Future scenarios for pest and disease management of major crops in California

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INTRODUCTION

In this analysis, we address five key elements of future pathogen and pest management in California: climate change, changing growing regions, labor requirements, and surveillance requirements for an invasive pathogen.

1) We evaluate potential changes in temperature favorability in 2035 and 2050 to a set of ten pathogens and pests that are major biosecurity concerns due to yield loss, market access loss, and quarantine restrictions.
2) We evaluate changes in precipitation in scenarios for 2035 and 2050 and historical irrigation patterns.
3) We evaluate changes in the growing regions for almond, grape, and tomato across the past decade, as an indicator for potential future trends in their production areas.
4) We evaluate potential future employment in agriculture in 2035 and 2050, for a scenario in which it follows trends observed across the past 30 years.
5) …In an associated analysis, we also evaluate the results of expert knowledge elicitation characterizing future scenarios for ten key pathogens and pests of almond, grape, and tomato…
6) We evaluate likely surveillance scenarios for Plum pox virus, a pathogen that could invade California, infecting important tree crops in the Rosaceae such as almonds, plums, peaches, and apricots.

For each of these factors, we discuss which sources of uncertainty might affect future scenarios and how they can be mitigated by incorporating information of local management systems.

2 METHODS

2.1 Potential temperature effects on pest range expansion

Pest targets. We focused on ten crop diseases or pests of economic and environmental importance for California: Fusarium wilt of tomato (*Fusarium oxysporum* f. sp. *lycopersici*), broomrape (*Orobanche ramosa*), the European grapevine moth (*Lobesia botrana*), Mediterranean fruit fly (*Ceratitis capitata*), melon fly (*Zeugodacus cucurbitae*), Mexican fruit fly (*Anastrepha ludens*), Oriental fruit fly(*Bactrocera dorsalis*), spotted lanternfly (*Lycorma delicatula*), Pierce's disease of grapes (*Xylella fastidiosa*), and the Japanese beetle (*Popilia japonica*). This selected list of insect pests, plant diseases and weeds includes pest species targeted in the CDFA's detection and emergency projects (https://www.cdfa.ca.gov/plant/pdep/target_pests.html)

Table 1. Temperature ranges reported for a set of key crop pathogens and pests. These species are evaluated in climate change scenarios for the future geographic distribution of temperature means in California.

Disease or pest name	Scientific name	Minimum temperature tolerated	Low optimum temperature	High optimum temperature	Maximum temperature tolerated	Life cycle stage	Evidence type	Reference
Fusarium wilt of tomato	*Fusarium oxysporum* f. sp. *Lycopersici*	9	28	28	37	Growth	Culture	(Clayton, 1923)
Fusarium wilt of tomato	*Fusarium oxysporum* f. sp. *Lycopersici*	19	25	31	35	Disease development	Greenhouse	(Clayton, 1923)
Fusarium wilt of tomato	*Fusarium oxysporum* f. sp. *Lycopersici*	17	27	27	34	Disease development	Greenhouse	(Clayton, 1923)
Pierce's disease	*Xylella fastidiosa*	12	25	32	34	Disease development	In vitro development and plant inoculation	(Feil & Purcell, 2001)
Spotted lanternfly	*Lycorma delicatula*	8.1	20	30	38	Development across stages		(Maino et al., 2022)
European grapevine moth	*Lobesia botrana*	8.9	30	30	33	Egg and larval development	Estimated from experiments	(Gutierrez et al., 2012)
European grapevine moth	*Lobesia botrana*	11.5	30	30	33	Pupal and adult development	Estimated from experiments	(Gutierrez et al., 2012)
Japanese beetle	*Popilia japonica*	10	27.5	31	34			(Kistner-Thomas, 2019)
Oriental fruit fly	*Bactrocera dorsalis*	13	25	33	36	Observational	Estimated from CLIMEX	(Stephens et al., 2007)
Oriental fruit fly	*Bactrocera dorsalis*	9	25	33	42	Observational	Estimated from CLIMEX	(De Villiers et al., 2016)
Mediterranean fruit fly	*Ceratitis capitata*	9.39	30	32	39.37	Eggs development	Estimated from constant temperature experiments	(Gilioli et al., 2021)
Mediterranean fruit fly	*Ceratitis capitata*	6.64	25	34	38.75	Larvae development	Estimated from constant temperature experiments	(Gilioli et al., 2021)
Mediterranean fruit fly	*Ceratitis capitata*	8.9	25	33	35.35	Pupae development	Estimated from constant temperature experiments	(Gilioli et al., 2021)
Mediterranean fruit fly	*Ceratitis capitata*	11.15	28	32	37.9	Adult development	Estimated from constant temperature experiments	(Gilioli et al., 2021)

Mexican fruit fly	*Anastrepha ludens*	5	15	15	30	Adult survival	Growth chambers with fruits	(Guillen et al., 2022)
Mexican fruit fly	*Anastrepha ludens*	15	25	27	30	Egg laying	Growth chambers with fruits	(Guillen et al., 2022)
Melon fly	*Zeugodacus cucurbitae*	13.9	32	34	37	Egg hatching	Growth chambers	(Ahn et al., 2022)
Melon fly	*Zeugodacus cucurbitae*	13.9	28.8	32.6	39	Larval and pupal development	Growth chambers	(Ahn et al., 2022)
Broomrape	*Orobanche ramose*	10	18	23	35	Conditioning and germination	Field experiments	(Kebreab & Murdoch, 1999)

Environmental niche model. For each pest or pathogen species, we developed a bioclimatic niche model based on temperature and host availability. We assumed each targeted pest has a minimum, optimal, and maximum temperature (cardinal temperatures) for development. These cardinal temperatures can be pest-specific and different across life cycle stages (e.g., soil survival versus infection for pathogens, or egg versus adult for arthropod pests). The rate of developmental processes likely maximizes at a species' optimal temperature. If a location's mean temperature exceeds the maximum temperature (or drops below the minimum temperature) tolerated by a species, physiological development is likely constrained. This pattern in developmental rate is widespread across pests and pathogens (Briere et al., 1999). We compiled information on cardinal temperatures for each pest or pathogen species from the literature (Table 1). Temperature is important for physiological response of poikilotherms and ectotherms. We preferentially selected temperature observations from field studies over in vitro or controlled environments. This preferential selection is to implicitly consider disease or infection (where contact with host is an important component) in our modelling approach, as opposed to growth in culture or survival components.

We develop a generic model to quantify temperature-dependent invasion risk or development rate $R(T)$:

$$R(T)_{x,y,t} = \left(\frac{T_{max} - T_{x,y,t}}{T_{max} - T_{opt}}\right)\left(\frac{T_{x,y,t} - T_{min}}{T_{opt} - T_{min}}\right)^{(T_{opt}-T_{min})/(T_{max}-T_{opt})}$$

In this nonlinear function for temperature-dependent developmental rate, $T_{x,y,t}$ is the atmospheric temperature at a certain location (x and y) in one of the potential future scenario years (t), T_{max}, T_{min}, and T_{opt} are the cardinal temperatures for a species' development. This thermal model has been previously used for quantifying the potential climate change effects on fungal pathogens globally (Chaloner et al., 2021).

Climate model. We adopted climate projections based on the Coupled Model Intercomparison Project Phase 6 (CMIP6). We obtained minimum and maximum temperature data from Cal-Adapt for California's Fifth Climate Change Assessment (https://cal-adapt.org/). Five global climate models (GCMs; EC-Earth3-Veg, ACCESS-CM2, EC-Earth3, UKESM1-0-LL, and HadGEM3-GC31-LL) have the best model performance in accurately simulating climate conditions in California. This statistically indistinguishable model performance is based on a balance representing local climate variables and regional to hemispheric scale processes (Krantz et al., 2021). We used ACCESS-CM2 as our GCM. We used these annual temperatures averaged across 2000, 2010, and 2020 as a baseline scenario of contemporary climate. We evaluated the potential effect of projected mean annual temperature for 2035, 2040, 2050, 2060, 2070, 2080, 2090, and 2100 as possible scenarios of climate futures. For each future scenario year, we considered temperature projections based on two Shared Scenario Pathways (SSPs): a middle of the road global emissions scenario represented by SSP2-4.5 (or "sustainable" scenario) and a very high global emissions scenario represented by SSP5-8.5 (or "business-as-usual" scenario).

2.1 Expert knowledge elicitation

Quantifying the potential effects of different change factors on crop yield loss caused by pests or diseases in the future is highly uncertain. Obtaining data to evaluate these potential effects in the short term is also a difficult task. This issue hinders the development of integrated assessments of pest or disease risks for a region and rapid decision making for pest risk mitigation. To provide a rapid qualitative foundation for this challenging issue, we conducted three expert knowledge elicitation (EKE) events. The first EKE included nn participants on November 6th 2023, the second EKE included 10 participants on January 29th 2024, and the third EKE included two participants on October 18th 2024. These EKEs aimed to gather information on expected changes in yield loss caused by specific pests or diseases in California by 2049 compared to now. A moderator led the EKE discussions virtually, and experts provided their opinions regarding these expected changes in yield loss. For each pest or disease target, we asked experts for their opinions regarding potential effects of five change factors on yield loss: climate change, labor availability, land use change, water availability, and all these factors combined. We developed a categorical ranking to record expert opinions for each combination of a pest/disease and a change factor: increased yield loss, minimal change in yield loss, decreased yield loss, high uncertainty, and no consensus. For each pest and change factor combination, we asked experts to reach a consensus opinion for these future scenarios as much as possible and, when not possible, to discuss why they think opposing effects might occur. We also explore individual expert opinions through individual surveys. Add something about experts' expertise…

2.2 Changes in water delivery systems and precipitation

We obtained information on the extent of area equipped for irrigation (AEI) from the Historical Irrigation Dataset (HID) (Siebert et al., 2015). The HID provides information on the percentage of AEI for 1900 to 2005 in 5 arc-minute resolution globally, from which we extracted AEI information for California for the years 1900, 1930, 1960, 1980, 1990, and 2005.

We used the same climate models and databases as indicated in the temperature-dependent risk section to analyze potential changes in yearly average precipitation. Here, potential changes refer to precipitation difference measured in absolute terms (mm/day) and relative terms (percentage change) for 2035 or 2050, compared to current precipitation patterns (2010-2020).

2.3 Changes in crop growing regions over the past decade for almond, grape, and tomato

We focused our analysis on three major crops produced in California: almond (*Prunus dulcis*), grape (*Vitis vinifera*), and tomato (*Solanum lycopersicum*). These crops are among the top 10 agricultural commodities for the California Department of Food and Agriculture (CDFA, https://www.cdfa.ca.gov/). We used the two most recent reports of the USDA Census of Agriculture (2022 and 2017) to assess historical patterns in growing regions for each crop species. Specifically, we evaluated county-level estimates of the total harvested acreage of almonds (bearing and nonbearing age acres), grapes (bearing and nonbearing age acres), and tomatoes (in the open for fresh market and processing). These USDA Censuses of Agriculture provide detailed crop information at the county level only, based on surveys from farmers (USDA, 2024a).

