

Climate change effects on walnut pests in California

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Abstract

Increasing temperatures are likely to impact ectothermic pests of fruits and nuts. This paper aims to assess changes to pest pressure in California's US\$0.7 billion walnut industry due to recent historic and projected future temperature changes. For two past (1950 and 2000) and 18 future climate scenarios (2041–2060 and 2080–2099; each for three General Circulation Models and three greenhouse gas emissions scenarios), 100 years of hourly temperature were generated for 205 locations. Degree-day models were used to project mean generation numbers for codling moth (*Cydia pomonella* L.), navel orangeworm (*Amyelois transitella* Walker), two-spotted spider mite (*Tetranychus urticae* Koch), and European red mite (*Panonychus ulmi* Koch). In the Central Valley, the number of codling moth generations predicted for degree days accumulated between April 1 and October 1 rose from 2–4 in 1950 to 3–5 among all future scenarios. Generation numbers increased from 10–18 to 14–24 for two-spotted spider mite, from 9–14 to 14–20 for European red mite, and from 2–4 to up to 5 for navel orangeworm. Overall pest pressure can thus be expected to increase substantially. Our study did not include the possibility of higher winter survival rates, leading to higher initial pest counts in spring, or of extended pest development times in the summer, factors that are likely to exacerbate future pest pressure. On the other hand, initiation of diapause may prevent an extension of the season length for arthropods, and higher incidence of heat death in summer may constrain pest population sizes. More information on the impact of climate change on complex agroecological food webs and on the response of pests to high temperatures is needed for improving the reliability of projections.

Keywords: climate change, codling moth, degree-day models, European red mite, fruits and nuts, *Juglans regia* L., navel orangeworm, two-spotted spider mite

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Introduction

Overwhelming evidence suggests that the global climate is changing. Many studies have shown that global temperatures have increased in recent decades, and it is virtually certain that they will continue to increase in the future (IPCC, 2007). Ectothermic organisms, whose body temperature depends directly on ambient temperature, are likely to respond rapidly to such changes (Deutsch *et al.*, 2008). As many plant pests fall into this category, it is important to include projections of climate change effects on these organisms into considerations on future food security (Gregory *et al.*, 2009). Such projections will also allow estimating future pesticide use trends and anticipating the effects of such trends on environmental health and development of resistance to pesticides among target pests.

Climate warming is likely to increase pest pressure for a variety of plant species (Paulson *et al.*, 2009). Parmesan & Yohe (2003) clearly showed that ranges and phenology of many biological species have already been affected. Evidence has been presented, for example, for increasing numbers of coffee berry borer generations in several countries (Jaramillo *et al.*, 2009), pest pressure increases in Canadian forests (Dukes *et al.*, 2009) and wider distributions of agricultural pests in Chile (Estay *et al.*, 2009). Such developments will almost certainly affect agriculture, leading to the expansion of pest ranges, allowing new pests to invade cropping areas and changing the dynamics and natural equilibrium states of agroecosystems (Trumble & Butler, 2009). New challenges will likely arise for agricultural pest management (Diffenbaugh *et al.*, 2008).

The direct influence of elevated atmospheric CO₂ and UV-B radiation on insect pests appears to be relatively insignificant compared with the effect of temperature

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(Bale *et al.*, 2002, Yin *et al.*, 2009), but Trumble & Butler (2009) note that pest behavior may be affected by CO₂-induced changes to plant metabolism. Nevertheless, the driving force behind pest responses to climate change will likely be higher temperatures (Bale *et al.*, 2002). Elevated winter temperatures increase the overwintering rates of arthropods, leading to higher initial populations in the spring or expansions of the ranges where pests can establish permanent populations (Liu & Trumble, 2007, Tougou *et al.*, 2009). For insects with multiple generations per year, increasing temperatures during the growing season will lead to more generations, likely requiring modifications in existing pest management strategies (Bale *et al.*, 2002). Pest development can be modeled fairly well by relatively simple functions of temperature (Herbert, 1981, Carey & Bradley, 1982, Sanderson *et al.*, 1989, UCIPM, 1999), and degree-day models are widely used by growers practicing integrated pest management. Based on daily or hourly temperature records, these models can estimate the numbers of pest generations that occur during the growing season.

The objective of this paper is to anticipate future pest pressure for four important pests of walnut (*Juglans regia* L.) in California, using existing degree-day models. California is one of the most important producers of walnuts in the world, contributing about 18% of the global supply (FAOSTAT, 2009) and 99% of US production (USDA, 2009). The annual crop value has been estimated at US\$0.7 billion (USDA, 2009), with virtually the entire crop produced in the Central Valley (Fig. 1). The most important walnut pests in California are codling moth (*Cydia pomonella* L.), webspinning spider mites (*Tetranychus* spp.), aphids (predominantly walnut aphid; *Chromaphis juglandicola* Kalt.) and, in some areas, walnut husk fly (*Rhagoletis completa* Cresson) (Steinmann *et al.*, 2008). Navel orangeworm (*Amyelois transitella* Walker) can also be a serious pest, particularly in the southern Central Valley (UCIPM, 2003, 2009). European red mite (*Panonychus ulmi* Koch) is a common arthropod pest in walnut, but under current climatic conditions, it rarely causes enough damage to warrant treatment. Most walnut pests are controlled with organophosphates, pyrethroids, growth-regulating insecticides or miticides (Steinmann *et al.*, 2008). Many of these chemicals are currently being reevaluated by regulatory bodies, and new or existing legislation in California might restrict the array of available pesticides in the near future (Steinmann *et al.*, 2008). Biological control is thus becoming increasingly important for California walnut growers (CDPR, 2009). It is already an important and established component in the management of aphids and to lesser extent webspinning spider mites, but so far has not been very successful for codling moth,

navel orangeworm or walnut husk fly. The future success of biological control strategies will depend largely on how climate and other factors affect the ecological balance between pests and control organisms in walnut orchards in the coming years. We hope to provide a first estimate of likely climate change effects by projecting pest generation numbers for various future scenarios.

