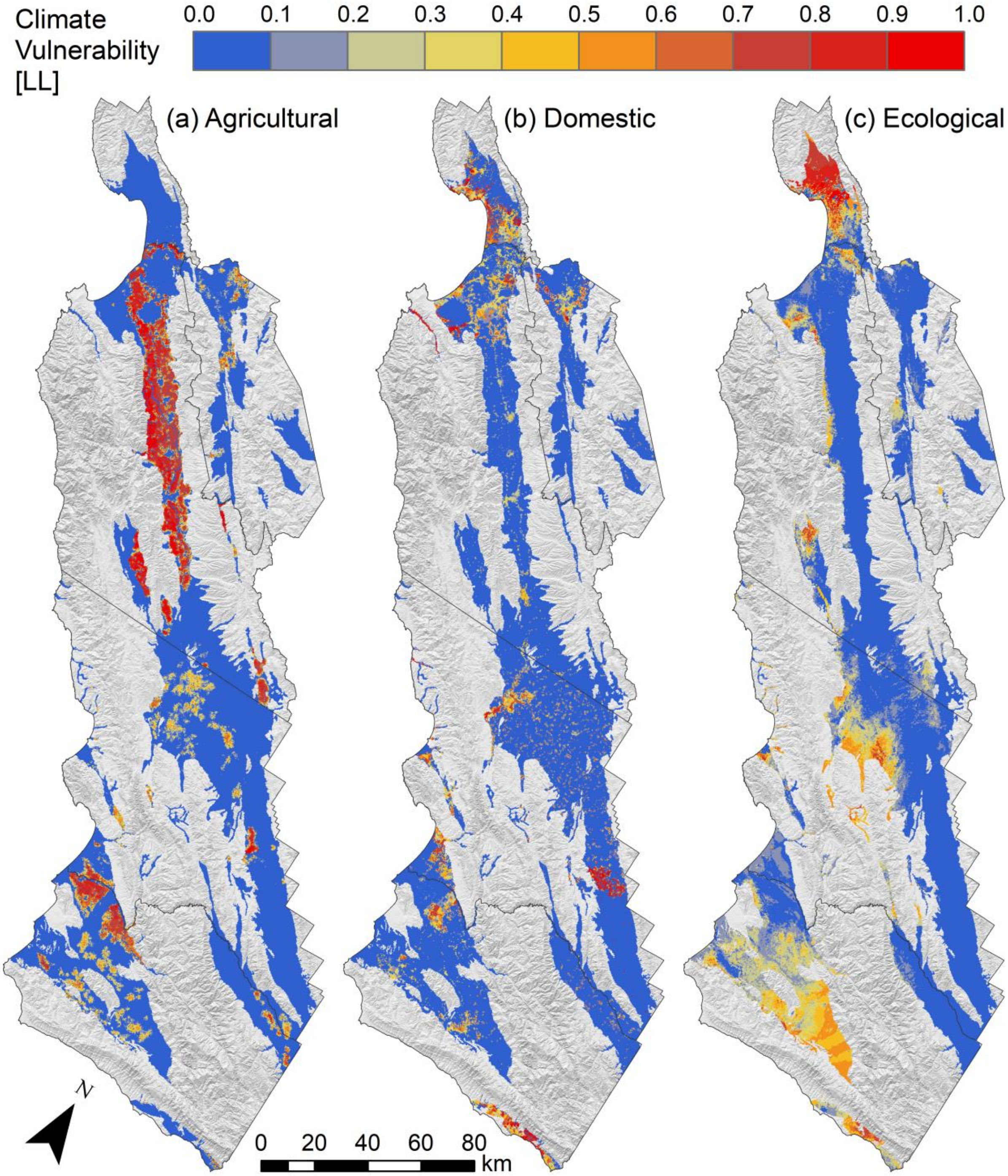

Figure A3.11. Spatial patterns of where RCP 8.5 climate changes will overlap with land-use change by 2061 to create hotspots of (a) increased irrigation water needs of crops, (b) household vulnerability to heat-related health impacts, and (c) loss of runoff and recharge that keeps freshwater ecosystems wet in California's Central Coast. The Land management Low intensity [LL] scenario (water demand caps with current supplies, no urban sprawl limits or new ecosystem preservation) is shown.