We also obtained publicly available crop-specific information from CroplandCROS (USDA, 2024b). CroplandCROS offers annual high-quality estimates for these crop species, with exceptionally high spatial resolution (grid cells of 30 m by 30 m). The reported accuracy of cropland distribution for these crop species in CroplandCROS is high: 94.6% for almonds, 83.3% for grapes and 77% for tomato for the 2009 estimates; 91% for almonds, 87% for grapes, for 91.4% tomato for the 2012 estimates; and 91.9% for almonds, 91.6% for grapes, 86.5% for tomato for the 2022 estimates (USDA, 2024c). Our analysis focused on these years because crop-specific reports for 2008 or earlier have limited accuracy. CroplandCROS provides fine spatial resolution but coarse temporal scale.

2.4 Historical and future changes in employment

We obtained data on agricultural employment in California from the Employment Development Department (EDD). This dataset covers monthly employment, earnings, and regional distributions for specific crop categories (vegetables and melons, grapes, and tree nuts). Then we forecasted employment trends until December 2050 using three time series models: SARIMAX, Holt-Winters Exponential Smoothing, and Prophet. We configured SARIMAX with non-seasonal and seasonal parameters ([1,1,1] and [1,1,1,12], respectively). For Holt-Winters, we set additive trends and seasonal components to model linear growth and seasonal patterns. The Prophet model included default settings, specifying a 0.95 interval width for confidence bounds. We fitted each model with the historical monthly data. SARIMAX and Prophet provided built-in confidence intervals, but Holt-Winters required manual calculation based on residual standard deviation. For uncertainty quantification and visualization, SARIMAX utilized standard errors, Holt-Winters applied residual-based intervals, and Prophet generated predictive intervals from observed data variability. The complete data set, analysis design, and Python scripts to reproduce this analysis are publicly available at
https://github.com/jrobledob/2024_California_Employment_Forecast_2025

2.5 Potential invasion scenarios for Plum pox virus (PPV) in California

Since PPV has a multi-species host range (Damsteegt, 2008), we first map the spatial distribution of wild and cultivated host species of PPV in California. We generated maps of relative occurrences of Rosaceae based on georeferenced records downloaded from the Global Biodiversity Information Facility (GBIF) on November 20th, 2024 (https://www.gbif.org/). This GBIF layer mostly consists of citizen science observations of wild species, gardens and historical records. Concurrently, we downloaded raster maps of stone fruit density (peaches, apples, almonds, cherries, apricots, plums, and nectarines) for the year 2023 from the CroplandCROS database (https://croplandcros.scinet.usda.gov/). This CroplandCROS layer represents cultivated Rosaceae. We normalized and aggregated each host layer and aligned them to the same spatial resolution and geographic extent. The final map of host density for PPV represents a weighted sum of the GBIF layer times 0.2 and the CroplandCROPS layer times 0.8.

We then created an adjacency matrix using the final map of host density in the msean() function of the geohabnet package (Keshav et al., 2024). In this adjacency matrix, columns and rows indicate the location identity and entries represent the relative likelihood of pathogen movement between locations. The relative likelihood of pathogen movement is a function of host availability and geographic distance between locations. Full details of the methodology and scripts are available at this GitHub repository: https://github.com/jrobledob/2024_California_Rosaseae_GBIF_and_Croplandcrops.

We then evaluated which locations in California are likely to be more efficient in surveillance once an epidemic by PPV occurs in the future. We used the smartsurv() function in the INA R package v1.0.0 (Garrett, 2021a) and the adjacency matrix obtained from geohabnet. The smartsurv function evaluates the importance of each location for sampling to detect spread of PPV. Specifically, the smartsurv function measures how many other locations remain free from PPV by the time it is detected at the sampling location (Garrett, 2021b). We assessed two scenarios for points of introduction in this smart surveillance analysis: (1) a scenario where the likelihood of pathogen introduction of plum pox virus was assumed to be equal across all locations, and (2) a scenario where the likelihood of introduction was constrained by proximity to potential introduction points, such as ports.

3 RESULTS

3.1 Temperature effects on crop diseases and pests

Based on temperature conditions in the baseline period (2000-2020), a large geographic extent in California has a high temperature suitability for the establishment of the Mediterranean fruit fly, Mexican fruit fly, Oriental fruit fly, spotted lanternfly, fusarium wilt of tomato, and pierce’s disease of grape (Figures 1-3). Meanwhile, the area with high temperature favorability for broomrape, European grapevine moth, and Japanese beetle is restricted to some portions of the Central Valley of California, and counties in southern California. The melon fly was the only pest species that temperature would be expected to be favorable in and restricted to counties of southern California.

Generally, RCP-8.5 represents a pessimistic scenario in greenhouse gas emissions, which would allow a stepper increase in temperature-associated pest risk. A sustainable scenario (RCP-4.5) is projected to keep average temperature increases below 2 °C globally, which would result in minor geographic changes in temperature suitability for each pest species in California. While a substantial increase in the temperature-tolerated area is likely for all pathogens and pests evaluated here, each pest or pathogen shows spatially different potential ranges and hotspots with temperature-associated risk (Figures 1-3).

This increase in temperature favorability is expected considering the temperature conditions averaged across RCP-4.5 and RCP-8.5. This increase is likely because the optimal development of diseases and pests evaluated here is associated with warm temperatures, which would be favored under projected global and local warming scenarios. This means that the potential range frontiers of the studied pests would expand towards currently cold locations. For example, broomrape would be expected to experience a substantial expansion in the area with temperature tolerated by this weed by 2035, but no major subsequent expansion would be expected by 2050. Additionally, temperature-associated risk would increase in intensity by 2035 and by 2050. For example, temperature in a large area of the Central Valley of California is moderately favorable for development of the European grapevine moth, but temperature favorability for this pest would increase by 10-20 % in the same region by 2050 (Figure 1). The general insight is that current surveillance plans would need to track possible introduction or spread of these pests in the future as climate change might shift their potential geographic ranges or risk hotspots in the future.

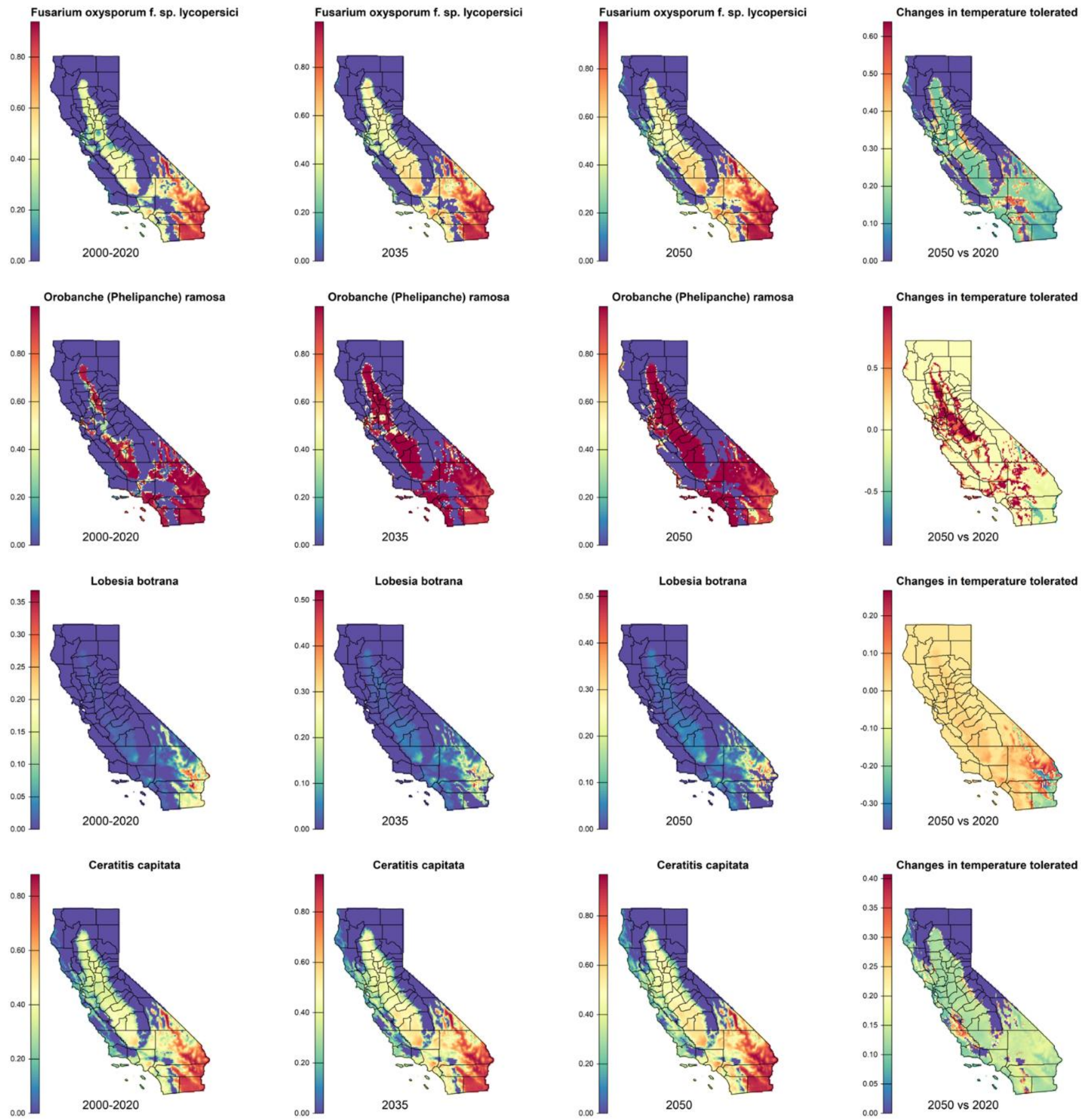

Figure *1*. Temperature suitability for four pests in California for 2000-2020 (current scenario), 2035, and 2050 [Three columns in the left]. Warmer colors represent higher temperature suitability and dark blue indicates temperature is unfavorable for the pest. The difference in temperature suitability for each pest species in 2050 is compared to the current temperature scenario (right column).