Materials and methods

Weather data

Analyzing climate change effects with the commonly used physiological models for insect pests requires long-term hourly temperature records. For California, hourly temperatures have been recorded since 1982 by the California Irrigation Management Information System (CIMIS, 2008). Because this dataset does not go back in time far enough to analyze long-term trends, the CIMIS data was supplemented with records of a long-term daily dataset maintained by the National Climatic Data Center (NCDC, 2008). This network had daily records since 1951 for most stations.

We obtained all available data for all 205 (active and inactive) stations of the CIMIS and 113 stations of the NCDC networks. Each CIMIS station was then assigned the closest station of the NCDC network, using the Euclidean Allocation function of a Geographical Information System (ARCGIS 9.3, ESRI, Redlands, CA, USA), and the respective temperature datasets were joined by date. For each CIMIS site, we also modeled daylength for each day of the year according to equations given by Spencer (1971) and Almorox *et al.* (2005). For the joint dataset, we then used partial least squares (PLS) regression to establish predictive equations for air temperatures for every hour of the day, based on daily minimum and daily maximum temperature from the daily temperature record and modeled daylength (Luedeling *et al.*, 2009a, 2009c):

$$T(h, d, l) = \text{PLS}_{\text{int}}(h, l) + \text{PLS}_{\text{day}}(h, l) \times \text{DL}(d, l) + \text{PLS}_{\text{min}}(h, l) \times T_{\text{min}}(d, l) + \text{PLS}_{\text{max}}(h, l) \times T_{\text{max}}(d, l),$$

with $T(h, d, l)$ the temperature at hour h (0–23) on day d at location l , PLS_{int} , PLS_{day} , PLS_{min} and PLS_{max} the coefficients of the regression equation for hour h at location l , and DL , T_{min} and T_{max} are the modeled daylength, measured minimum temperature and measured maximum temperature on day d at location l . The resulting regression equations were very successful in explaining observed hourly temperatures, with an overall coefficient of determination (r^2) of 0.967. The predictive equations allowed translation of daily temperature data into hourly records. Synthetic 100-year daily temperature records were generated for each climate scenario using the LARS-WG stochastic weather generator (Semenov, 2008). This software analyzes historic daily temperature records, computes statistical parameters describing the dataset, and uses these statistics to generate synthetic datasets for a user-defined climate scenario. Climate scenarios consist of deviations of