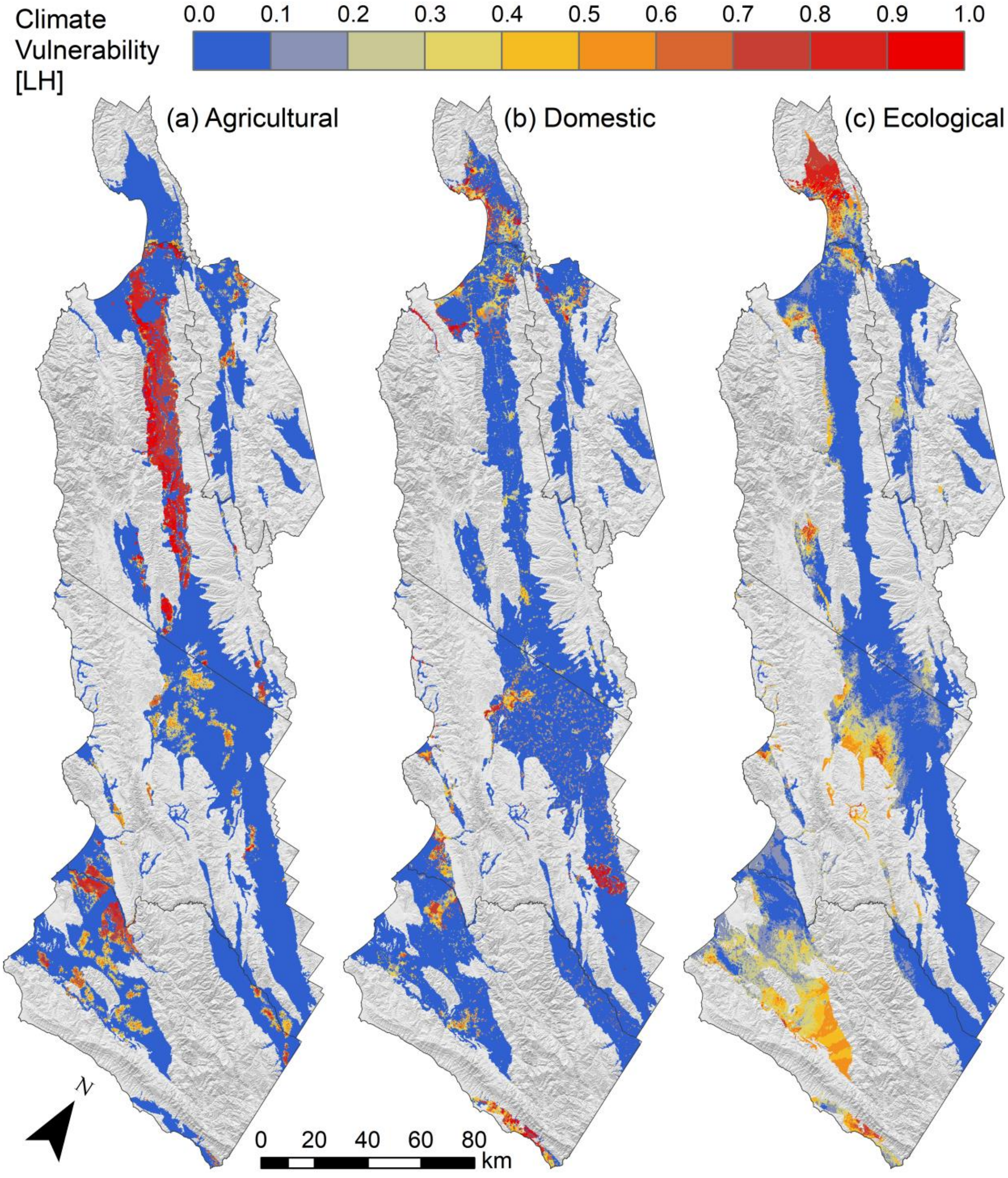

Figure A3.12. Spatial patterns of where RCP 8.5 climate changes will overlap with land-use change by 2061 to create hotspots of (a) increased irrigation water needs of crops, (b) household vulnerability to heat-related health impacts, and (c) loss of runoff and recharge that keeps freshwater ecosystems wet in California's Central Coast. The Land management High intensity [LH] scenario (water demand caps with current supplies, urban sprawl limits and new ecosystem preservation) is shown.