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Identifying drivers of change and predicting future land-use impacts in established farmlands

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ABSTRACT

There is growing consensus that global food systems will need to undergo substantial transformations to ensure continued food security and to halt environmental degradation. Such efforts will have to include more sustainable management of existing farmscapes. Here, we examine drivers of cropland transitions between 13 crop commodities cultivated in Kern County, California. We parameterized multinomial logistic regression models of crop choices, using observed data from 2002 to 2018. We then simulated future crop choices under three scenarios exploring the consequences of climate change, water shortages and policy response, and projected impacts on three agroecosystem pressures (water-use, soil erosion, pesticide-use), and three agroecosystem services (profits, nutrition, and carbon sequestration). Agricultural land-use transitions were especially sensitive to biophysical factors, profits and neighborhood effects. Our results illustrate how climate change may lead to landscape-level crop replacement by 2050, with likely significant socio-ecological consequences.

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Agriculture; climate change; ecosystem services; land-use; profits; water


Introduction

The place of agriculture in human-nature interactions is complex. Agricultural activities are, on the one hand, directly associated with environmental degradation and greenhouse gas emissions (Ramankutty et al., 2018; Webb et al., 2020); they are also highly dependent on agroecosystem health and resilience (Robertson & Swinton, 2005). Agriculture fundamentally underpins human survival through the provision of food, materials and income: crop cultivation directly supports rural livelihoods, and supplies rural and urban communities along local and global supply chains (Ramankutty et al., 2018; Webb et al., 2020). Today, global agricultural land-use (e.g. farmland and livestock pastures) occupies an estimated 40% of all land (Foley et al., 2005), constituting the largest terrestrial ‘biome’ (Campbell et al., 2017).

Although global predictions vary, the total extent of agricultural land is expected to at best remain stable, and most likely continue to expand, albeit at slowing rates (Ramankutty et al., 2018; Rockström et al., 2017). To protect remaining natural ecosystems from further expansion, continued efforts are needed to reduce land conversion rates and mitigate or reverse degradation through land restoration efforts (Cameron et al., 2017; Keesstra et al., 2018; Liang et al., 2018). In addition, ensuring the continued health and resilience of existing farmlands (e.g. through sustainable intensification

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practices) is also paramount and should hold a place of importance in ongoing dialogues about sustainable land management (Cassman & Grassini, 2020; Pretty et al., 2018). Ongoing land-sharing versus land-sparing debates, which were initially centered around balancing food production and biodiversity conservation (e.g. Fischer et al., 2014; Green et al., 2005), have evolved to increasingly recognize the many trade-offs and complexities underlying agricultural land-use transitions (e.g. Fischer et al., 2017; Grass et al., 2019). Nevertheless, evolving socio-ecological dynamics *within* established global cropland areas remain understudied.

Indeed, land-use within already existing agricultural areas is hardly static; in these landscapes, agricultural land-use transitions may occur as a result of drivers like market-driven specialty crop booms (e.g. Meyfroidt et al., 2019), farmland abandonment (Li & Li, 2017) or global-scale cropland homogenization (Preprint). As a consequence of such land-use transitions, changes in crop-type selection may have multiple impacts on resource use (water, soil, fertilizer, pesticide) and ecosystem service provision (nutrition, income, habitat, carbon sequestration, etc.), due to the differing agronomic demands and utility of specific crop types. For instance, export-oriented crops are generally associated with higher profits due to increased market demand, but may also lead to higher input use and environmental degradation (e.g. Lienhard et al., 2020). Permanent crops like orchard trees or vineyards may mitigate short-term economic risks for farmers but are also associated with higher establishment costs, and decreased flexibility for farmers (Mall & Herman, 2019). Although such dynamics are likely to have important repercussions on ecosystems and local communities (García-Ruiz & Lana-Renault, 2011; Lienhard et al., 2020), their potential positive or negative impacts are still not well understood (Meyfroidt et al., 2019).

Additionally, as climate change impacts on agriculture are becoming clear, and popular media (e.g. Flavelle, 2021; Milman, 2021) is elevating these effects, calls for wide-ranging transformation and political action are growing (Campbell et al., 2018; Webb et al., 2020). Land-use transformations will thus also need to account for climate-change-driven shifts in precipitation, temperature and hydrology regimes, which may impact the suitability of long-established agricultural regions for continued crop production (Calzadilla et al., 2013; King et al., 2018). In this context, understanding complex land-use dynamics within agricultural landscapes is even more important. This knowledge may highlight climatic vulnerabilities and trade-offs for particular regions (Biazin & Sterk, 2013; Scherr et al., 2012) and can further be used to identify current bottlenecks and inform targeted policy interventions and management solutions with higher likelihoods of acceptance or adoption by farmers (Dumont et al., 2021; Kennedy et al., 2020). Yet, our understanding of transitions and adaptations within existing agricultural landscapes to climate change is limited. Likewise, there is growing evidence of the importance of spatial dynamics (e.g. field-size, cropland configuration, landscape diversity) on agro-ecological functions such as pest stability, carbon sequestration or soil erosion control within agricultural landscapes (Larsen & Noack, 2017; Wartenberg et al., 2021). These dynamics may become even more important as climate-related stressors add additional challenges to crop production (Brown et al., 2014; L. Parker et al., 2019) and global demand for specific commodities impacts economic contexts (Goldhamer & Fereres, 2017). Still, spatially explicit models within agricultural landscapes remain uncommon. As stresses continue to build on existing croplands, these research gaps should be filled.

Methodologies integrating spatial analysis and econometrics can help us understand land-use change and have been successfully applied across different geographies (Bockstael, 1996; Piquer-Rodríguez, Butsic et al., 2018). Moreover, spatially explicit econometric models constitute a useful tool to model the impacts of projected future land-use transitions under different climate- or policy-related scenarios (Lee & Sumner, 2015; Lewis & Alig, 2014; Piquer-Rodríguez, Baumann et al., 2018; Radeloff et al., 2012). In the context of changing cropping patterns, interactions between economic, biophysical and other drivers of change remain lightly researched, in part due to data limitations related to accurately quantifying and mapping heterogeneous crop types and associated agro-ecological indicators (Macaulay & Butsic, 2016; Wartenberg et al., 2021). Few studies have modeled parcel-level land-use transitions between different agricultural crops to assess interacting drivers of

crop-cover change. Understanding crop transition dynamics and their potential long-term implications can inform agricultural land management decisions that minimize socio-ecological trade-offs for farmers and ecosystems. Our main goal here is to examine the drivers and impacts of land-use transitions *within* existing agricultural landscapes and use our findings to better understand future land use and ecosystem service outcomes.