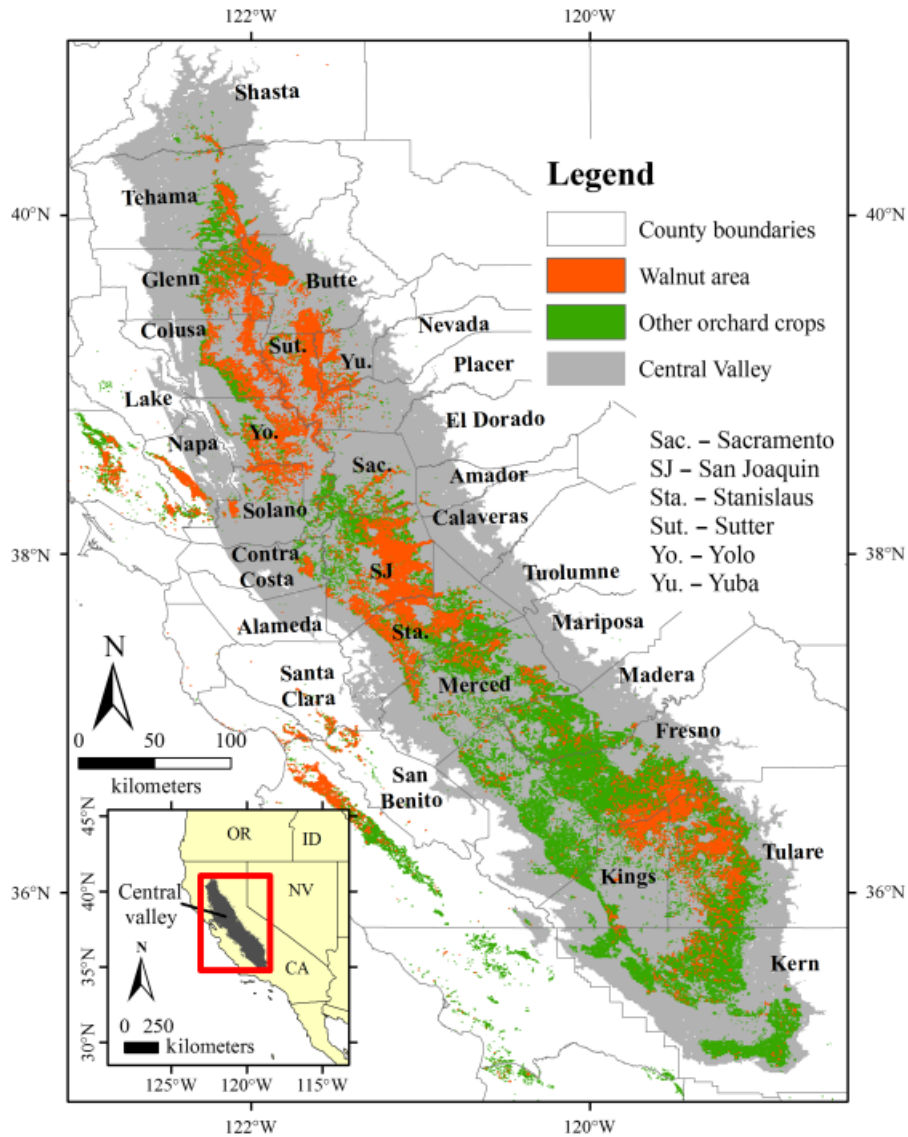


Fig. 1 Overview of the distribution of walnut orchards (orange) and other tree crops (green) in California’s Central Valley. The inset map shows the location of the Central Valley within the State of California (data from USDA-NASS, 2007).

minimum and maximum temperature, precipitation and solar radiation, as well as some statistical parameters, from the mean of the calibration period, with separate change inputs for each month of the year. Except for the specified changes, generated weather records retain all statistical properties of the calibration dataset. Using the stochastic weather generator, we produced 100 synthetic yearly records for each climate scenario. Rather than time series, these records constitute 100 replicates of the record for the year analyzed in the climate scenario, with a random seed introducing variability (Semenov, 2008). The distribution of climate variables, e.g. degree days for a certain pest, among these 100 replications allows an assessment of the probability, with which certain events, e.g. a certain number of degree days, will occur in the scenario. For calibration of the weather generator, we used all available daily temperature data between 1951 and 2006.

Climate scenarios

We analyzed 20 climate scenarios, representing mean climatic conditions at two past and two future points in time. For the past scenarios, we calculated separate linear regressions for minimum and maximum temperatures and precipitation for each month and each station of the NCDC network. Using the regression equations, we estimated mean daily temperature extremes and mean precipitation for each month for scenarios representing conditions in 1950 and 2000. We preferred this regression-based approach over using the actual measured values for these years, because these estimates were less likely to be impacted by interannual variability. Input scenario files for the weather generator were produced by calculating the difference between these estimates and the mean of each variable for the entire calibration period.

Future degree days were estimated based on statistically downscaled climate projections for minimum and maximum daily temperatures (averaged monthly) from three General Circulation Models (GCMs) – UKMO-HadCM3, CSIRO-MK3.0, and MIROC3.2 (medres) – each run under the SRES A2, A1B, and B1 greenhouse gas emissions scenarios from the Intergovernmental Panel on Climate Change AR4 (IPCC, 2007). The A2 scenario describes a world of continuously increasing population and slow and fragmented technological change. In the B1 scenario, global population peaks at 9 billion in 2050, and gradually declines after that. This scenario assumes continued economic growth, a fast transition towards a service and information economy, and rapid introduction of clean and resource efficient technologies. The A1B scenario makes similar assumptions as B1 about population development, but assumes a more balanced portfolio of energy sources in the future, with a substantial contribution of fossil fuels. When used in GCMs, the effects of these emissions scenarios are a relatively slow increase in global temperatures for the B1 scenario, a faster increase for A1B, and the strongest warming for the A2 scenario. The nine future projections (three models by three emissions scenarios) were first statistically down-scaled to a 5 arc-min resolution using the PRISM (<http://www.prism.oregonstate.edu>) climate dataset to calibrate the downscaling (R. Neilson, unpublished data). Then the average minimum daily and maximum daily temperatures for each month during 2041–2060 and during 2080–2099 were calculated for each of the CIMIS weather station locations using a customized version of the ClimateWizard climate-change analysis toolbox (<http://www.ClimateWizard.org>; Girvetz *et al.*, 2009) that analyzed the downscaled GCMs described above. A 20-year period was averaged to give a robust estimate of temperatures around 2050 (mid 21st century) and around 2090 (late 21st century) that is not influenced by year-to-year fluctuations in the projected climate.

Insect physiology models

The synthetic 100-year hourly temperature records for each climate scenario were used as inputs for physiological models describing the life cycle of four walnut pests: Codling moth, two-spotted spider mite (*Tetranychus urticae* Koch), European red mite and navel orangeworm. In spite of their importance for the walnut industry, walnut husk fly and walnut aphid could not be investigated, because no models are available that describe their temperature response. Physiological models were obtained from the University of California Integrated Pest Management Website (UCIPM; <http://www.ipm.ucdavis.edu>). The life cycles of all these pests can reliably be described by the degree-day concept, in which the physiological time of an organism is quantified as a product of time and temperature. Typically, temperatures above a lower (T_{lower}) and below an upper threshold (T_{upper}) are considered physiologically effective (<http://www.ipm.ucdavis.edu/WEATHER/ddconcepts.html>). The contribution of an hour of temperatures between these thresholds to the annual total number of degree days is thus:

$$T_{lower} \leq T \leq T_{upper} \Rightarrow DD_h = (T - T_{lower})/24,$$

with DD_h the number of degree days during hour h , T the current temperature, and 24 used to convert the number to degree days (rather than degree hours). Depending on the pest analyzed, physiological models differ in their treatment of temperatures above the upper threshold. For the Horizontal Cutoff Method, the number of degree days is calculated as if temperatures equaled the upper threshold temperature:

$$T \geq T_{upper} \Rightarrow DD_h = (T_{upper} - T_{lower})/24,$$

whereas for the vertical cut-off method, hours with temperatures above the upper threshold are not counted at all:

$$T \geq T_{upper} \Rightarrow DD_h = 0.$$

The Intermediate Cutoff Method reduces the number of degree days counted for temperatures above T_{upper} as:

$$T \geq T_{upper} \Rightarrow DD_h = [T - T_{lower} - 2(T - T_{upper})]/24.$$

The total number of degree days until a certain point in time t is determined by adding up all hourly contributions between the beginning of the season t_0 and t :

$$DD(t) = \sum_{h=t_0}^t DD_h$$

In this equation, t_0 is the observed biofix, the date when a specific growth stage of a pest is first detected. In this study, April 1 was chosen as the start date for all pest models. The total number of degree days for each year was calculated according to insect-specific parameters and calculation methods (Table. 1), based on the work by UCIPM (1999) for codling moth, Carey & Bradley (1982) for two-spotted spider mite, Herbert (1981) for European red mite and Sanderson *et al.* (1989) for navel orangeworm. The end of the season was set to Oct 1. Total numbers of degree days for each pest were then converted to the number of generations that were likely to occur in each year at each site and for all climate scenarios. degree days necessary for one generation were 619 for codling moth (mean generation time; UCIPM, 1999), 120.5 for two-spotted spider mite (egg to egg; Carey & Bradley, 1982), 161.8 for European red mite (egg to egg; Herbert, 1981) and 410 for navel orangeworm (adult to adult; Sanderson *et al.*, 1989).

Spatial interpolation

For each weather station location, pest pressure of all four pests was quantified by the mean number of generations over the synthetic 100-year record for each climate scenario. These point estimates were then spatially interpolated, using the Kriging technique (12 neighbors, spherical semivariogram, 20 arc-minute resolution), to cover the entire area of California. As some locations in California are at substantial distances from the closest weather station, such simple interpolation introduces fairly large errors for such locations. We corrected for these errors, using a California-wide grid of mean annual temperatures between 1971 and 2000, calculated as the mean of the minimum and maximum temperature grids provided

Table 1 Parameters and calculation methods for the physiological pest models

Insect	T_{lower} (°C)	T_{upper} (°C)	Cut-off method	Start date	End date
Codling moth	10	31.1	Horizontal	April 1	October 1
Two-spotted spider mite	11.7	None	Horizontal	April 1	October 1
European red mite	10.6	None	Horizontal	April 1	October 1
Navel orangeworm	12.8	34.4	Vertical	April 1	October 1

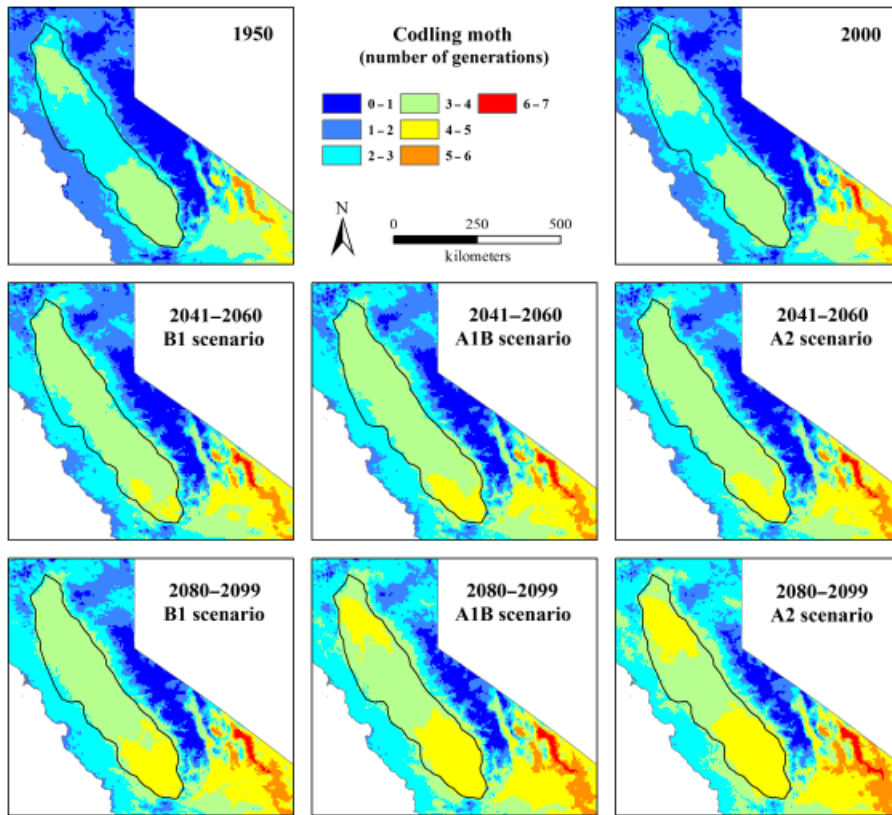


Fig. 2 Number of generations of codling moth throughout California for all climate scenarios. Future scenarios were averaged from projections for three General Circulation Models. The black lines in all maps indicate the outline of the Central Valley, where most walnuts are grown.

by the PRISM Group (<http://www.prism.oregonstate.edu/>). For each climate scenario, the number of generations of each pest among all weather stations was linearly correlated with the mean annual temperature for the station. The resulting regression equations (mean r^2 of 0.71) were used as a best-guess estimate for the influence of local climate on the number of generations for each pest. For adjusting the interpolated generation surfaces, we first used an Inverse Distance Weighting algorithm (including six neighboring points) to interpolate a mean temperature surface through the point estimates of mean annual temperature for all weather stations. Subtracting the resulting grid from the mean annual temperature surface for California provided an estimate of the variation in climatic conditions that was not accounted for by simple interpolation of estimated numbers of insect generations through all weather

station locations. We then multiplied this surface by the slope of the regression between mean annual temperature and number of generations for each pest, and added the result to the original interpolated pest generation grid. For each greenhouse gas emissions scenario and projection time, the pest generation grids for all three GCMs were then averaged, producing one grid for each combination of pest, emissions scenario and point in time.