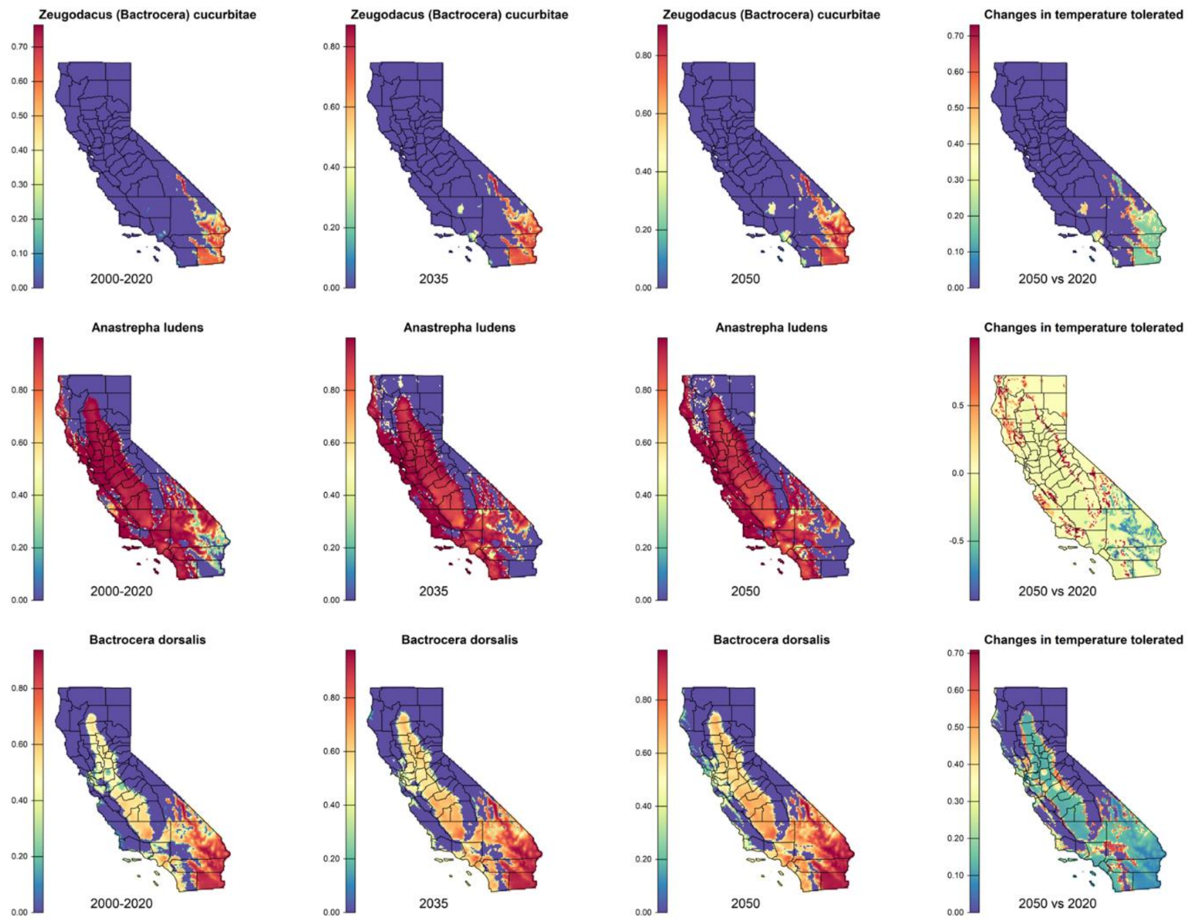

Figure *2*. Temperature suitability for three pests in California for 2000-2020 (current scenario), 2035, and 2050 [Three columns in the left]. Warmer colors represent higher temperature suitability and dark blue indicates temperature is unfavorable for the pest. The difference in temperature suitability for each pest species in 2050 is compared to the current temperature scenario (right column).

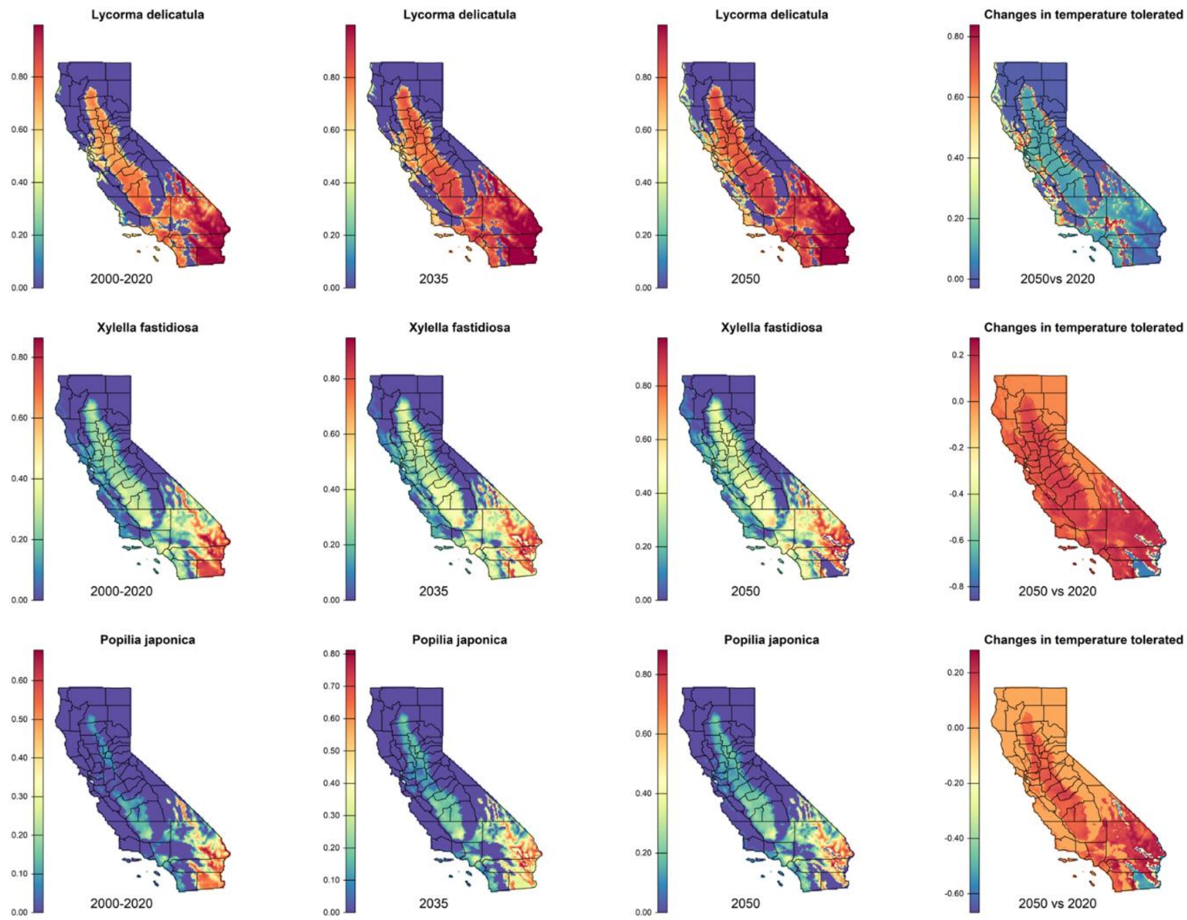

Figure 3. Temperature suitability for three pests in California for 2000-2020 (current scenario), 2035, and 2050 [Three columns in the left]. Warmer colors represent higher temperature suitability and dark blue indicates temperature is unfavorable for the pest. The difference in temperature suitability for each pest species in 2050 is compared to the current temperature scenario (right column).

3.1 Expert knowledge elicitation (EKE)

Figure 4 (EKE) indicates the consensus opinions on the possible impacts of various crop pests and diseases on yield loss in California by 2049, influenced by environmental and socioeconomic factors. These opinions included impacts across five dimensions: climate change, labor availability, land use change, water availability, and overall change by 2049. For grapes, pests and diseases like glassy-winged sharpshooter, and spotted lanternfly are expected to cause increased yield losses overall. While climate change effects are mixed, land use changes are expected to consistently exacerbate impacts, and labor and water availability have moderate but similar effects. Yield losses for panicle and shoot blight in pistachios and canker in almonds are expected to worsen due to climate change and land use changes. Plum pox virus in almonds has a substantial uncertainty overall, but is thought to be highly sensitive to these same drivers. Similarly, viruses in lettuce and leaf spot in strawberries are expected to intensify in impact, with climate and land use changes playing a major role. Labor and water availability have stable, moderate effects. Overall, these results suggest that climate change and land use changes are likely dominant factors driving increases in yield loss in the future. Labor and water availability would have smaller effects on crop yield losses. However, high uncertainties exist for most pests and diseases, particularly in relation to climate change.

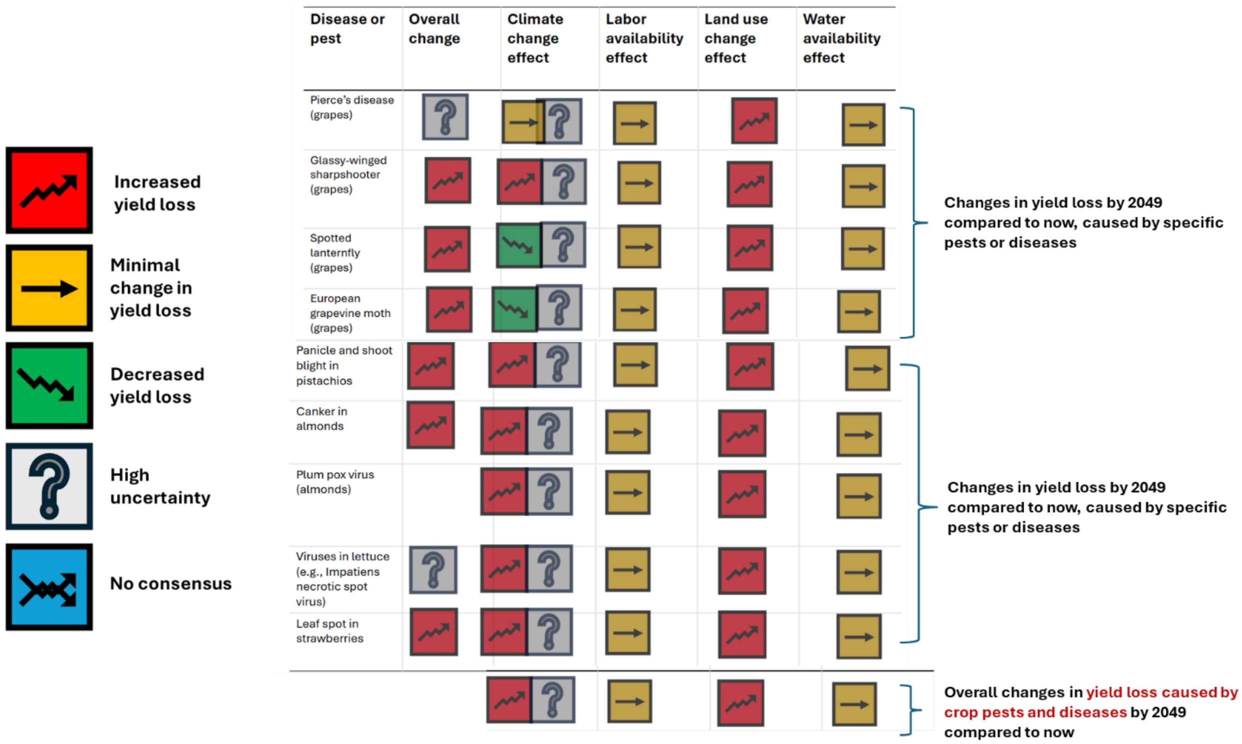

Figure 4. Experts' collective opinions on possible yield losses caused by crop pests and diseases in California by 2049, and the role of a set of influencing factors. The overall opinions about changes in yield loss are analyzed alongside the contributing effects of climate change, labor availability, land-use change, and water availability for some pests and diseases affecting specific crops. Symbols indicate trends as follows: increasing (red upward arrow), stable (yellow rightward arrow), decreasing (green downward arrow), high uncertainty (gray question mark), or lack of expert consensus (intersecting lines).