We focus on the highly intensified farming landscape in Kern County, California, one of the top-producing agricultural regions in the United States (Bourque et al., 2019) and likely worldwide (Pathak et al., 2018). California's agricultural sector, which produces a third of the US' vegetables and two-thirds of the country's fruits and nuts (CDFA, 2019), is increasingly facing unique challenges from climate-related events such as unpredictable fluctuations in temperatures and precipitation patterns, increased likelihood of persistent heat waves and drought conditions, more frequent and intense floods, earlier spring snowmelt, and higher crop water demands (Cooley et al., 2015; Pathak et al., 2018; Wilson et al., 2015). In this context, understanding the drivers of agricultural land-use change and their potential environmental and socioeconomic consequences, has important implications in terms of identifying and minimizing trade-offs for future landscape management (e.g. Piquer-Rodríguez, Butsic et al., 2018). Kern County's agricultural production has shifted from annual row crops to highly profitable nut crops between 2002 and 2018 (Arellano-Gonzalez & Moore, 2020; Schauer & Senay, 2019). This trend has been accompanied by regional increases in profits and calorie production, concurrent with increases in water-use and soil erosion risks (Wartenberg et al., 2021). Because our study area is one of the most diverse, productive and profitable farmlands in the United States, the methodological and outcome-related insights from this research can contribute to larger conversations about the impacts of dynamic farming on ecosystems and the environment globally.

We integrate parcel-level crop data with parcel-level biophysical and economic parameters to study the drivers and impacts of crop transitions in this region. In a first step, we use multinomial logit regressions to understand how drivers influence land-use transitions between different crops grown in Kern County during the time-period 2002–2018. We consider spatial and temporal variations in parcel size and slope, neighboring crop-cover, soil quality, evapotranspiration, profit, and distance to roads, cities, protected areas and water sources to estimate drivers of land-use choices across the most common 13 agricultural crop-classes found in our study region. Second, we use the predicted probabilities derived from our models to simulate future land-use to 2050 based on scenarios that explore potential climate change pathways. We apply simulated changes in water use and crop profitability as proxies for climate change impacts on land-use drivers. Finally, using our simulation results, we then examine how future land use could impact six ecosystem services and pressure indicators relevant to the region. We focus on profits and calorie production as proxies of economic and nutritional benefits from agriculture (Goldstein et al., 2012; Mitchell et al., 2020), carbon sequestration as an indicator for agroecosystem function (Lal, 2018), and water use, soil erosion and pesticide use as indicators for resource-use intensity (Möhring et al., 2020; Quine & Van Oost, 2020; Schauer & Senay, 2019).

Methods

Study region

Our study examined agricultural crop-type changes in the Kern County water basin (Figure 1), which contains the County's main agricultural area. Agricultural production in Kern County is highly diversified; it contributes a gross value of \$7.5 billion annually (Kern County Department of Agriculture and Measurement Standards, 2020), providing a significant proportion of the nuts, fruits and vegetables consumed in the United States (CDFA, 2019; USDA Climate Hubs, 2021). Historically, much of the county's agricultural land was established on Yokuts and Chumash territory (Native Land Digital, 2020). Following the establishment of widespread livestock ranching and wheat farming by Mexican and European settlers in the 1800s, technological advances and changing market

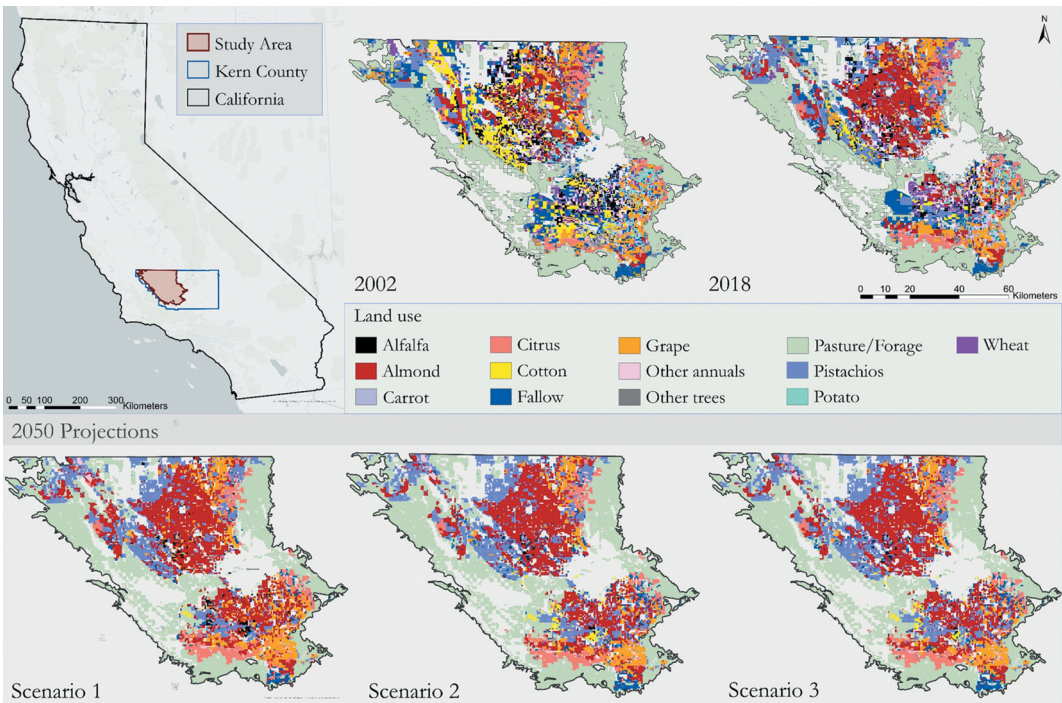


Figure 1. Map of study area and crop cultivation maps based on observed land-use in 2002 and 2018, and on projections along our future land-use scenarios: historical baseline (scenario 1); climate change (scenario 2); and climate change plus adaptation measures (scenario 3).

forces led to large-scale transformations of the landscape, with large shifts to vegetable, fruit and wine cultivation by the early 1900s, and to cotton farming by the 1930s (Olmstead & Rhode, 2017). Since the early 2000s, Kern’s agricultural production has seen rapid expansion of tree-crops (in particular, almonds and pistachios), along with decreasing cultivation of annual crops like alfalfa and cotton (e.g. Wartenberg et al., 2021). The region is characterized by a semi-arid climate. Recent years have seen an increase in severe drought events, e.g. in 2007–2009, 2012–2016 (Schauer & Senay, 2019) and 2021 (NOAA, 2021). Farmers in Kern County now face growing concerns of groundwater and surface water depletion related to poorly managed irrigation practices (Bourque et al., 2019; Faunt et al., 2016).