To quantify the projected area for each number of generations for all pests, we converted all grids to integer format by truncating the generation number value calculated for each cell. This new value represents the number of generations that can be completed with the available number of degree days. For each resulting integer grid, we then tabulated the area within the Central Valley for each number of generations,

using a processing cell size of about 27 km². The Central Valley was defined as all areas within a rough outline of the Valley, which were at elevations below 500 m according to the SRTM30 elevation model (GLCF, 2008).

Table 2 Mean number of generations throughout the Central Valley for climate scenarios representing conditions in 1950, 2000, and for 2041–2060 and 2080–2099 under the B1, A1B, and A2 emissions scenarios

Pest	Mean number of generations in the Central Valley							
	1950		2041–2060			2080–2099		
			2000	B1	A1B	A2	B1	A1B
Codling moth	2.5	2.7	3.0	3.1	3.1	3.2	3.5	3.6
Two-spotted spider mite	12.8	13.7	15.9	16.6	16.8	17.3	18.7	19.7
European red mite	10.5	11.3	12.9	13.4	13.6	14.0	15.0	15.7
Navel orangeworm	2.6	2.9	3.1	3.1	3.1	3.1	3.2	3.2

Results

Codling moth

Throughout California, the mean number of codling moth generations predicted by the calculated number of degree days ranged from 0 to 5 for the 1950 climate scenario (Fig. 2), with an overall mean of 2.5 generations for the Central Valley, the most important agricultural area of the state (Table. 2). All other scenarios showed substantial increases. Most of the Central Valley experienced two or three generations per year in 1950 (Table. 3). By 2000, the area with three generations had already expanded by about 30%. For all future scenarios, the average generation number for the Central Valley is projected to exceed three generations (Table. 2), and substantial areas will likely support four generations of codling moth (Table. 3). By the end of the 21st century, almost all of the Central Valley will support either three or four generations (Table. 3). For the warmest scenario analyzed (A2; 2080–2099), four generations of codling moth were projected for more than half of the Central

Table 3 Projected area (km²) in California's Central Valley, where given numbers of pest generations occurred for climate scenarios representing conditions in 1950, 2000, and for 2041–2060 and 2080–2099 under the B1, A1B, and A2 emissions scenarios

Pest generations	1950	2000	2041–2060			2080–2099		
			B1	A1B	A2	B1	A1B	A2
<i>Codling moth</i>								
1	1295	27	–	–	–	–	–	–
2	34 820	25 228	5481	3323	3239	2109	487	81
3	39 108	49 943	63 672	61 130	59 787	54 500	38 592	31 536
4	–	54	6 211	10 805	12 362	18 518	36 131	43 534
<i>Two-spotted spider mite</i>								
<10	5243	2044	108	–	–	–	–	–
10–11	17 262	5783	2288	1508	1345	512	27	–
12–13	18 176	24 827	6676	4201	3902	3153	1618	566
14–15	26 754	27 087	21 347	18 878	17 141	13 394	4449	3071
16–17	7206	14 767	24 443	21 274	21 258	19 054	18 145	11 692
18–19	161	269	18 709	22 809	23 438	25 306	19 115	18 238
20–21	–	–	1238	6086	7588	13 314	24 858	21 633
≥ 22	–	–	–	54	54	189	6794	18 238
<i>European red mite</i>								
<10	22 780	7578	1652	1057	650	271	–	–
10–11	27 839	33 452	14 355	7641	6552	4312	1763	922
12–13	23 267	30 583	28 006	27 638	27 292	24 215	14 947	6072
14–15	1217	3545	29 171	31 350	31 759	31 239	25 120	25 155
16–17	–	–	1815	7370	8908	14 887	30 220	29 654
18–19	–	–	–	–	–	108	3038	13 255
≥ 20	–	–	–	–	–	–	–	108
<i>Navel orangeworm</i>								
1	1031	109	–	–	–	–	–	–
2	26 269	8226	3043	2120	1955	1170	–	54
3	47 111	64 449	63 738	63 110	63 659	63 132	60 462	62 781
4	597	2172	8259	9730	9424	10 662	14 503	12 127