3.2 Projected changes in future precipitation

Historically, the area of irrigated cropland in California has expanded both in extent and intensity (Figure 5). Groundwater demand is likely to grow in the coming decades if irrigation continues this historical pattern. Artificial water supply will highly likely remain an important element of agricultural adaptation in a warming climate. Previous scenario analyses indicate that California requires more than 50% reduction in groundwater withdrawal if a sustainability policy is implemented in the future (where groundwater withdrawals are restricted to the level of average annual recharge) (Haqiqi et al., 2023).

Small changes in total precipitation throughout California are projected by either a sustainable or business-as-usual scenario (Figure 6). Here, we can assume total precipitation as a proxy of natural water supply for agricultural production (rainfed agriculture), where the timing of water availability is not controlled. However, an increased water demand for the region is likely if annual rainfall is distributed in fewer intense events and the dry season is prolonged. California is expected to experience a moderate increase in drought severity in the coming decades (Cook et al., 2015) and reduction in groundwater storage in the region is likely an issue (Haqiqi et al., 2023).

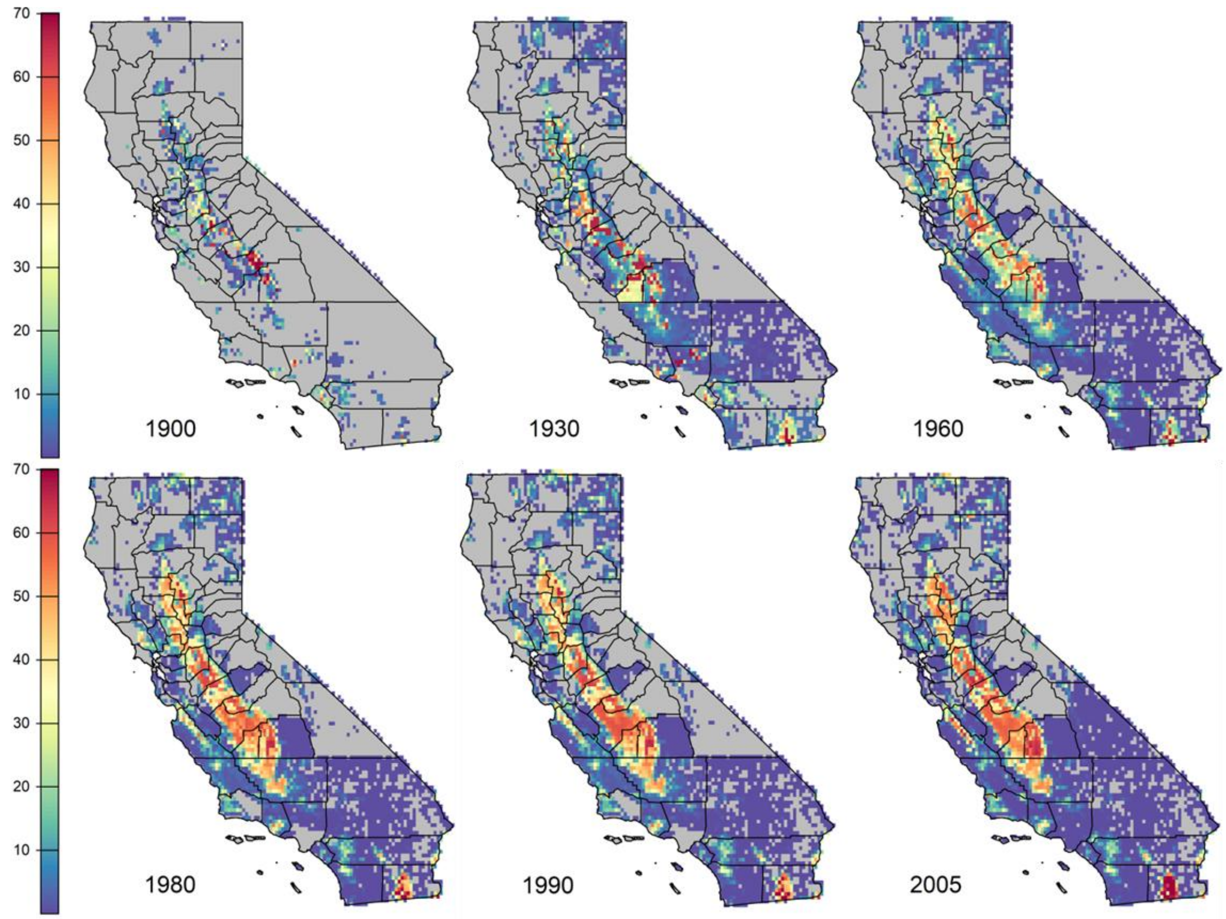

Figure 5. Historical changes in percentage area equipped for irrigation (AEI) in California from 1900 to 2005.

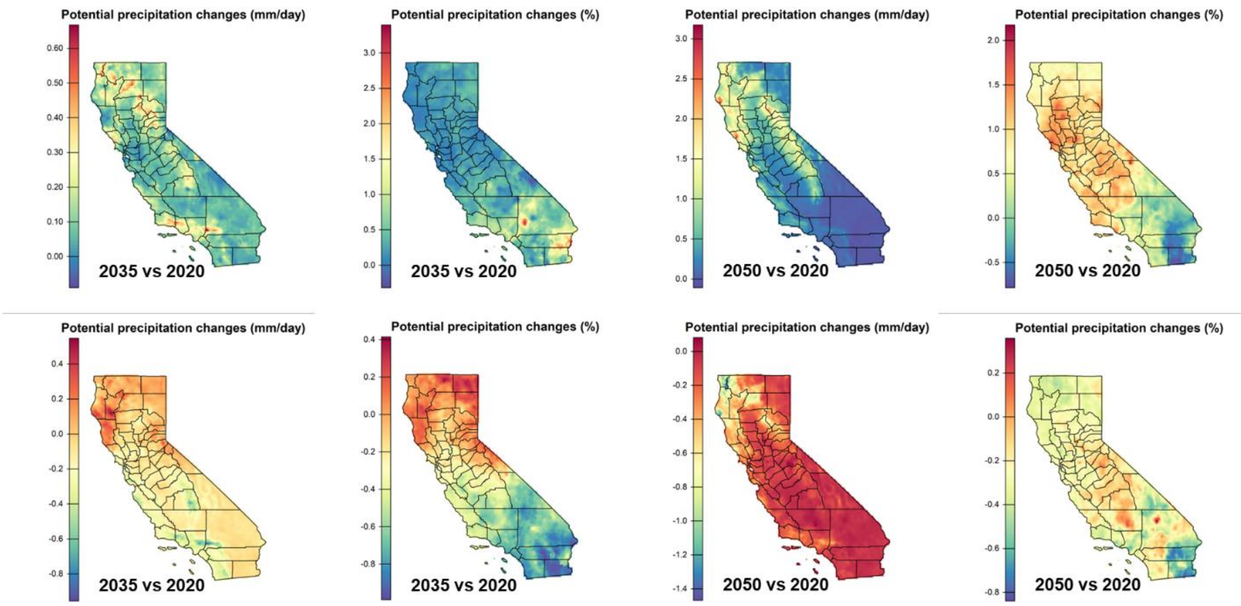

Figure 6. Projected changes in annual mean precipitation (expressed as mean mm/day) in the future (2035 and 2050) compared to current precipitation patterns in California. Potential precipitation changes under a sustainable scenario (rcp 45; top row) are contrasted with a business-as-usual-scenario (rcp 85; bottom row). In both cases, changes are shown in absolute terms (mm/day) and percentage projected terms (%).

3.3 Observed changes in crop growing regions for almond, grape, and tomato

Based on the USDA Census of Agriculture, there was a total increase in harvested area for almonds in most counties of California, while the harvested area for grape and tomato tended to decrease in many counties in the last five years. The harvested area with almonds has generally increased in most of the counties previously cultivating almond (Figure 1), especially in Sacramento where almond harvested doubled for the period under analysis. However, the area harvested with almond reduced substantially in San Joaquin (~90%) and El Dorado (~50%). Kern, Fresno, Madera, Merced and Stanislaus remained the top counties harvesting almond in both years with a tendency to increase (~50%).

Fresno, San Joaquin, Sonoma and Napa were the top counties with harvested acreage of grapes in California in both years analyzed, each county with less than 25% changes in harvested area from 2017 to 2022. Main increases in grape harvested area (>50%) include Marin, San Mateo and Colusa. Most counties though had a slight decrease in harvested area for grapes (<25%). For tomato, the top counties with total harvested area were in Fresno, Merced, San Joaquin and Yolo in both years. Major increases in tomato harvested area (increase in more than 100%) were in San Diego, Santa Clara, Santa Cruz and Monterey. The majority of counties though tended to decrease (<100%) or remain the same in tomato harvested areas during this period.