Modeling parcel-level crop-cover transitions

We developed parcel-level land-cover maps in two-year intervals from 2002 to 2018, based on crop boundary maps developed by Kern County’s Department of Agriculture and Measurement Standards, merged with bi-annually available data from California’s Farmland Mapping and Monitoring Program (Moanga, 2020; Wartenberg et al., 2021). The resulting nine land-cover vector maps document 13 distinct agricultural crop-type classes at the agricultural parcel level (Table 1). We collected data for geographic and economic drivers of land-use change: parcel size, neighbor land-cover, parcel slope, soil productivity index, mean annual actual evapotranspiration, profit, distance to water sources (canals and wells), distance to infrastructure (roads, city limits and developed areas), and distance to protected areas (Table 2). Land-cover and indicator data for each study year was then extracted from a point-data grid with 1856 m resolution (equivalent to the mean parcel size across our study area).

Table 1. Crop-type classification for 121 distinct crop species produced in Kern County between 2002 and 2018.

Crop-type Classification		Kern County Original Crop Classes
1	Alfalfa	Alfalfa
2	Almond	Almond
3	Carrot	Carrot
4	Citrus	Citrus; Grapefruit; Kumquat; Lemon; Orange; Tangelo; Tangerine
5	Cotton	Cotton
6	Fallow	Fallow land
7	Grape	Grape
8	Other field crops	Artichoke; Arugula; Asparagus; Barley; Bean; Beet; Bermuda grass; Blackberry; Blueberry; Bok-choy; Broccoli; Cabbage; Cantaloupe; Cauliflower; Celery; Chinese Green; Chive; Cilantro; Collard; Corn; Cucumber; Daikon; Dandelion green; Dill; Eggplant; Fennel; Berries; Gai-choy; Gai-lon; Garbanzo; Garlic; Gourd; Grain; Green onion; Hemp/Cannabis; Herb/spice; Honeydew melon; Jojoba bean; Kale; Kohlrabi; Leek; Lettuce; Melon; Musk melon; Mustard; Mustard greens; Napa cabbage; Oat; Onion; Ornamentals (Flowering Plants, Flowers, Vines); Okra; Parsley; Parsnip; Peas; Peppers; Pepper spice; Pumpkin; Radish; Rape; Rutabaga; Rye; Safflower; Sorghum; Soybean; Spinach; Squash; Strawberry; Sugarbeet; Sweet basil; Sweet potato; Swiss chard; Tomato; Triticale; Turf/sod; Turnip; Vegetable; Vegetable leaf; Watermelon; Yam, Zucchini
9	Other trees	Apple; Apricot; Avocado; Cherry; Chestnut; Fig; Jujube; Kiwi; Nectarine; Olive; Ornamentals (Christmas Trees); Peach; Pear; Pecan; Persimmon; Plum/Prune; Pomegranate; Stone fruit; Walnut
10	Pasture/Forage	Forage hay/silage; Lovegrass; Pasture; Pastureland; Rangeland; Ryegrass; Sudangrass; Vetch
11	Pistachios	Pistachio
12	Potato	Potato
13	Wheat	Wheat

Parcel size was computed using geospatial tools in ArcGIS Pro (Environmental Systems Research Institute, 2021). Neighbor land-cover refers to the percent of neighboring points with a land-cover different from each original datapoint in our grid. To compute total profit per year and per land-cover class we applied the methodology developed in Wartenberg et al. (2021) using the following equation:

$$P_{i,y} = R_{i,y} - C_{i,y}$$

with profit **P**, revenue **R** and cost **C** distinct for each crop-type class **i** and year **y**. Profit was calculated based on county-level crop-specific total revenue values as reported in public crop reports for the 9 study years (Kern County Department of Agriculture and Measurement Standards, 2020; USDA, 2021), and crop-specific total cost values, which account for operating costs and overhead expenses (UC Davis Agriculture and Resource Economics, 2021; Penn State Extension, 2015; Washington State University CAHNRS, 2021). All currency values were converted to 2018 USD to maintain comparability of values across all study years (U.S. Bureau of Labor Statistics, 2020). Mean annual actual evapotranspiration values were derived from annual spatial raster datasets developed by Schauer and Senay (2019).

We used STATA statistical software version 16.1 to develop multinomial logit regressions examining parcel-level crop-cover transitions. Since multinomial logit models are difficult to parametrize for panel data, we followed most multinomial models with multiple time points and used a pooled approach (Lubowski et al., 2008). Multinomial models estimate, for each base land use, the probability of an observation transitioning to every other land use. A general model can be written:

$$f(k, i) = B_{0,k} + B_{1,k}X_k + \dots + B_{m,k}X_k + e_i$$

Where $f(k, i)$ is the predicted probability that observation i has the outcome k , $B_{0,k}$ is an outcome-specific intercept, $B_{1,k}X_k + \dots + B_{m,k}X_k$ the effect of coefficients of independent variables B_1 to B_m , and e_i is an observation-specific error term. Model results provided for each observation in our dataset the probability that it will transition to another land-use, based on its observation-specific characteristics.

We ran separate models for each potential starting land use (base case). For example, our model for alfalfa transitions predicted the likelihood that a parcel, planted with alfalfa in any given year, would remain under alfalfa cover or would convert to one of our other 12 land-cover classes within

Table 2. Spatial dataset description with mean value and standard deviation (in parentheses) given for all non-categorical variables.

Spatial Variable	Mean (s.d.)	Description	Data Source
Land cover	Categorical	Parcel-scale bi-annual crop boundary polygons for 120+ crop types cultivated in the study area from 2002 to 2018.	Kern County annual crop boundary datasets & Farmland Mapping and Monitoring Program datasets, processed using methodologies described in detail in Moanga (2020) & Wartenberg et al. (2021).
Parcel size	259.51 (205.05)	Parcel size (ha)	Parcel polygons in our bi-annual land cover layers
Neighbor land-cover	Varies by crop	Proportion of neighboring points in our data-grid with a land-cover different from each original point.	Raster-converted bi-annual land cover layers (at 1856 m resolution), processed using a spatial analysis of rook neighborhoods for individual cells.
Parcel slope	1.86 (4.04)	Terrain slope (decimal degrees)	ESRI Living Atlas Slope
Soil quality	Categorical variable	Soil productivity index classification 1: excellent 2: good 3: fair 4: poor 5: very poor	Natural Resource Conservation Service (NRCS) STORIE soil productivity index, calculated for Kern County
Mean annual evapotranspiration	0.39 (0.40)	Landsat-based bi-annual actual evapotranspiration, reported in m/year, 30 m resolution	Schauer & Senay (2018), Supplemental Material
Profit	5.50 (8.42)	Bi-annual profits, reported in thousands of 2018 adjusted USD.	Kern County crop reports, California annual statistical reviews, UC Davis Agricultural Extension Program cost study files, processed using methodologies described in Wartenberg et al. (2021).
Roads	3,983.88 (5,041.10)	Distance to roads (km)	Kern County Planning Department
City limits	49,164.52 (45,703.29)	Distance to city limits (km)	Conservation Biology Institute
Designated protected areas	13,447.72 (11,941.82)	Distance to designated protected areas (km)	California Protected Areas database (CPAD)
Irrigation canals	21,311.53 (19,177.64)	Distance to irrigation canals (km)	California State Geoportal – Canals and Aqueducts local
Groundwater wells	38,135.62 (25,188.68)	Distance to groundwater wells (km)	California Water Boards, Groundwater Ambient Monitoring and Assessment Program

a 2-year interval. For each individual model, coefficients were then estimated for the base case, along with 12 alternatives. In total, we ran 13 different multinomial logit models, one for each land use as the base case, with each model having 13 sets of estimated coefficients (one for each transition including staying in the base case). The model was parameterized using the geographic and economic drivers of land-use change (Table 2) included as independent variables in our models. For each individual model, correlation was checked between dependent variables. For variables that were highly correlated we kept the one which explained more variation. Because these correlations changed depending on the base case, the model specification differed slightly between cases.