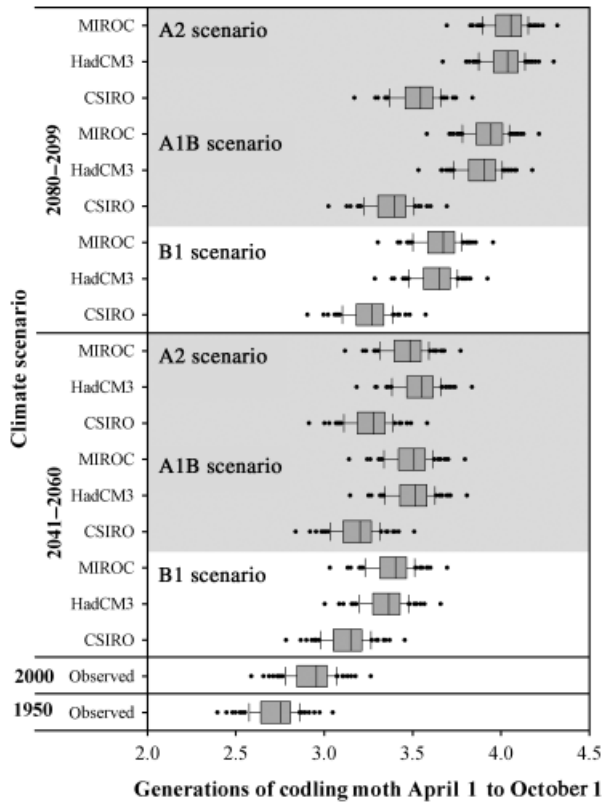


Fig. 3 Distribution of the number of codling moth generations projected for Davis, CA, over the 100 replicates of each climate scenario. In box plots, the central line is the median of the distribution, the edges of the boxes are the 25% and 75% quantiles, the error bars indicate the 10% and 90% quantiles, and all dots are outliers beyond those limits.

Valley. Variation between the three emissions scenarios was low compared with variation over time, as shown for Davis, California in Fig. 3. Half of the yearly estimates fell within a range of 0.15 generations around the mean, on average over all scenarios, with 80% of the values within 0.28 generations around the mean.

Two-spotted spider mite and European red mite

Both mite species have much shorter generation times than codling moth and are thus able to produce more generations per year. For the two-spotted spider mite, 10–18 generations occurred in the Central Valley in 1950 (Fig. 4). By 2000, this number had only increased slightly. By the middle of the 21st century, 14–22 generations will likely be normal, and up to 25 generations might occur by 2100. European red mites had slightly longer generation times, resulting in slightly fewer generations (Fig. 5).

By 2080–2099, between 18% and 54% of the Central Valley are projected to have more than 20 generations of

two-spotted spider mites, which did not occur in the area at all in either of the past scenarios (Table. 3). Generation numbers for European red mites in California ranged from less than 10 to over 20 in 1950, and increased after that (Fig. 5). In the Central Valley, 98% of the area had <14 generations in 1950. Generation numbers were higher for all other scenarios, exceeding 14 generations on between 41% and 54% of the area in 2041–2060, and between 62% and 91% for the end of the 21st century (Table. 3).

In 1950, the mean generation numbers for the Central Valley were 12.8 for the two-spotted spider mite and 10.5 for the European red mite (Table. 2). For the future scenarios, two-spotted spider mite is projected to have between 15.9 and 19.7 generations, while future climates will support between 12.9 and 15.7 generations of European red mite (Table. 2).

Navel orangeworm

Almost the entire area of the Central Valley supported two or three generations of navel orangeworm per year in 1950 (Fig. 6; Table. 3). By 2000, three generations were common in 86% of the Valley, an expansion by 37%. The size of this area remained roughly similar for all future scenarios, while only between 11% and 16% of the Central Valley reached four generations. Due to use of the vertical cut-off method in calculating degree days for this species, the statewide maximum number of generations, which was projected for the Death Valley region (which is not used for agriculture), decreased from 6 to 5 for all future scenarios. For the same reason, the average for the whole Central Valley was very similar for all future scenarios (Table. 2).

Discussion

The climate change projection results clearly indicate that generation numbers are going to rise for most pests. Because of their short generation time, mites are likely to respond with the biggest increase among the pests analyzed. This development could pose a problem for growers in the near term, since popular miticides such as propargite are increasingly regulated due to human health concerns and often have long re-entry intervals and use restrictions (Fouche, 1995), while many alternative products are more expensive. Climate change may also affect the natural enemies of mites, both directly and indirectly. Webspinning mites are often considered 'secondary pests' in the sense that orchard populations may be maintained below economically damaging levels by management practices that favor natural enemy populations. Any changes in the distribution ranges, population sizes or generation