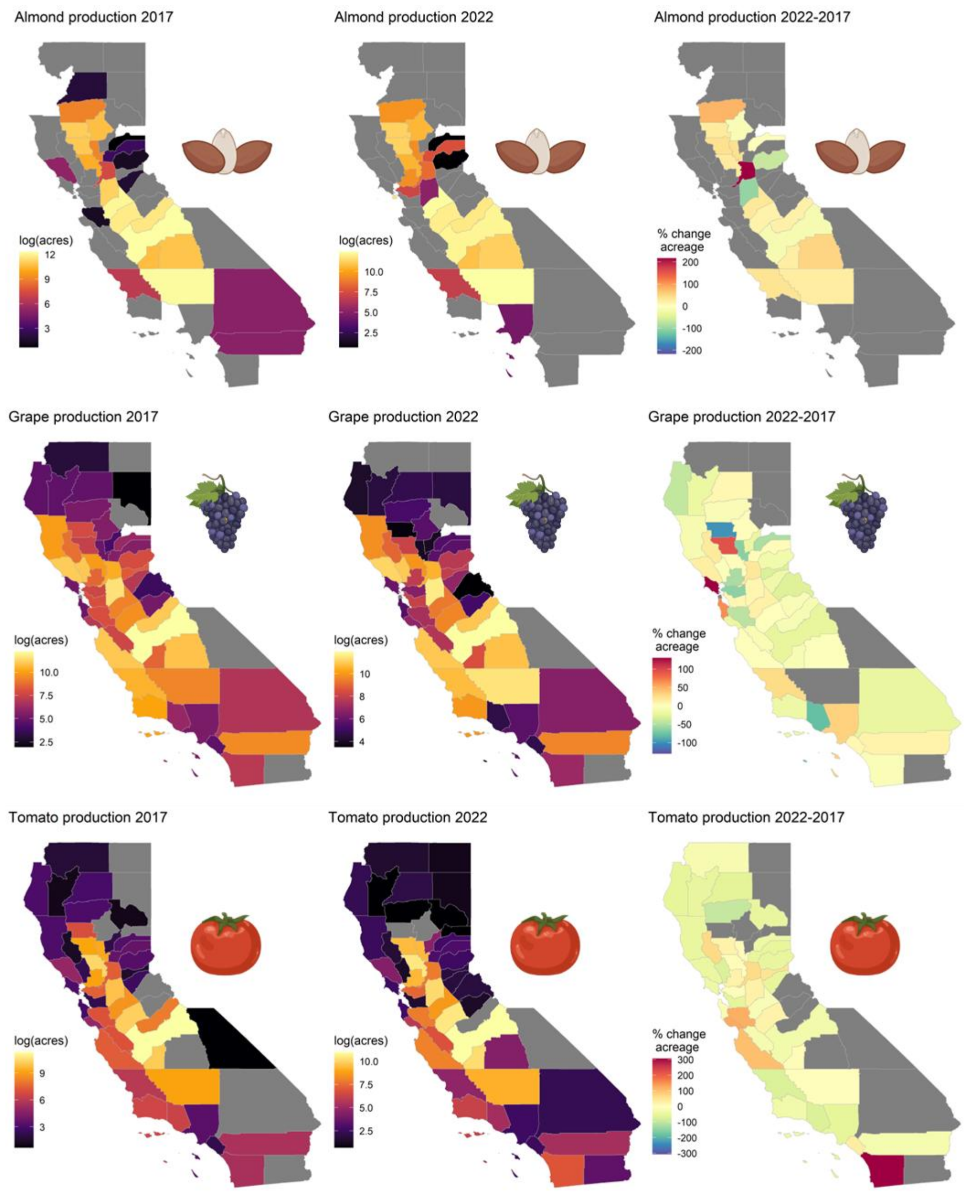

Figure 7. Changes in crop growing regions of three major crops in California (almond, grape, and tomato) from 2017 to 2022, based on the USDA Census of Agriculture.

…Baseline estimates of historical cropland transition = current (?2022) – past (2009)…

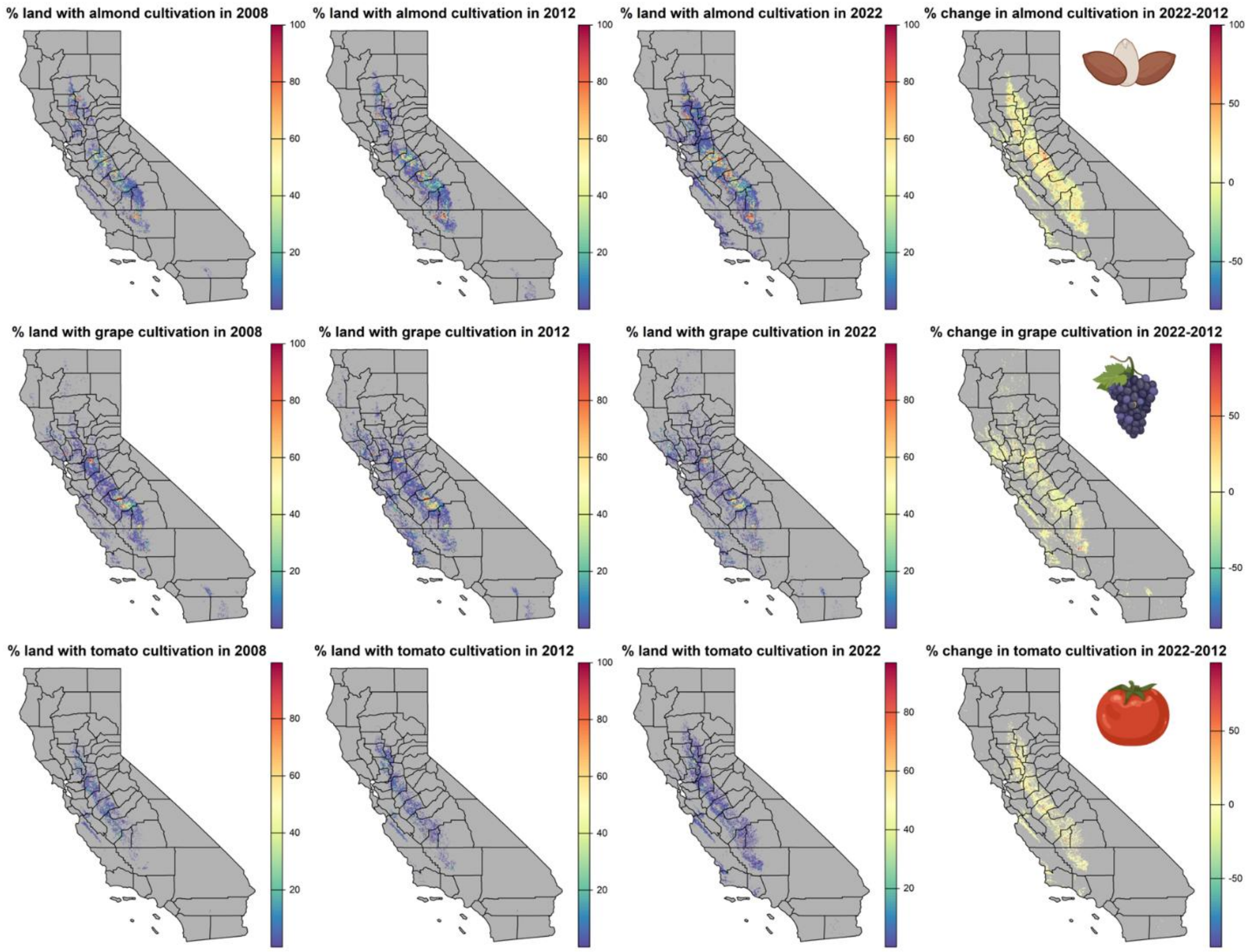

Figure 8. Changes in crop growing regions of three major crops in California (almond, grape, and tomato), based on CroplandCROS.

3.4 Changes in employment in agriculture

Overall, the three evaluated forecasts (SARIMAX, Exponential Smoothing, and Prophet), built using historical employment data from January 1990 to March 2024, suggest that labor demand from California's total crop production and tree nuts will increase through 2050. In contrast, labor demand for vegetable and melon farming, as well as grape farming, is expected to decline (Figure 9). However, the models did not always agree, and the forecasts have high uncertainty. To illustrate this, we can compare labor demand for total crop production, tree nuts, vegetable and melon, and grapes in December 2023 (with 146,400, 25,800, 18,100, and 18,100 employments, respectively) to forecasted values for the same month in 2030 and 2050. For total crop production, SARIMAX predicts increases of 29% and 94% by 2030 and 2050, respectively, while Exponential Smoothing forecasts increases of 2% and 12%, and Prophet predicts decreases of 20% and 43%. Similarly, for tree nuts, SARIMAX and Exponential Smoothing forecast growth (8% and 36% for both models in 2030 and 2050, respectively), while Prophet indicates a modest increase (0.8% and 9% in 2030 and 2050, respectively). In contrast, vegetable and melon labor demand is projected to decline, with all models forecasting a decrease: SARIMAX projects

a 10% decline by 2030, while Exponential Smoothing suggests a 39% decline. For 2050, SARIMAX forecasts a 31% decrease, while Prophet predicts a 65% reduction.
For grapes, a similar downward trend is observed, with reductions ranging from 1% to 58% by 2030 (SARIMAX and Prophet, respectively), and by 2050, Exponential Smoothing suggests a 75% decrease. High uncertainty in the predictions in some cases led to negative labor demand estimates for 2050. Although such values are unrealistic, they underscore the need to estimate the minimum labor requirements necessary to sustain production, even in highly mechanized systems. Quantifying these minimum values could improve forecast accuracy by establishing a realistic lower bound for labor under hypothetical mechanization scenarios.

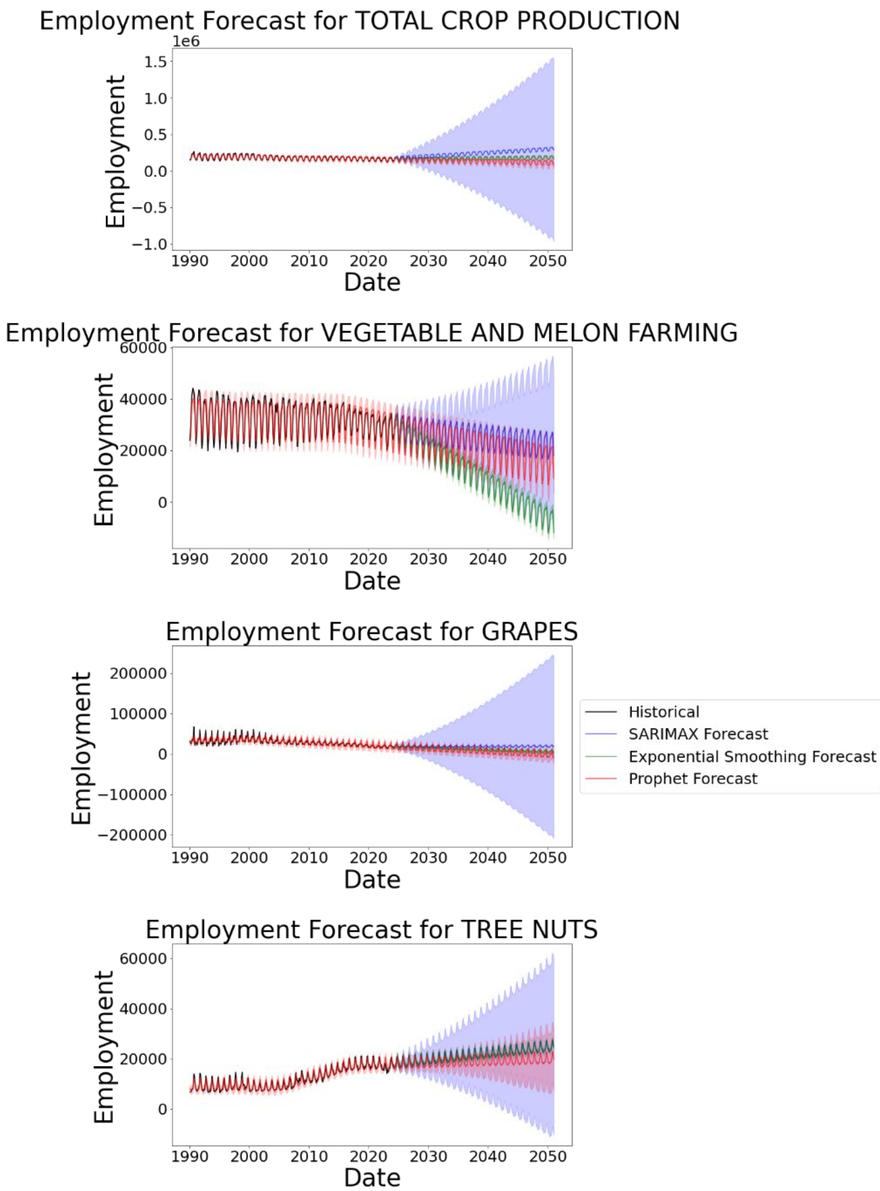

Figure 9. Forecasts based on historical employment data in California suggest that employment for total crop production and tree nuts will slightly increase through 2050, while employment for

vegetable and melon, and grape farming is expected to decline, although predictions have high uncertainty. Historical data is plotted in black, SARIMAX forecast in blue, Exponential Smoothing in green, and Prophet in red. Shaded areas represent the 95% confidence intervals.