Future land-cover predictions

We developed future land-use projections along three scenarios, which explore the consequences of climate change on water availability and economic returns, and on subsequent agricultural land-use decisions (SI Table S1). Scenario 1 (*baseline*) assumes a continuation of historical trends from 2002 to 2018 in terms of profits and environmental parameters.

Scenario 2 (*climate change*) was based on the extreme dry hydrologic scenario developed under California's 4th Climate Change Assessment, and which considers a 30% reduction in statewide water inflows from snowmelt and precipitation in the Sierra Nevada and California Coast Ranges (MacVean et al., 2018; Medellín-Azuara et al., 2018). Under this scenario, we assumed no notable changes in policies and regulations from 2018. To simulate water shortages linked to climate change, we applied crop-specific water-use decline rates, using evapotranspiration as a proxy (SI Table S1); these rates were based on projected changes in irrigated crop area by 2050 (Medellín-Azuara et al., 2018). To simulate the economic consequences of drought and temperature changes on agricultural yields, we applied crop-specific projected changes in gross revenue that address climate-dependent yield effects and climate-independent factors such as technological adaptation and crop market projections (Medellín-Azuara et al., 2018). We further simulated a 50% increase in agricultural production costs arising from a 40% increase in water pumping costs (Medellín-Azuara et al., 2016); and a 10% increase in production costs arising from the implementation of additional measures for climate adaptation (SI Table S1).

Under scenario 3 (*climate change + adaptation*) we explored potential impacts of climate adaptation measures, modeled here as the combined implementation of water-conservation measures through California's Sustainable Groundwater Management Act (SGMA), plus additional broader agro-ecological farm management measures. To reflect long-term water conservation through SGMA implementation (California Department of Water Resources, 2021), we assumed that post-SGMA water supply deficits amount to 50% of the water-use declines applied in Scenario 2. We further simulated yield increases linked to improved water management assumptions under the SGMA, which were reflected in a 50% revenue increase compared to Scenario 2. We assumed that the implementation costs associated with local SGMA measures (Niles & Hammond Wagner, 2019; Rudnick et al., 2016) may offset potential future savings in irrigation costs. However, we additionally assumed that the implementation of comparatively cost-effective agroecological farming practices would contribute a 25% reduction of costs compared to Scenario 2 (SI Table S1). For instance, a focus on soil conservation and improved water-retention capacity, e.g. through crop residue application or reduced tillage (Basche & DeLonge, 2019; Lal, 2009; Morris & Bucini, 2016), and other systems-based farm management approaches (Basche & Edelson, 2017; Morris & Bucini, 2016) may contribute to improved climate and drought resilience across Kern County.

Landscape simulations were created to reflect each of these three scenarios. The simulations were set up using STATA statistical software version 16.1. First, we calculated transition probabilities for each of our grid points based on 2018 observed crop-type classes, using the results of our multinomial logit models. These probabilities were then compared to a random draw; based on this each grid point was either modeled to transition or stay in the same crop-type class (e.g. (Butsic et al., 2010; Lewis & Plantinga, 2007)). This represents a single two-year time step. After each step, the underlying data (profit, neighbors, water availability) was updated to match newly assigned crop-types, and transition probabilities were recalculated. We repeated this process 16 times until the simulation reached the year 2050. Differences between scenarios were accounted for in the simulations by changing the value of water availability and profit in accordance with each scenario. For each scenario, this simulation was run 1000 times. The reported results refer to mean outcomes based on 1000 iterations per scenario (Figure 2).

Agroecological impacts

Based on projected landscape configurations for each scenario, we modeled ecosystem service and pressure indicator values per crop-type class across the total study area based on methodologies developed in Wartenberg et al. (2021). Our analysis includes three ecosystem

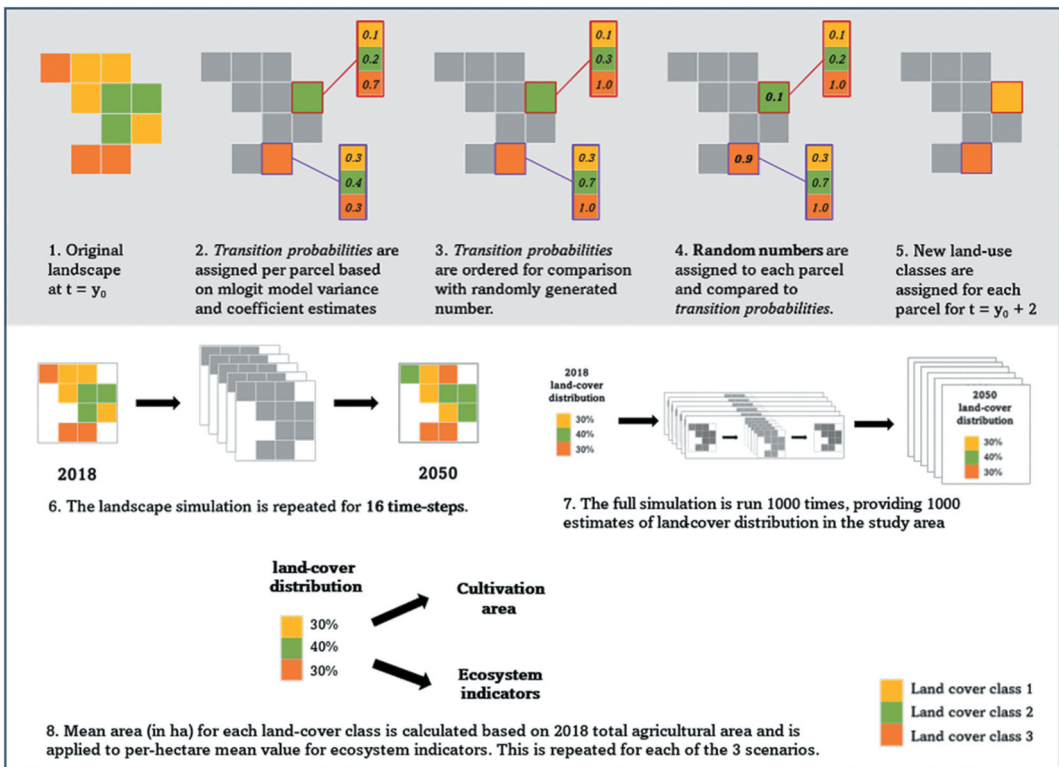


Figure 2. Illustration of modeling and landscape projection methodology.