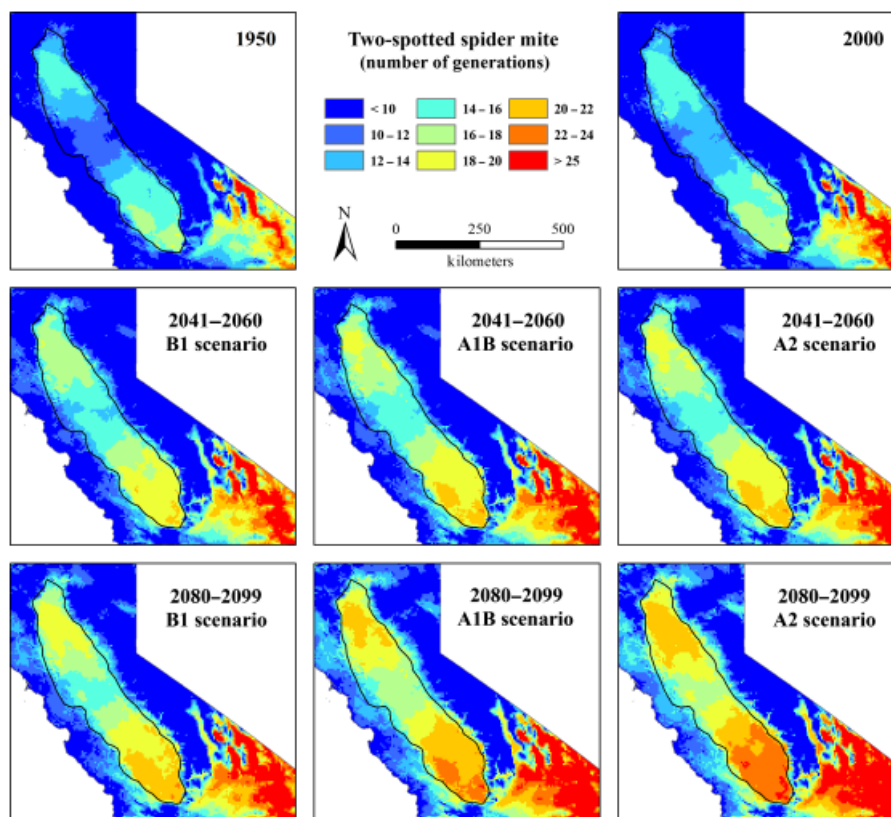


Fig. 4 Number of generations of two-spotted spider mite throughout California for all climate scenarios. Future scenarios were averaged from projections for three General Circulation Models. The black lines in all maps indicate the outline of the Central Valley, where most walnuts are grown.

numbers of these natural enemies could therefore substantially affect mite pest pressure, either positively or negatively. Unfortunately, degree-day models to predict insect physiology are only available for certain pests, and almost no beneficial insects, so that there is no basis at present for predicting how climate change may affect their ecological balance. In addition to direct effects, climate change could potentially increase mite pressure through indirect effects resulting from changes in management practices for other pests. For example, increased codling moth pressure might make more insecticide applications necessary to suppress it. This, in turn, could result in greater mortality of natural enemies of mites, disrupting biological control and increasing pest mite outbreaks and the need to control them (Dutcher, 2007). With increasing numbers of mites, and potentially fewer licensed miticides or restricted use rates and numbers of applications, mite damage might become a more severe problem than it is at present. Increased codling moth pressure might also amplify the damage potential from navel orangeworm, which may use entry holes made by codling moth larvae to infest walnut fruit. This might increase the

damage potential of navel orangeworm, even though the generation numbers are predicted to remain relatively stable.

Growers will potentially depend more than they currently do on nonchemical pest-control. Both navel orangeworm and mites overwinter in crop residues. Navel orangeworm can thus be controlled by removal of 'mummy nuts,' the overwintering sites of this pest (UCIPM, 2009), and mite dispersal is possible reduced by avoiding dusty conditions in orchards (Luedeling *et al.*, 2009b, UCIPM, 2009). These field sanitation measures are likely to increase in importance in the future.

Our study can only give a first indication of the direction in which pest pressure is headed. Agroecosystems are complex and many factors that affect pests are difficult to model with certainty. It is also uncertain, whether or not a longer time span will be available for pests to develop each year. While temperatures may be favorable for insect development for a longer time span, the phenology of most insects is coupled with crop phenology and physiology, which might remain limiting factors for pest development. The phenology of walnuts and other tree crops is assumed to be a function

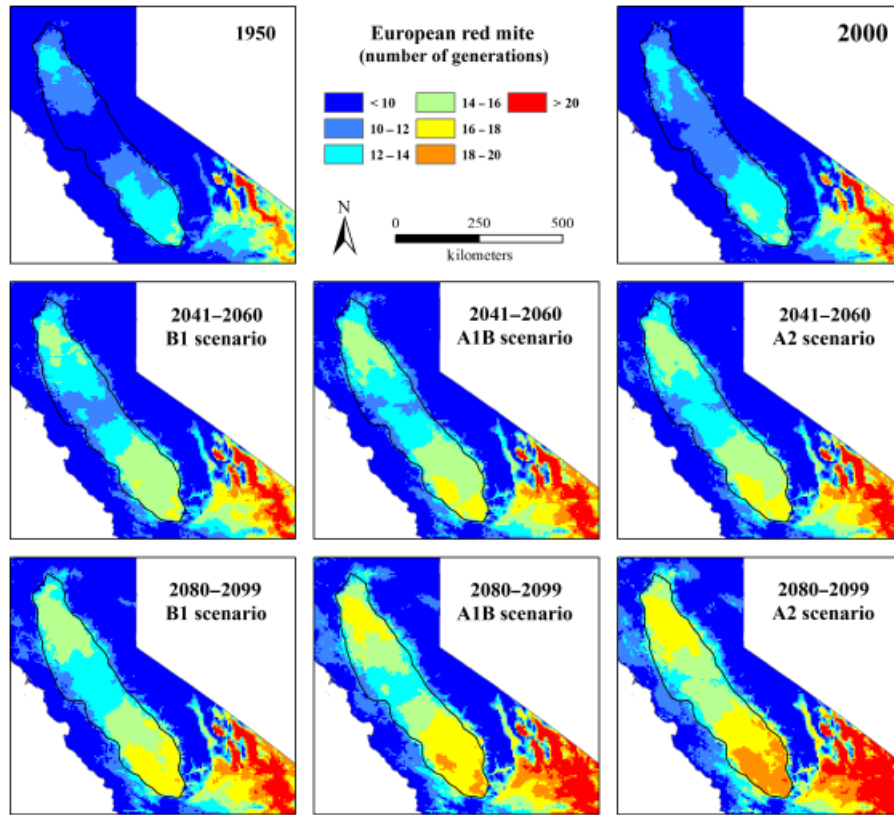


Fig. 5 Number of generations of European red mite throughout California for all climate scenarios. Future scenarios were averaged from projections for three General Circulation Models. The black lines in all maps indicate the outline of the Central Valley, where most walnuts are grown.

of winter chilling and spring heat, but how exactly these two factors interact is largely unknown. Hence, the timing of tree phenology cannot be forecast reliably at this point (Luedeling *et al.*, 2009e), making estimations of season length for many pests difficult.