3.5 Surveillance for scenarios of Plum pox virus invasion in California

The evaluation of potential infection sites for Rosaceae and stone fruits in California revealed distinct spatial patterns in risk under the two introduction scenarios: equal likelihood of pathogen introduction across locations and likelihood constrained by proximity to ports (Figure 10). Analysis of cultivated Rosaceae showed that the influence of pathogen introduction likelihood, whether influenced by ports or evenly distributed, was minimal. However, the Central Valley consistently emerged as the region of greatest risk, reflecting the high density of stone fruit cultivation in this area. For wild Rosaceae occurrences based on the GBIF dataset, the impact of proximity to ports was more pronounced. Risk decreased in northern California as distance from ports increased. In contrast, regions in the Central Valley and southern California exhibited elevated risk due to their proximity to likely introduction points, such as ports. This spatial pattern underscores the significance of introduction points for the spread of pathogens in wild Rosaceae. When integrating cultivated Rosaceae (CroplandCROPS) and wild Rosaceae occurrences (GBIF), the effects of constrained introduction likelihood became more evident. In northern and southern California, proximity to ports was associated with relatively lower risk compared to the equal likelihood scenario. In the Central Valley, however, risk remained consistently high regardless of the introduction scenario, driven by the area's dense agricultural activity and crop diversity.

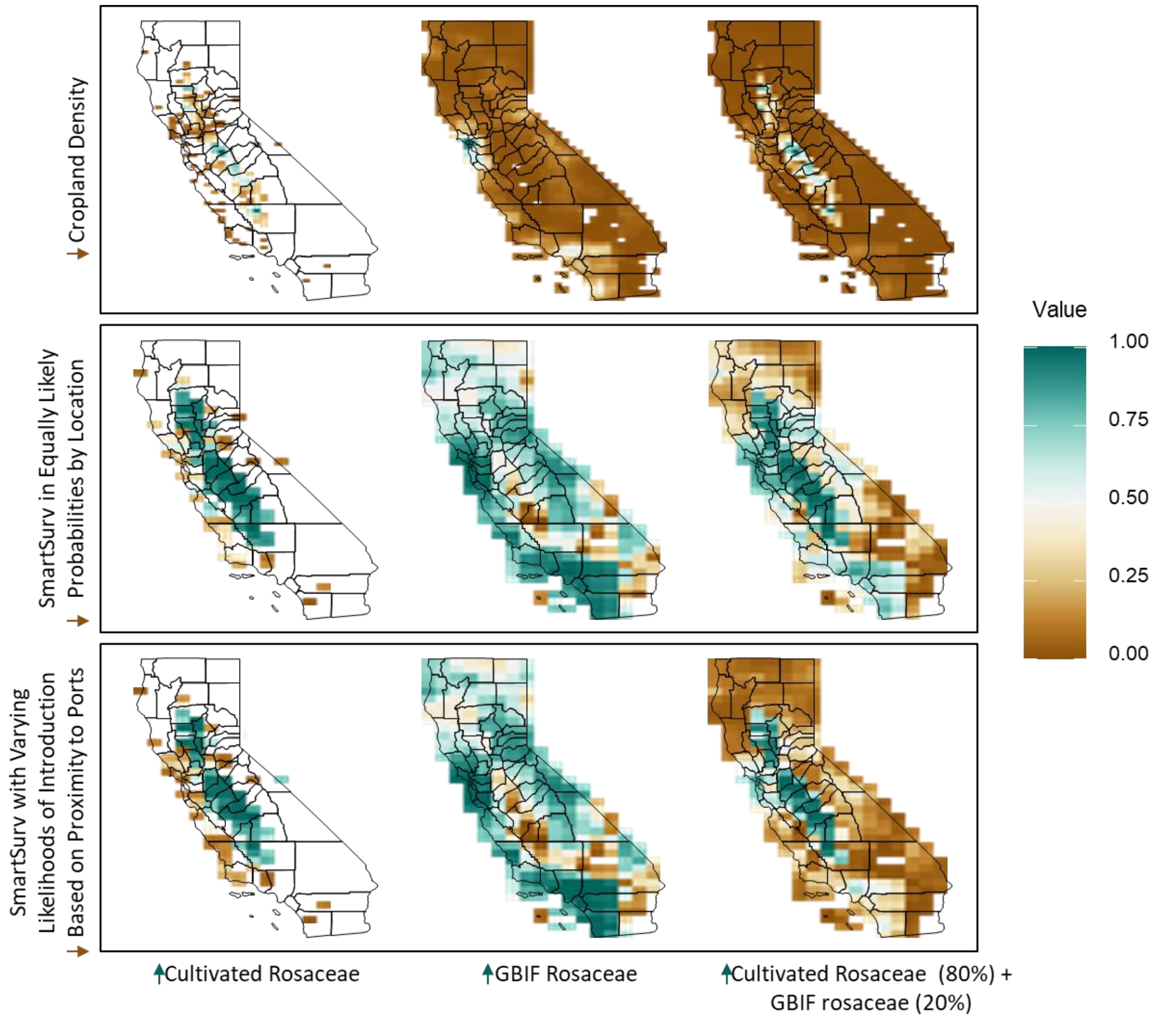

Figure 10. Scenarios for the importance of locations in surveillance for a future potential invasion of Plum pox virus in simulated epidemics. High-value areas for surveillance are concentrated in the Central Valley, with northern and southern regions showing variable importance, influenced by proximity to ports. The geographic distribution of value for surveillance is indicated for Rosaceae and stone fruits in California under two introduction scenarios: (row 2) equal likelihood of introduction across locations, and (row 3) introduction likelihood constrained by proximity to ports. Value for surveillance is shown for (Column 1) cultivated Rosaceae, (Column 2) all Rosaceae (GBIF), and (Column 3) combined datasets.

DISCUSSION

We provide a simple geographic assessment of future pest risks in California, which could serve as a first step for developing a more detailed and integrated evaluation of the effects of these risk factors on yield losses in the future. Here, we discuss considerations for decision-making based on each analysis, as well as opportunities to strengthen each analysis in follow-up steps.

4.1 Effects of temperature change

Temperature changes in 2035 and 2050 will potentially increase the general risk of the selected pests in California, either in terms of an expansion in the area with a temperature tolerated by the pest or increased suitability of locations that are already favorable. This analysis could be improved by including other important aspects of each pest's biology. In these simple ecological niche models, the main source of uncertainty was choosing the future scenarios for climate projections. Despite choosing distinct future climate projections, the findings remain very similar across the selected scenarios. Future modeling approaches could target more realistic scenarios for pest development, for example, (i) considering different stages of the life cycle of a pest or pathogen, (ii) including other environmental factors influencing pest development such as humidity or edaphic factors, and (iii) coupling pest models with spatially explicit crop growing models. While an annual time scale used in the climatic modeling approach may be a good fit for the biannual or annual life cycle of the Japanese beetle, this method may be less appropriate for pathogens and pests with shorter life cycles. A finer temporal resolution to account for variation within a year could improve these ecological niche models. A particularly important consideration is the validation of these models with available georeferenced data of occurrence of each pest in California. Here we provided a future scenario approach, but we could build on this with a 'hindcasting' approach that assesses the importance of environmental factors on the historical distribution and introduction of pests and pathogens in California, to provide better-calibrated predictions in the future.

Expert knowledge elicitation

Expert opinions highlight that crop pests and diseases in California are likely to be increasingly influenced by climate change and land use changes in the future, posing significant risks to agricultural yields. Climate change may amplify pest severity by enhancing pest spread (Garrett et al., 2022). These expert expectations supported our projected findings on the potential distribution of pests across California. Land use changes like habitat disruption may exacerbate pest outbreaks (Pongsiri et al., 2009). These trends emphasize the urgent need for sustainable land management and climate adaptation strategies tailored to California's diverse agricultural systems. Experts perceived labor and water availability as less impactful than climate and land use changes, but these factors pose critical challenges. Persistent labor shortages could hinder timely pest control efforts (Deguine et al., 2021), and water scarcity further reduces crop productivity and threatens food security (Lamaoui et al., 2018). Below, we discuss in more detail these two issues. Our findings based on expert knowledge elicitation provide key qualitative expectations for future changes in each main factor likely affecting pest management. However, there are quantitative uncertainties about how specific pests will respond to every changing factor. These uncertainties underscore the need for further research to refine predictive models and implement targeted interventions. Below, we discuss possible approaches for quantitative integration of the effects of each of these changing factors in pest management models.

4.2 Projected changes in future precipitation

The area equipped for irrigation (AEI) in California has expanded and intensified in the last century, especially in the Central Valley (Figure 5). California's agriculture is strongly dependent on water for irrigation. Irrigation can promote disease or pest development (Baroudy et al., 2018; Hong & Moorman, 2005). For example, De Villiers et al. (2016) found that irrigation is a key factor in predicting the global distribution of *Bactrocera dorsalis*. It is widely known that water splashing play a key role in pathogen dissemination while leaf or canopy and soil moisture is important for the establishment of foliar and soilborne pathogens (Hong & Moorman, 2005). However, there are two important data limitations: uncertainty about temporal and spatial irrigation patterns in the future and lack of irrigation data for specific crops. Here, we used precipitation projections to capture one element of water availability in California in the future. In general, annual precipitation levels are projected to experience limited changes in the future regardless of possible future emission scenarios (Figure 6). Irrigation will continue to be required for agricultural production.