pressure indicators: water use, soil loss, and pesticide application. We used Landsat-derived actual evapotranspiration values across all agricultural parcels in our study area as a proxy for agricultural water-use; spatially explicit data were obtained from Schauer and Senay (2019). Total soil loss was used as an indicator for soil erosion risk. Soil loss values were modeled using the Natural Capital Project's InVEST (Integrated Valuation of Ecosystem Services and Tradeoffs) Sediment Delivery Ratio (SDR) model (Natural Capital Project, 2019). Finally, toxicity-adjusted pesticide application rates were estimated based on parcel-specific pesticide types and application rates and oral toxicity levels for listed pesticide products (Wartenberg et al., 2021).

We also estimated values for three ecosystem service indicators: economic benefits, carbon sequestration, and calorie production. To represent direct economic benefits from agricultural production we estimated profits, using the equation described above. Calorie production was calculated for each crop-type class based on the USDA average kcal content per 100 g of unprocessed crop (USDA, 2020; Wartenberg et al., 2021). For alfalfa and pasture/forage, we translated the kcal contents from livestock fodder to meat and dairy product nutritional contents by applying a conversion factor of 7.5% (Shepon et al., 2016). To approximate different crop-type classes' carbon (C) sequestration potentials, we used crop-specific reference values for annual C sequestration rates (in $\text{Mg C ha}^{-1} \text{ yr}^{-1}$) compiled from existing literature (Wartenberg et al., 2021).

For each ecosystem indicator, we used ArcGIS spatial analysis tools to integrate crop-specific tabular datasets with our 2002 and 2018 land-cover maps and to determine mean indicator values per hectare for each land-cover class. To model future indicator values across the study area, we then applied crop-specific mean per hectare indicator values to the estimated area for each land-cover class predicted under each of our three land-use scenarios.

Results

Dynamics & drivers of agricultural crop transitions from 2002 to 2018

From 2002 to 2018, land-cover of major annual row crops (alfalfa, cotton, wheat), associated with lower profits per hectare, decreased from 20% to 7%; this transition was primarily driven by a decline in cotton cultivation (from 10% to 1%). In contrast, the cultivation area for high-value orchard crops (almond, citrus, pistachio) doubled from 15% to 29%; in particular, pistachio cultivation increased from 4% of the total agricultural land area in 2002 to 9% in 2018. The land area used for pasture and forage, grape cultivation and fallow remained relatively constant (Figure 1).

Although there was a great deal of change between 2002 and 2018, the most common outcome across all crops was for a parcel to remain in its given use (SI Table S2). Almond, citrus, grape, pasture and pistachio, which were associated with higher per-area profit values, had the highest probabilities of remaining stable (greater than 92%); horticultural crops (carrot, potato, other annuals) had the highest probabilities of conversion. The probability of conversion from other crop-type classes to higher-value crops was relatively low (5% and less), and the probability of conversion from higher-value crops to other land-use classes except fallow was negligible (less than 1%). Probabilities of conversion amongst fallow, horticultural and annual crop classes ranged from 5% to 17%.

Slope, evapotranspiration and soil productivity emerged as primary drivers for agricultural land-use conversions during the study period. We found significant marginal effects of slope, evapotranspiration and soil productivity on conversions from all land-use classes (SI Tables S3 & S4). Neighbor parcel cover and profit were also important drivers for most crop transitions. Marginal effects of neighbors were highly significant ($p < 0.001$) across all land-use transitions except from the base land-use classes alfalfa and tree crops. For profit, marginal effects were highly significant ($p < 0.001$) across all land-use transitions (SI Tables S5, S6 & S7). Other variables included in our models (distance to *protected areas*, distance to *wells*, *roads*, *city limits* and *developed areas*) did not appear to have significant impact on crop transitions (data not shown). Pseudo R_2 values for our multinomial logit models ranged from 0.06 (for conversions from alfalfa) to 0.23 (for conversions from pasture/forage land).

Future land-use pathways

Under Scenario 1, which projected observed change rates from 2002 to 2018 to simulate future land-use change by 2050, results indicated a 13% decrease in the cultivation area of major annual row crops (alfalfa, cotton and wheat), including a 57% decline in wheat cultivation. In contrast, the cultivation area for high-value orchard crops (almond, citrus, pistachio) increased by 35%, occupying a predicted 279,169 ha by 2050. Fallow land and areas under pasture and forage crop cultivation decreased by 25% and 12%, respectively, compared to 2018 levels. Grape cultivation area remained relatively stable, decreasing by 2% (Figure 3; Table 3). Scenarios 2 and 3 simulated climate change conditions under a 30% reduction of hydrological inflow, coupled with i) no notable changes in policies and regulations (scenario 2); ii) the combined implementation of SGMA and agro-ecological farming measures (scenario 3). Landscape projections under both scenarios predicted a decline in grape cultivation areas by approximately 30% compared to 2018 observed levels, respectively. The area under orchard crops increased by 27% and 29%, respectively, under both scenarios. This was driven by an increase in pistachio and other tree orchards, whereas the expansion of almonds and citrus was low. Under both scenarios, the cultivation area of all horticultural and row crops decreased compared to 2018 baselines, except for cotton, which increased (Figure 3). Under scenario 3 we observed a higher increase in tree crop area, and a higher decrease in row crops compared to scenario 2 (Figure 3; Table 3).