It is likely that degree-day models will have to be adjusted, when temperatures exceed what has typically been observed in the field. Temperatures above the upper threshold of commonly used models may cause increased levels of heat death among pest organisms, constraining reproductive rates and probably also generation numbers. Temperature ranges used in the development of degree-day models generally represent temperatures that were observed in the past, and may not remain valid in a warmer future. This process may counteract some of the increases in generation numbers projected in this study. Refined insect physiology models, which include more accurate representations of the effects of heat extremes, will be necessary to account for this uncertainty in projections of future pest pressure.

It is also difficult to project climate change effects on the time, when overwintering arthropods enter diapause. While temperature affects this process, photo-

period has also been implicated, and diapause is likely initiated by a combination of these two variables (Jacobo-Cuellar *et al.*, 2005). There is insufficient data to reliably estimate when this is likely to happen in the future. It should be noted, however, that for codling moth and navel orangeworm, diapause likely starts before October 1 in California, so that our study may be overestimating generation numbers. Whether or not diapause-related processes will change in a warmer future has, to our knowledge, not been studied, but an investigation by Jacobo-Cuellar *et al.* (2005) showed a large variation in the timing of diapause entry for codling moth in Mexico. There may thus be potential for adaptation to a new climate regime in arthropods, an issue that merits further investigation.

To prepare for likely climatic conditions in the future, pesticide regulators and registrants should include considerations of ecosystem complexity and the potential impacts of climate change on such complex systems in their pesticide regulation policy and product development decisions. Detailed knowledge of temperature responses of organisms in the present climate is scarce, and even for those processes that can be modeled, there

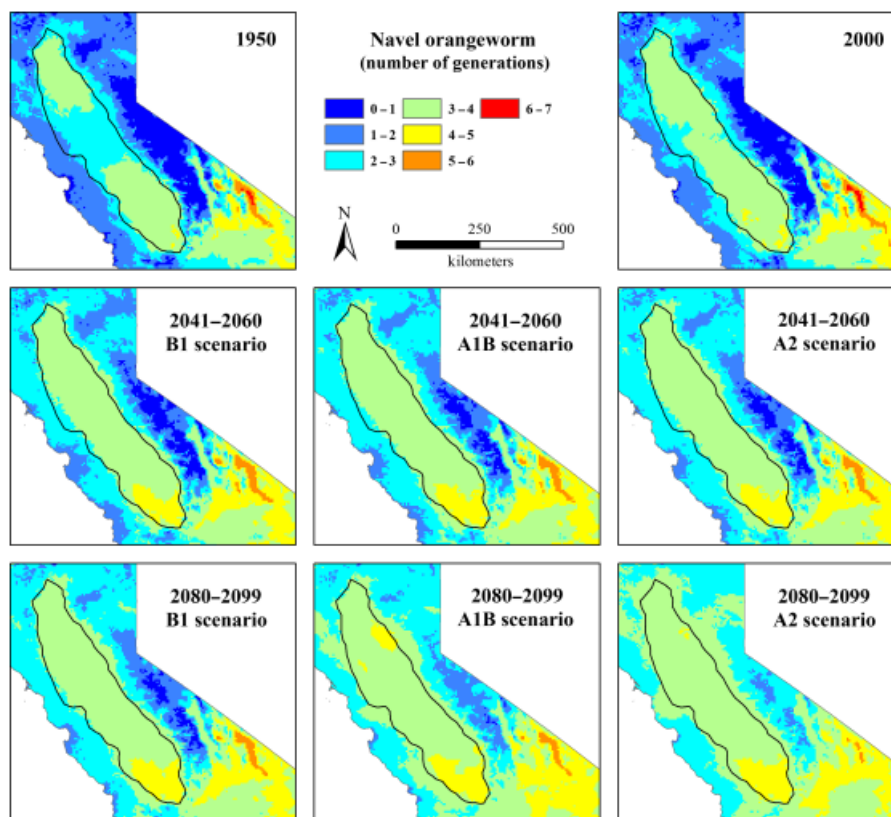


Fig. 6 Number of generations of navel orangeworm throughout California for all climate scenarios. Future scenarios were averaged from projections for three General Circulation Models. The black lines in all maps indicate the outline of the Central Valley, where most walnuts are grown.

is no guarantee that models will remain valid in a different climate (Luedeling *et al.*, 2009d). Thus, additional research is needed before climate change effects to specific agroecosystems can be projected with greater certainty.

Detailed predictions of the effects of the projected changes on pest management strategies are difficult, but several adjustments to current practice will likely be necessary. More rapid developmental rates of arthropods in a warmer climate will enable insect populations to increase from uncritical to damaging levels in a shorter period of time. Growers could respond to these changes by increasing the intensity of pest monitoring and shortening the response time to the detection of critical pest populations. Alternatively, and probably more feasibly, pest thresholds for pesticide applications could be reduced. Another change to pest dynamics will be that pests appear earlier in the growing season and occur later in the year, thus impacting tree physiology and growth at times that have previously not been subject to high pest pressure. These changes will very likely require substantial modifications of current pest management strategies, in order to adjust to the changing environment.

Conclusions

Increasing temperatures are likely to change pest dynamics in California, according to all future climate scenarios analyzed. Generation numbers of codling moth, navel orangeworm, web-spinning spider mites and European red mites are likely to increase, generating new challenges for pest control. More research into the details of agroecological food webs is needed, in order to project the implications of climate change for pest pressure with greater certainty. The validity of insect physiology models that are commonly used in integrated pest management under warmer climatic conditions should also be investigated.

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