However, how precipitation will change during growing seasons requires a more detailed evaluation of future projections. Importantly, the utility of precipitation for agriculture may be reduced if the same amount of rain is experienced in fewer larger precipitation events. Likewise, pest-specific analyses would be useful, clarifying the effects of future changes in precipitation, across seasons and locations in California. We propose to develop a time series analysis that integrates precipitation/irrigation and temperature variations within the year (ideally daily), their potential effects on crops, and their potential effects on key pests and diseases.

4.3 Changes in growing regions for almond, grape, and tomato

Based on historical county-level data, California's almond, grape and tomato cultivation has increased in the last five years (Figure 7). Despite differences in data sources used, these results are also consistent with higher resolution estimates for these three crops across California (Figure 8). These results indicate that there is high host availability for the local spread of crop-specific pathogens or pests, a risk factor if new pathogens or pests are introduced or emerge (Margosian et al., 2009)(Xing et al., 2020). High-resolution crop distribution data as in CroplandCROS could be used to develop more complete pest-specific risk assessment (Magarey et al., 2011) and evaluate pest-specific management scenarios across California (Garrett, 2021a). For example, Cunniffe et al. (2016) incorporated host availability data to assess management of the spread of sudden oak death in California.

This consistency between CroplandCROS and the Census of Agriculture as well as the high accuracy of crop distribution in CroplandCROS for these crops indicate that we could use this crop distribution information for future pest risk analysis. Current host availability information can be used to assess the potential spread of pathogens and pests across California (Keshav et al., 2024) if crop distribution remains the same in the future. However, there are apparently no available projections of how climate change would affect the geographic distribution of these crops in California in the future. There are, however, some studies evaluating how climate change would affect the production of these crops in California. For example, Cammarano et al. (2022) found that processing tomato production in California would generally decrease due to climate change. Likewise, Pathak and Stoddard (2018) found that climate change would affect tomato growing season in California. To our knowledge, there is no modeling approach evaluating how production of these crops would be simultaneously affected by climate change and pests/diseases in the future, especially in terms of identification of which locations will be most at risk within California. A basic approach could be combining the temperature-based projections for each pest (Fig. 1-3) with host availability maps (Fig. 8). Future more robust modeling approaches could also focus on daily or seasonal changes in both crop-growing regions and potential pest distribution in California under climate change scenarios.

4.4 Changes in employment in agriculture

Although the models of future employment in agriculture did not always converge on the same forecast, they generally suggest that labor demand in California's total crop production and tree nut sectors will increase through 2050. Conversely, labor demand for vegetable and melon farming, as well as grape farming, declined (Figure 9). It is important to note that these forecasts are based solely on employment trends over time within each agricultural subsector. While some external factors affecting agricultural employment may be indirectly reflected in historical data, specific drivers of trend changes cannot be explicitly captured. This limitation introduces large uncertainty in future predictions, particularly those extending to 2050. Factors that could impact labor demand in California include an aging workforce, immigration policies, wages and working conditions, urbanization and cost of living, technological advancements, shifts in crop types and production, climate change, water scarcity, and labor competition from other sectors.

The influences of these factors are complex, and although their impact on labor availability is evident, it has rarely been quantified. California's agricultural sector has, however, attempted to adapt to these challenges. Between 2015 and 2019, the average age of agricultural workers in California was 40 years, with 84 percent of California crop workers born outside the United States, primarily from neighboring countries like Mexico (Ornelas et al., 2022). In California, 49% of the agricultural labor force comprised undocumented migrants (Rosenbloom, 2022). This composition makes the sector highly susceptible to immigration policies and associated costs, which could sharply decrease labor demand as wages rise (Richards, 2018). For example, wages for H-2A workers—temporary agricultural workers under the specific visa—have sharply increased, while agricultural product prices are constrained by competitive pressures (Duvall, 2023; Richards, 2018). Additionally, the growing interest in California real estate has driven up housing prices and living costs near agricultural areas, creating further challenges for agricultural workers (Phillips et al., 2022). In response to these challenges that constrain labor availability, California's agricultural businesses have increasingly adopted mechanization and specialized technology. Examples of strategies to overcome labor shortages include the well-documented shift in the tomato and tree nut industries from manual harvesting to mechanization (Baur & Iles, 2022; de la Peña, 2015).

4.5 Plum pox invasion scenarios

In the Plum pox virus (PPV) invasion scenarios in California, the Central Valley consistently emerges as a high-risk zone under both uniform likelihood and port proximity dependent introductions. This elevated risk is primarily due to the area's intensive stone fruit production and extensive commercial networks (Lazicki et al., 2016; Norton et al., 2007). Conversely, wild Rosaceae populations in northern and southern California exhibit greater vulnerability to port-based introductions. Thus, pathogen incursion may be amplified by high-traffic trade corridors and frequent plant material exchange (García et al., 2024). These findings underscore the importance of strategically allocating limited surveillance resources to high-density agricultural zones and major port regions, rather than relying on uniform coverage, to optimize detection efforts and mitigate disease spread in critical risk areas (Kalaris et al., 2014).

Future development of this modeling framework would benefit from integrating additional high-resolution data layers, including nursery locations, road networks, and known plant trade routes, to refine our understanding of local variability (Pautasso & Jeger, 2014). Such enhancements must be accompanied by uncertainty assessments, particularly given the potential biases in occurrence datasets, including those sourced in GBIF (Pironon et al., 2024; Poppenwimer et al., 2023). Improved temporal modeling, which accounts for empirical pathogen dispersal rates, seasonality, and vector dynamics, would also shed light on how PPV invasion risk may evolve under climate change and shifting agricultural practices. Beyond single-pathogen analyses, a broader perspective that contemplates simultaneous introductions of multiple invasive threats could indicate opportunities for synergistic surveillance strategies. Ultimately, iterative feedback loops with growers, port authorities, and regulatory agencies will help ensure that these technical insights translate into practical, proactive measures for safeguarding California's stone fruit industry.

Research frontiers and potential next steps building on these analyses

Evaluating surveillance strategies in general. We could provide an analysis of current surveillance strategies in California, developed in collaboration with CDFA teams to target their specific questions and what they experience as the greatest uncertainties. This analysis would draw on experience in evaluating surveillance strategies in several countries. For example, models of potential pathogen or pest spread, such as in the plum pox virus example here, can be used to evaluate how a pathogen or pest is most likely to disperse through California agricultural systems and landscapes, based on current knowledge. Particular locations may play important roles in invasion or saturation by pathogens and pests, by acting as a hub for dispersal or a bridge between different parts of the landscape. This analysis could also be designed for ongoing improvement as new information becomes available, as well as providing information about the most important new information to collect based on model sensitivity analyses.

Plum pox virus. As described above, the analysis for Plum pox virus, or other potentially invasive pest species identified as key for future planning can be built on by evaluating scenarios for management identified by CDFA teams. Analyses could include assessment of the benefits (and costs) of different approaches to state-wide management, in terms of avoidance or postponement of yield and quality losses and potential quarantines and trade barriers for products.

Analyses of specific types of precipitation events. As described above, in this initial analysis, we have evaluated current and projected future precipitation in terms of mean precipitation rates. Another dimension of important changes in precipitation is the potential distribution of precipitation into fewer larger precipitation events. Changing to fewer larger precipitation events makes agricultural operations more challenging in general, with the potential for droughts, fires, and flooding. In a next phase, we could evaluate future precipitation changes in finer temporal resolution, to clarify which locations are likely to require adjustments to water management and associated pest management adaptation requirements.

Expert knowledge elicitation. The expert knowledge elicitation activities in the current project were somewhat limited in terms of the expert time that we were able to access. In a future project in which incentives were in place for experts to invest a day of their time in a more intensive expert knowledge elicitation, we could produce more valuable and general results. For example, perhaps experts could be paid for their time and the activity could be combined with other professional development activities at the same location, so that the time investment would be attractive to experts.

REFERENCES

Ahn, J. J., Choi, K. S., & Huang, Y.-B. (2022). Thermal effects on the development of *Zeugodacus cucurbitae* (Coquillett) (Diptera: Tephritidae) and model validation. *Phytoparasitica*, *50*(3), 601-616. https://doi.org/10.1007/s12600-022-00985-5

Baroudy, F., Habib, W., Tanos, G., Gerges, E., Saab, C., Choueiri, E., & Nigro, F. (2018). Long-distance spread of *Verticillium dahliae* through rivers and irrigation systems. *Plant Disease*, *102*(8), 1559-1565. https://doi.org/10.1094/PDIS-08-17-1189-RE

Baur, P., & Iles, A. (2022). Replacing humans with machines: a historical look at technology politics in California agriculture. *Agriculture and Human Values*, *40*(1), 113-140. https://doi.org/10.1007/s10460-022-10341-2

Briere, J. F., Pracros, P., Le Roux, A. Y., & Pierre, J. S. (1999). A novel rate model of temperature-dependent development for arthropods. *Environmental Entomology*, *28*(1), 22-29. https://doi.org/https://doi.org/10.1093/ee/28.1.22

Cammarano, D., Jamshidi, S., Hoogenboom, G., Ruane, A. C., Niyogi, D., & Ronga, D. (2022). Processing tomato production is expected to decrease by 2050 due to the projected increase in temperature. *Nature Food*, *3*(6), 437-444. https://doi.org/10.1038/s43016-022-00521-y

Chaloner, T. M., Gurr, S. J., & Bebber, D. P. (2021). Plant pathogen infection risk tracks global crop yields under climate change. *Nature Climate Change*, *11*(8), 710-715. https://doi.org/10.1038/s41558-021-01104-8

Clayton, E. E. (1923). The relation of temperature to the Fusarium wilt of the tomato. *American Journal of Botany*, *10*(2), 71-88. https://doi.org/10.2307/2435575

Cook, B. I., Ault, T. R., & Smerdon, J. E. (2015). Unprecedented 21st century drought risk in the American Southwest and central Plains. *Science Advances*, *1*, e1400082. https://doi.org/10.1126/sciadv.1400082

Cunniffe, N. J., Cobb, R. C., Meentemeyer, R. K., Rizzo, D. M., & Gilligan, C. A. (2016). Modeling when, where, and how to manage a forest epidemic, motivated by sudden oak death in California. *Proceedings of the National Academy of Science of the United States America*, *113*(20), 5640-5645. https://doi.org/10.1073/pnas.1602153113

Damsteegt, V. (2008). Plum pox virus (sharka). *42203*. https://doi.org/10.1079/cabicompendium.42203 de la Peña, C. (2015). Good to think with: Another look at the mechanized tomato. *Food, Culture & Society*, *16*(4), 603-631. https://doi.org/10.2752/175174413x13673466711769

De Villiers, M., Hattingh, V., Kriticos, D. J., Brunel, S., Vayssieres, J. F., Sinzogan, A., Billah, M. K., Mohamed, S. A., Mwatawala, M., Abdelgader, H., Salah, F. E., & De Meyer, M. (2016). The potential distribution of Bactrocera dorsalis: considering phenology and irrigation patterns. *Bulletin of Entomological Research*, *106*(1), 19-33. https://doi.org/10.1017/S0007485315000693