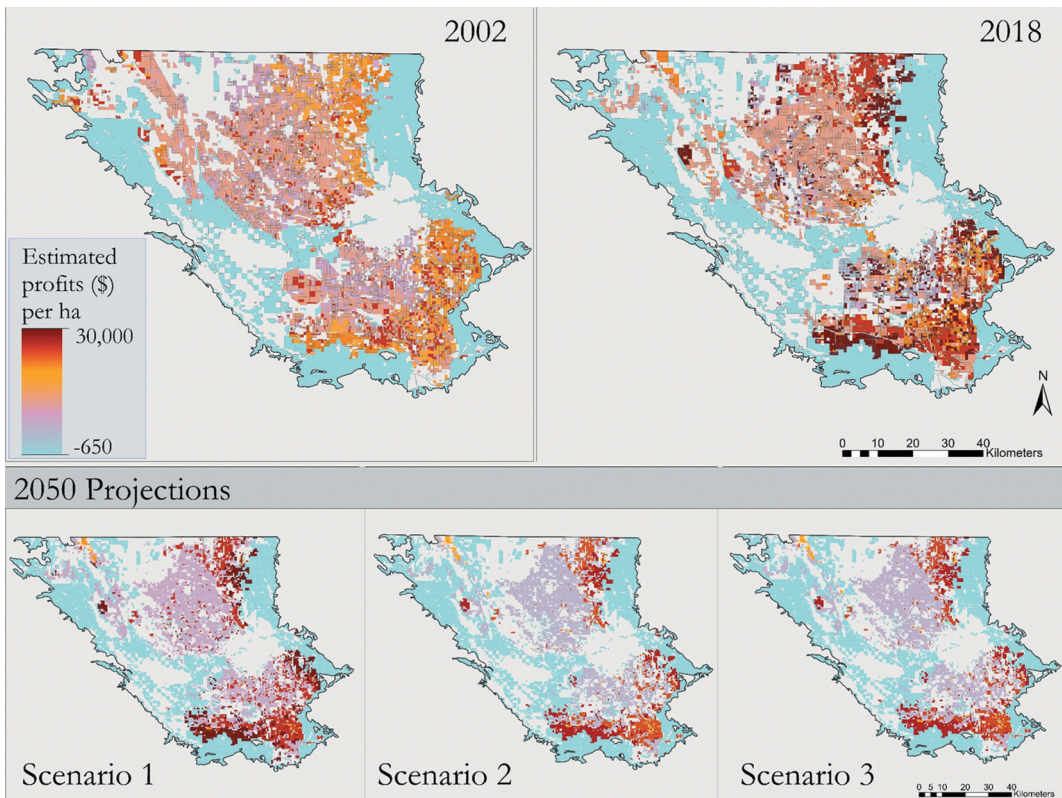


Figure 3. Mean per-area estimated profits (in USD per ha) based on observed land-use in 2002 and 2018, and projected mean per-area estimated profits in 2050 along our future land-use scenarios: historical baseline (scenario 1); climate change (scenario 2); and climate change plus adaptation measures (scenario 3).

Agroecological implications

Under baseline historical projections (scenario 1), we found an increase in the provision of our three ecosystem service indicators by 2050. Calorie production at the landscape scale increased by 9%, carbon sequestration potential increased by 10% due to increased tree-crop cultivation area, and total projected profits across the study area increased by 14%. Under extreme climate change conditions and with no changes in policies or regulations compared to the 2018 baseline (scenario 2), our projections indicate mixed outcomes. Although total calorie production was projected to increase by 12% compared to 2018 levels, profits were projected to decrease by 20% during the same time span. The simulated implementation of adaptation measures (scenario 3) led to a reduction of both positive and negative impacts: calorie production increased by 11%, carbon sequestration by 3%, and profits declined by 13% compared to 2018 baselines (Figure 4; Table 4).

For ecosystem pressures, we found that under baseline historical projections (scenario 1), changes in the total annual impact of the three indicators were variable. Evapotranspiration at the landscape scale increased by 6% by 2050; predicted soil loss increased by 4%, and total pesticide use decreased by 1%. Under climate change conditions and with no policy change (scenario 2), our projections similarly indicate mixed outcomes. Evapotranspiration was reduced compared to scenario 1 outcomes (with a 1% increase from 2018 levels), and pesticide use was projected to decrease by 6%. Soil loss remained relatively stable with a 1% increase. The combined implementation of SGMA and agroecology measures (scenario 3) mitigated the magnitude of soil loss compared to scenario 2 but led to slightly higher pesticide use and the same levels of water-use (Figure 4; Table 4).

Table 3. Kern County agricultural crop area distribution. Mean and standard deviation values for observed cropland area and from 1000 future landscape projection iterations are reported in hectares, and percent change values are given in relation to observed 2018 values.

	Observed			2050 Projections					
	2002	2018	2018	Baseline Scenario		Climate Change		Climate Change + Adaptation	
				Mean ha (<i>sd</i>)	%Δ	Mean ha (<i>sd</i>)	%Δ	Mean ha (<i>sd</i>)	%Δ
<i>Alfalfa</i>	43,871	19,099	21,239 (841)	11.2%	16,181 (758)	-15.3%	15,764 (758)	-17.5%	
<i>Almond</i>	52,829	109,553	123,119 (1,642)	12.4%	109,288 (1,592)	-0.2%	111,940 (1,592)	2.2%	
<i>Carrot</i>	12,595	10,573	7,427 (518)	-29.8%	8,223 (568)	-22.2%	7,768 (531)	-26.5%	
<i>Citrus</i>	26,644	31,604	47,482 (1,023)	50.2%	37,591 (909)	18.9%	37,591 (834)	18.9%	
<i>Cotton</i>	70,668	10,156	12,273 (667)	20.9%	21,372 (872)	110.4%	19,288 (834)	89.9%	
<i>Fallow</i>	83,109	70,635	53,014 (1,326)	-25.0%	56,463 (1,364)	-20.1%	55,894 (1,326)	-20.9%	
<i>Grape</i>	48,350	49,528	48,315 (1,175)	-2.5%	33,792 (1,023)	-31.8%	34,977 (1,023)	-29.4%	
<i>Other annuals</i>	40,885	26,943	9,436 (568)	-65.0%	10,042 (606)	-62.7%	9,890 (606)	-63.3%	
<i>Other trees</i>	9,953	8,792	12,492 (638)	42.1%	18,227 (834)	107.3%	16,560 (758)	88.4%	
<i>Pasture/Forage</i>	249,099	275,796	243,320 (1,213)	-11.8%	255,030 (1,326)	-7.5%	256,470 (1,326)	-7.0%	
<i>Pistachio</i>	25,534	65,368	108,568 (1,288)	66.1%	115,464 (1,364)	76.6%	116,715 (1,326)	78.6%	
<i>Potato</i>	8,652	7,579	5,154 (413)	-32.0%	2,918 (303)	-61.5%	2,956 (341)	-61.0%	
<i>Wheat</i>	26,912	18,644	8,102 (568)	-56.5%	15,271 (758)	-18.1%	14,248 (720)	-23.6%	

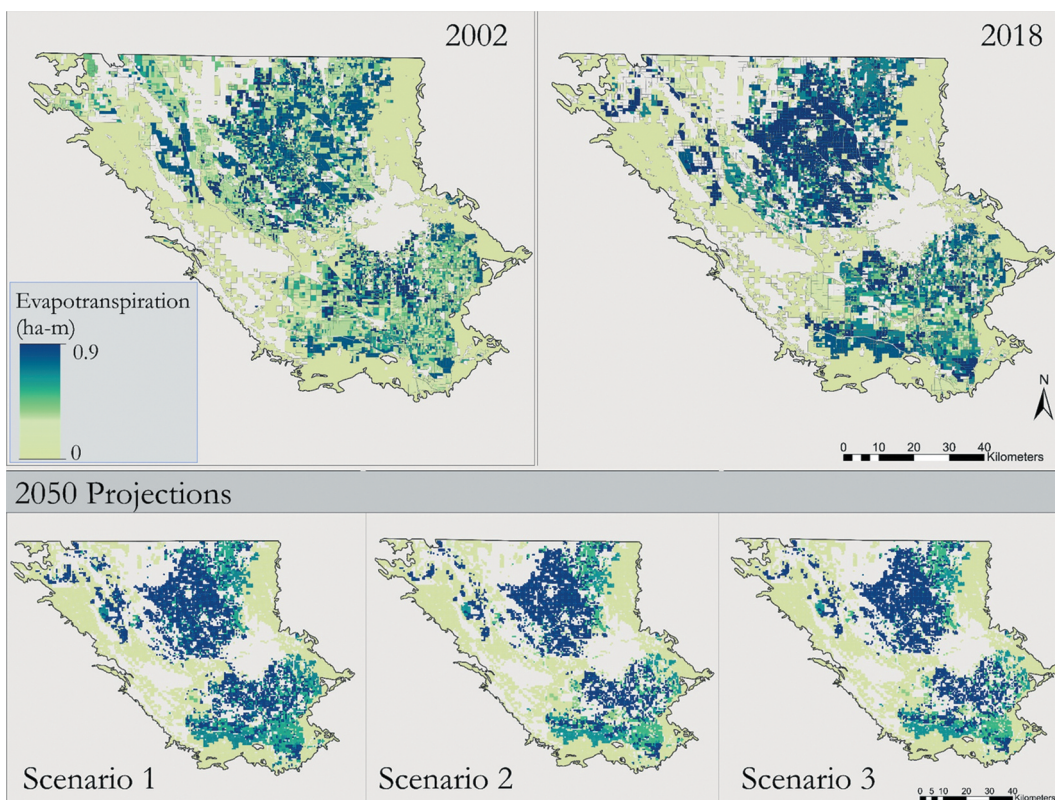


Figure 4. Mean per-area estimated evapotranspiration (in ha-m) based on observed land-use in 2002 and 2018, and projected mean per-area estimated evapotranspiration in 2050 along our future land-use scenarios: historical baseline (scenario 1); climate change (scenario 2); and climate change plus adaptation measures (scenario 3).

Table 4. Total ecosystem service and pressure indicator values across the study area in 2002 and 2018, and percentage increase from the 2018 baseline for 3 future land-use scenarios (in parentheses).

	Observed		2050 Projections		
	2002	2018	Scenario 1 <i>baseline</i>	Scenario 2 <i>cc</i>	Scenario 3 <i>cc + adaptation</i>
<i>Ecosystem Services</i>					
Calories (million kcal)	150,307,470	184,801,045	201,250,932 (+9%)	207,724,501 (+12%)	205,116,000 (+11%)
Profits (million 2018 USD)	2,352	5,224	5,965 (+14%)	4,154 (-20%)	4,539 (-13%)
Carbon sequestration (tC)	248,223	322,598	383,603 (+10%)	354,765 (+1%)	359,841 (+3%)
<i>Ecosystem Pressures</i>					
Soil loss (metric tons)	283,822	303,854	314,608 (+4%)	305,801 (+1%)	305,167 (0%)
Pesticides (kg)	4,210,349	3,970,046	3,929,332 (-1%)	3,742,500 (-6%)	3,754,137 (-5%)
Water use (ha-m)	250,871	258,170	274,873 (+6%)	260,305 (+1%)	260,895 (+1%)

Discussion

Global food security and land use patterns will be partially determined by what happens to already existing farmland, yet there is a research gap in understanding the dynamics of current farmland under climate stress. We investigate this topic in an agricultural hotspot – Kern County California – which may provide a useful example of how farmers in a globally integrated landscape, with access to technology and capital, can respond to climate-driven change. Simulating three different climate and policy scenarios, we explore the consequences of changing environmental and socioeconomic contexts. Under the assumption of extreme dry hydrologic climatic futures, as predicted in California's 4th Climate Change Assessment (Medellín-Azuara et al., 2018), our results suggest that climate change may indeed alter land-use patterns in Kern County, with likely repercussions for agricultural markets at local and global scales (Pathak et al., 2018).

Climate change has been predicted to lead to global shifts in agricultural climate zones and to exacerbate food security concerns in economically vulnerable regions, increasing global inequalities (Anderson et al., 2020; Iglesias et al., 2011); our results illustrate potential impacts of change in one of the most productive agricultural regions worldwide (Pathak et al., 2018). In terms of crop replacement, changes were highly crop-dependent: in most cases cultivation shifts followed historical trends, with the exception of crops like grapes and citrus, which decreased significantly under climate change scenarios. We found that these shifts were associated with landscape-wide socio-ecologic changes, as we observed notable increases in regional calorie production and decreases in profits. Notably, water use was projected to increase across all of our scenarios, with only limited impact on modeled adaptation measures, suggesting that current solutions may not sufficiently address future water shortage issues.

Drivers of change: parcel-specific vs. farmer-driven factors

Previous studies have identified biophysical variables as strong drivers of land-use conversions between agricultural and other land-uses, for instance, in Argentina (Piquer-Rodríguez, Butsic et al., 2018) and in Spain (Corbelle-Rico et al., 2015). We expected similar dynamics in the context of cropland-to-cropland transitions, as plant growth and crop yield productivity are directly dependent on water availability, topography and physical soil characteristics (Kravchenko & Bullock, 2000; Mueller et al., 2010). Our results confirm this to some extent. Despite variability in the relative elasticity of our 13 crop-classes to the different drivers of change assessed in this study, the biophysical variables *soil productivity*, which assesses the productive capacity of agricultural soils based on soil type, texture and topography indicators (Table 2), *evapotranspiration* and *slope*, emerged as major drivers of crop conversions across the majority of modeled land-use transitions. Economic net returns are also a well-studied driver of land-use decisions (Lubowski et al., 2008; Piquer-Rodríguez, Baumann et al., 2018). Neighborhood effects, in which land-use occurring in neighboring parcels impacts transition probabilities in the main parcel, have further been identified as significant driver of land-use transition likelihoods (Corbelle-Rico et al., 2015; Verburg et al., 2004). We similarly expected economic productivity and neighborhood effect, as indicated by the respective variables *neighbor land-use* and *profit*, to significantly influence land-use transitions in our study area. Our results confirmed this, as both variables showed significant marginal effects across all modeled crop-class transitions.