Deguine, J.-P., Aubertot, J.-N., Flor, R. J., Lescourret, F., Wyckhuys, K. A., & Ratnadass, A. (2021). Integrated pest management: good intentions, hard realities. A review. *Agronomy for Sustainable Development*, *41*(38). https://doi.org/10.1007/s13593-021-00689-w

Duvall, Z. (2023). New H-2A wage rule set to crush family farms. *The Zipline*. https://www.fb.org/the-zipline/new-h-2a-wage-rule-set-to-crush-family-farms

Feil, H., & Purcell, A. H. (2001). Temperature-dependent growth and survival of *Xylella fastidiosa* in vitro and in potted grapevines. *Plant Disease*, *85*, 1230-1234. https://doi.org/10.1094/PDIS.2001.85.12.1230

García, J. A., Rodamilans, B., Martínez-Turiño, S., Valli, A. A., Simón-Mateo, C., & Cambra, M. (2024). Plum pox virus: An overview of the potyvirus behind sharka, a harmful stone fruit disease. *Annals of Applied Biology*, *186*(1), 49-75. https://doi.org/10.1111/aab.12958

Garrett, K. A. (2021a). Impact network analysis and the INA R package: Decision support for regional management interventions. *Methods in Ecology and Evolution*, 1-14. https://doi.org/10.1111/2041-210x.13655

Garrett, K. A. (2021b). User guide to impact network analysis (INA). *CGIAR Research Program on Roots, Tubers and Bananas (RTB)*, 32. https://doi.org/10.4160/9789290605768

Garrett, K. A., Bebber, D. P., Etherton, B. A., Gold, K. M., Plex Sula, A. I., & Selvaraj, M. G. (2022). Climate change effects on pathogen emergence: Artificial intelligence to translate big data for mitigation. *Annual Review of Phytopathology*, *60*, 357-378. https://doi.org/10.1146/annurev-phyto-021021-042636

Gilioli, G., Sperandio, G., Colturato, M., Pasquali, S., Gervasio, P., Wilstermann, A., Dominic, A. R., & Schrader, G. (2021). Non-linear physiological responses to climate change: the case of *Ceratitis capitata* distribution and abundance in Europe. *Biological Invasions*, *24*(1), 261-279. https://doi.org/10.1007/s10530-021-02639-9

Guillen, L., Pascacio-Villafan, C., Osorio-Paz, I., Ortega-Casas, R., Enciso-Ortiz, E., Altuzar-Molina, A., Velazquez, O., & Aluja, M. (2022). Coping with global warming: Adult thermal thresholds in four pestiferous *Anastrepha* species determined under experimental laboratory conditions and development/survival times of immatures and adults under natural field conditions. *Frontiers in Physiology*, *13*, 991923. https://doi.org/10.3389/fphys.2022.991923

Gutierrez, A. P., Ponti, L., Cooper, M. L., Gilioli, G., Baumgärtner, J., & Duso, C. (2012). Prospective analysis of the invasive potential of the European grapevine moth *Lobesia botrana* (Den. & Schiff.) in California. *Agricultural and Forest Entomology*, *14*(3), 225-238. https://doi.org/10.1111/j.1461-9563.2011.00566.x

Haqiqi, I., Bowling, L., Jame, S., Baldos, U., Liu, J., & Hertel, T. (2023). Global drivers of local water stresses and global responses to local water policies in the United States. *Environmental Research Letters*, *18*(6). https://doi.org/10.1088/1748-9326/acd269

Hong, C. X., & Moorman, G. W. (2005). Plant pathogens in irrigation water: challenges and opportunities. *Critical Reviews in Plant Sciences*, *24*(3), 189-208. https://doi.org/10.1080/07352680591005838

Kalaris, T., Fieselmann, D., Magarey, R., Colunga-Garcia, M., Roda, A., Hardie, D., Cogger, N., Hammond, N., Tony Martin, P., & Whittle, P. (2014). The role of surveillance methods and technologies in plant biosecurity. In G. Gordh & S. McKirdy (Eds.), *The handbook of plant biosecurity* (pp. 309-337). Springer. https://doi.org/10.1007/978-94-007-7365-3_11

Kebreab, E., & Murdoch, A. J. (1999). A model of the effects of a wide range of constant and alternating temperatures on seed germination of four *Orobanche* species. *Annals of Botany*, *84*(4), 584-557. https://doi.org/10.1006/anbo.1998.0948

Keshav, K., Plex Sulá, A. I., & Garrett, K. A. (2024). geohabnet: Geographical risk analysis based on habitat connectivity. *R package version 2.1.2 (https://CRAN.R-project.org/package=geohabnet)*.

Kistner-Thomas, E. J. (2019). The potential global distribution and voltinism of the Japanese beetle (Coleoptera: Scarabaeidae) under current and future climates. *Journal of Insect Science*, *19*(2), 1-13. https://doi.org/10.1093/jisesa/iez023

Krantz, W., Pierce, D., Goldenson, N., & Cayan, D. (2021). *Memorandum on evaluating global climate models for studying regional climate change in California*. https://www.energy.ca.gov/sites/default/files/2022-09/20220907_CDAWG_MemoEvaluating_GCMs_EPC-20-006_Nov2021-ADA.pdf

Lamaoui, M., Jemo, M., Datla, R., & Bekkaoui, F. (2018). Heat and drought stresses in crops and approaches for their mitigation. *Frontiers in Chemistry*, *6*, 26. https://doi.org/10.3389/fchem.2018.00026

Lazicki, P., Geisseler, D., & Horwath, W. R. (2016). *Peach and nectarine production in California*.

Magarey, R. D., Borchert, D. M., Engle, J. S., Colunga-Garcia, M., Koch, F. H., & Yemshanov, D. (2011). Risk maps for targeting exotic plant pest detection programs in the United States. *EPPO Bulletin*, *41*, 46-56.

Maino, J. L., Schouten, R., Lye, J. C., Umina, P. A., & Reynolds, O. L. (2022). Mapping the life-history, development, and survival of spotted lantern fly in occupied and uninvaded ranges. *Biological Invasions*, *24*(7), 2155-2167. https://doi.org/10.1007/s10530-022-02764-z

Margosian, M. L., Garrett, K. A., Hutchinson, J. M. S., & With, K. A. (2009). Connectivity of the American agricultural landscape: Assessing the national risk of crop pest and disease spread. *BioScience*, *59*(2), 141-151. https://doi.org/10.1525/bio.2009.59.2.7

Norton, M., Duncan, R., & Hasey, J. (2007). Growing processing cling peaches in California: An overview. *UC Peer Reviewed*, *8276*, 6.

Ornelas, I., Fung, W., Gabbard, S., & Carroll, D. (2022). *California findings from the National Agricultural Workers Survey (NAWS) 2015-2019: A demographic and employment profile of California farmworkers*.

Pathak, T. B., & Stoddard, C. S. (2018). Climate change effects on the processing tomato growing season in California using growing degree day model. *Modeling Earth Systems and Environment*, *4*(2), 765-775. https://doi.org/10.1007/s40808-018-0460-y

Pautasso, M., & Jeger, M. J. (2014). Network epidemiology and plant trade networks. *AoB Plants*, *6*(0). https://doi.org/10.1093/aobpla/plu007

Phillips, S., Reid, C., Cuff, D., & Wong, K. (2022). Housing and community development in California: An in-depth analysis of the facts, origins and trends of housing and community development in California. *UCLA: The Ralph and Goldy Lewis Center for Regional Policy Studies*, 1-107. https://escholarship.org/uc/item/32m1g6xk

Pironon, S., Ondo, I., Diazgranados, M., Allkin, R., Baquero, A., Cámara-Leret, R., Canteiro, C., Dennehy, Z., Govaerts, R., Hargreaves, S., Hudson, A., Lemmens, R., Miliken, W., Nesbitt, M., Patmore, K., Schmelzer, G., Turner, R., van Andel, T., Ulian, T., Antonelli, A., & Willis, K. (2024). The global distribution of plants used by humans. *Science*, *383*, 293-297. https://doi.org/10.1126/science.adg8028

Pongsiri, M. J., Roman, J., Ezenwa, V. O., Goldberg, T. L., Koren, H. S., Newbold, S. C., Ostfeld, R. S., Pattanayak, S. K., & Salkeld, D. J. (2009). Biodiversity loss affects global disease ecology. *BioScience*, *59*(11), 945-954. https://doi.org/10.1525/bio.2009.59.11.6

Poppenwimer, T., Mayrose, I., & DeMalach, N. (2023). Revising the global biogeography of annual and perennial plants. *Nature*, *624*(7990), 109-114. https://doi.org/10.1038/s41586-023-06644-x

Richards, T. J. (2018). Immigration reform and farm labor markets. *American Journal of Agricultural Economics*, *100*(4), 1050-1071. https://doi.org/10.1093/ajae/aay027

Rosenbloom, R. (2022). *A profile of undocumented agricultural workers in the United States* (2331-5024
2330-2488). (Center for Migration Studies of New York (CMS) Report, Issue.

Siebert, S., Kummu, M., Porkka, M., Döll, P., Ramankutty, N., & Scanlon, B. R. (2015). A global data set of the extent of irrigated land from 1900 to 2005. *Hydrology and Earth System Sciences*, *19*(3), 1521-1545. https://doi.org/10.5194/hess-19-1521-2015

Stephens, A. E., Kriticos, D. J., & Leriche, A. (2007). The current and future potential geographical distribution of the oriental fruit fly, Bactrocera dorsalis (Diptera: Tephritidae). *Bulletin of Entomological Research*, *97*(4), 369-378. https://doi.org/10.1017/S0007485307005044

USDA, U. S. D. o. A. (2024a). *Census of Agriculture*. https://www.nass.usda.gov/AgCensus/

USDA, U. S. D. o. A. (2024b). *CroplandCROS*. https://croplandcros.scinet.usda.gov/

USDA, U. S. D. o. A. (2024c). *CropScape and Cropland Data Layer - Metadata*. https://www.nass.usda.gov/Research_and_Science/Cropland/metadata/meta.php

Xing, Y., Hernandez Nopsa, J. F., Andersen, K. F., Andrade-Piedra, J. L., Beed, F. D., Blomme, G., Carvajal-Yepes, M., Coyne, D. L., Cuellar, W. J., Forbes, G. A., Kreuze, J. F., Kroschel, J., Kumar, P. L., Legg, J. P., Parker, M., Schulte-Geldermann, E., Sharma, K., & Garrett, K. A. (2020). Global cropland connectivity: A risk factor for invasion and saturation by emerging pathogens and pests. *BioScience*, *70*(9), 744-758. https://doi.org/10.1093/biosci/biaa067