Although parcel slope and soil quality are parcel-dependent and relatively time-invariant, evapotranspiration rates and economic profitability are susceptible to changing climatic and socioeconomic contexts. Simulations of future water-use and profit levels (SI Table S2) along three different land-use scenarios led to significant variations in crop allocation across the study area (Table 3). Our results confirm that while crop productivity and associated planting decisions may be governed in great part by parcel-specific biophysical limitations, for instance, in terms of soil parameters (Marcos-

Martinez et al., 2017; Prestele & Verburg, 2020), we can additionally expect significant changes in agricultural landscapes arising from changing socioeconomic and climatic conditions (Anderson et al., 2020; G. Fischer et al., 2005).

Climate change, regional profit losses and food production shifts

Our modeled land-use trajectories for 2050 indicate that predicted water shortages and related impacts on farm management costs and crop profitability in Kern County, which have been linked to climate change and unsustainable water-use practices (Hanak et al., 2019), may have notable consequences for future land-use in the region. Our results suggest a continuation of observed historical declines of annual row crops (Table 3), which are linked to lower profits and relatively high per-area water use (Wartenberg et al., 2021). In addition, our predictions indicate a decline of vineyards and almonds, and the expansion of pistachios and other tree crops (Table 3), which are associated simultaneously with high profits and lower water requirements.

These dynamics are linked to changes in ecosystem functions. Our projections point towards significantly reduced total profits, as well as increased calorie production by 2050 under climate change conditions (driven by increases in the cultivation-area footprint of tree crops with high caloric density). We are not aware of other studies that have linked climate change with localized calorie production increases. However, studies have suggested links between climate change and shifting orchards in the Himalayan Foothills and the Mediterranean, related to changes in regional suitability for crop cultivation (Rahimzadeh, 2017; Rodrigo-Comino et al., 2021). This suggests that climate change is already contributing to landscape-wide crop transitions, although the direction of crop shifts remains difficult to predict given the complex drivers behind farmers' decision-making (Kristensen, 2016; Niles et al., 2019). Our work provides additional evidence illustrating how we may expect agricultural shifts to take place in already existing farmlands.

We further predicted decreases in agricultural water consumption, linked to increased fallowing under climate change conditions, compared to our baseline scenario (Table 4). This echoes findings from other semi-arid regions (Alonso-Sarría et al., 2016; Dharumarajan et al., 2017) where water scarcity contributed to accelerated farmland abandonment, with consequences for local food security. Nevertheless, in our study area, predicted water use under climate change conditions remained above 2018 levels. In our models, profitability of high-value crops with, in some cases, high per-area water-consumption (e.g. almonds, citrus) may have offset the costs associated with growing water pressures.

Ultimately, future changes in crop production patterns will have significant downstream consequences for human well-being – most immediately for local communities in producing regions, but also along regional and global supply chains. For instance, our data predicted that all three scenarios would lead to significant decreases (ranging from 63% to 65%) in the cultivation of *other annuals*, which encompasses all non-tree fruit and vegetable crops except for carrots and potatoes (Table 1). Given Kern County's important role for horticultural production in the US (CDFA, 2019), this could lead to disruption in food production processes, and to a reconfiguration of agricultural production to other more suitable regions within California and the US. Such a shift would likely have significant repercussions for farm laborers and local communities and may further lead to displacement of natural vegetation and increased ecosystem degradation in regions more biophysically suited for future crop production.

Limited impacts of climate adaptation on ecosystem pressures

We modeled the implementation of climate adaptation measures to examine how policy and management interventions might contribute to the configuration of future landscapes. Our scenario outputs indeed indicate variation in predicted land-use trajectories between scenarios 2 and 3, highlighting the important role of local policies in shaping agricultural landscapes. Our results

suggest that the combined implementation of SGMA and farm-management measures could mitigate predicted declines in pasture and forage areas and in high-value crop cultivation (Table 3). However, climate adaptation measures, exemplified here by the implementation of water conservation and agro-ecological farming practices, were not projected to have significant impacts in terms of reducing ecosystem pressures, particularly regarding water-use (Table 4). Our findings thus point towards potential limitations of existing adaptive measures. Although we see the continuation of ongoing adaptation efforts as necessary, particularly to minimize immediate burdens on directly impacted communities, they urgently need to be coupled with accelerated policy efforts for more expansive and transformative solutions (Anderson et al., 2020; L. E. Parker et al., 2020; Pathak et al., 2018). These should aim to curb climate change by more aggressively targeting carbon emission reduction. They should also promote resilient and ecologically sustainable pathways of food production and land-use – for instance, by targeting integrated landscape management strategies (including for soil and water conservation), bolstering financial and societal incentives for farmers and consumers, considering local needs, and pushing for the internalization of current environmental ‘externalities’ in global and regional markets (e.g. Mupepele et al., 2021).

In our simulations, we applied 2018 values for all ecosystem indicators except for evapotranspiration and profit, for which we modeled future values. We found that variability across scenarios was relatively low compared to changes from 2002 to 2018, particularly for calorie production, carbon sequestration, soil erosion and pesticide use (SI Figures 1–4). We acknowledge that our approach does not account for potential changes over time in the per-area performance of the selected indicators, which could be driven by variations in crop age, yield productivity, plant density, soil management etc. nor for potential technology or management improvements, for instance, in terms of water-use efficiency. We further note that the values applied to our calorie and profit indicators do not necessarily reflect future variations in the individual crops contained within the ‘other annuals’ and ‘other tree’ land-use classes; this may reduce the accuracy of our future projections. In addition, our models do not account for the future loss of farmland, currently predicted at 200,000–300,000 hectares under SGMA implementation for the whole San Joaquin Valley (Hanak et al., 2019). The impacts of this are uncertain. Continued water scarcity and increased land fallowing may lead farmers to transition to increasingly drought-resistant crops on remaining land, or to non-agricultural land-uses entirely, impacting food and commodity crop supply chains. Increased fallowing in California’s Central Valley has also been predicted to lead to substantial GDP decline and job losses (Hanak et al., 2019), threatening local livelihoods and exacerbating environmental and socio-economic inequalities in the region (Flores-Landeros et al., 2021; Ramirez & Stafford, 2013).

In conclusion, we found that agricultural land-use transitions in Kern County were especially sensitive to both parcel-specific and time-invariant factors (slope and soil quality) and to factors, which are more susceptible to external variations driven by climate change and market dynamics (evapotranspiration and profits). Our future landscape simulations illustrated the potential impact of climate change on water shortages and agricultural price fluctuations, which could lead to significant land-use transformation and profit losses by 2050. The climate adaptation measures included in our scenarios led to reduced losses in terms of calorie production, profits and carbon sequestration. While our results highlight the potential of such measures for climate adaptation, they also point towards possible limitations, as our climate adaptation scenario shows minimal impact on landscape-level ecosystem pressures. Ultimately, our results suggest that established agricultural landscapes will undergo significant transformations in the next decades to adapt to societal and climatic change. Public policy should be prepared to address the fallout from these changes.

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Disclosure statement

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