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To cite this article: John T Abatzoglou *et al* 2025 *Environ. Res. Lett.* **20** 034017

ENVIRONMENTAL RESEARCH
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RECEIVED
19 June 2024

REVISED
19 December 2024

ACCEPTED FOR PUBLICATION
4 February 2025

PUBLISHED
14 February 2025

LETTER

Shorter growing seasons may moderate climate change effects on crop water demands

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Keywords: agriculture, climate, phenology

Supplementary material for this article is available online

Abstract

Rising evaporative demand (ETo) with a warming climate contributes to diminished water availability in water-stressed agricultural regions globally. While increased ETo typically necessitates increased irrigation, we explore how crop phenological response can moderate this challenge. Focusing on five key agricultural crops in California's San Joaquin Valley (SJV), we employ coupled water balance and phenology models to project crop water demands as a function of increased ETo and changing phenology. All crops exhibited accelerated growth from a shortened growing season with warming. The shortened crop maturation period partially to fully offset increased crop water demands due to rising ETo, with the largest phenological influence for annual crops such as tomato and corn. By contrast, models that do not account for phenological changes showed increased irrigation demands of approximately 3.5%–4.5% per °C of global warming primarily due to increased ETo. Integration with dynamic phenological models for the five key crops across the extent of agricultural land in the SJV showed a 1.6% decrease in irrigation needs under a 2 °C warming scenario. While phenological change alongside plant physiological responses to increased atmospheric CO_2 may help buffer the impact of climate change on crop irrigation demand, decreased crop yields with a shorter growing season and continued reliance of groundwater reserves for agricultural water use and reduced spring snowpack will threaten coupled agricultural and water security in the region.

1. Introduction

Agricultural hubs in semi-arid climates such as California's San Joaquin Valley (SJV) play a vital role in global food production. However, it is well recognized that water resources are demonstrably overused in portions of California and other semi-arid agricultural regions [1], leading to rapid depletion of groundwater reserves. Climate change has compounded this water imbalance through increased evaporative demand and diminished snowpack, paving the way for more severe droughts [2–4]. Such changes jeopardize not only the long-term viability of agriculture in affected areas but also that of local economies and the water security of vulnerable communities [5, 6]. Continued climate change threatens to further impact water resources for agriculture [7, 8], thereby necessitating adaptation efforts to secure the future of these critical food-producing regions.

Observations and projections show increased evaporative demand, or reference evapotranspiration (ETo), for California with climate change [4, 9]. Increased evaporative demand in agricultural lands generally translates into increased crop water demand and irrigation requirements [10], which may be untenable given the imbalance in water resources in many semi-arid agricultural regions. However, the direct 'more ETo means more water needed' relationship has been challenged by several lines of scientific inquiry. Increased atmospheric carbon dioxide concentrations both promote stomatal closure that reduces evaporative losses and enhances water use efficiency [11, 12], and increase Leaf Area Index and plant biomass that boosts transpiration rates [13]. The overall direction and magnitude of such physiological effects varies based on plant functional type and soil moisture [14, 15], although increased water use efficiency may increase crop water productivity in some crops [16, 17]. Management changes like adopting drought-resistant cultivars, switching crops, and employing water-saving techniques like deficit irrigation or mulching can further curtail water demand in water limited regions.

At the same time, climate change is altering phenology—or the seasonality of biologic processes—across diverse ecosystems, including managed agricultural systems [18, 19]. Earlier crop phenology creates potential for crops to leverage higher soil moisture and lower evaporative demand in spring—particularly in Mediterranean climates [20]. Hastened crop maturation may thus lower water and irrigation requirements later in summer when evaporative demand is often near its peak [21]. For example, in semi-arid Mediterranean agricultural regions, annual crops such as winter wheat may see slight reductions in irrigation needs imparted through climate change-driven phenological shifts [22]. However, the role of phenology at moderating increasing evaporative demand is likely to vary across crops [23]. For example, perennials require irrigation demands after harvest, while extreme heat impacts development and yields of some other crops [24].

As climate change alters evaporative demand, a critical question emerges: how will crop phenology respond, and can these changes offset the anticipated increase in irrigation requirements? We explore this question in the context of California's SJV, a diverse agricultural region facing significant water challenges, including the potential substantial reduction in irrigated agriculture to comply with sustainable groundwater regulation [25]. We examine changes in crop water demand for crops using a sensitivity analysis that couples established thermal phenological models alongside crop water demand models under warming scenarios. In water scarce regions where water limitations may ratchet up in the coming decades, choices about cropping systems and water management are needed to adhere with sustainability goals. Hence it is potentially valuable to interrogate which crops exhibit sufficient phenological plasticity to 'take advantage' of warming and mitigate additional irrigation requirements.

2. Approach/methods

We focus our analysis on California's SJV. The SJV offers the ideal setting due to its extensive cropland, diverse crop portfolio, significant water challenges (both current and future), and projected increases in ETo [8]. We chose five representative crops widely grown in the SJV: three perennials, almonds, grapes, and alfalfa and two annuals, corn and tomatoes. These five crops account for approximately 58% of SJV's irrigated land, 60% of the region's agricultural irrigation water use, and roughly 53% of the gross agricultural value [25]. Moreover, these five crops have very different crop water demands. Thus, understanding their phenological response to climate change may provide insight for ensuring SJV's agricultural sustainability in the face of evolving water demands.

We leverage established phenological models for these five crops following previous approaches (supplemental information; tables S1 and S2). These models primarily rely on temperature accumulation to predict key phenological stages like budburst, flowering, and maturity, as well as for vernalization requirements in the case of perennials. Thresholds used for budburst, flowering, maturation are provided in table S1. While annual crops had static planting dates of 1 April, we perform an additional experiment that used 15 March planting dates commensurate with warming climate [26]. Alfalfa is a perennial but is not subject to vernalization requirements in warmer climates such as in the SJV. We fix its growing season to commence on 15 February and continue through October each year following previous crop parameterizations for alfalfa [27]. Furthermore, the thermal-based developmental model for alfalfa allows for multiple cuttings per year, and accounts for projected changes in the number of cuttings per year with warming. Whereas other studies may wish to employ more sophisticated phenological models, including those for specific varietals, we use a generalized approach herein to best examine the research questions posed.

We calculate crop water requirements as potential crop evapotranspiration (ETc) through a phenostage-varying crop coefficient method by scaling reference evapotranspiration (ETo) by crop coefficients (K_c) based on phenological stages (table S2). We use the standardized Penman–Monteith approach [28] to calculate grass reference evapotranspiration (ETo) over the contemporary observational period. Crop coefficients (K_c) vary both by crop and by phenostage due to characteristics such as albedo, leaf area, canopy cover, and crop height that distinguish it from the grass reference surface in ETo. Phenostages of K_c are determined using thermal units (i.e. growing degree days) for each crop following prior work [28]. For annuals, we adopt a fixed $K_c = 0.15$ outside of the growing season (between harvest and planting) and do not accrue water deficits post-harvest in our crop water demand calculations.

A simple water balance model is used to track hydrological fluxes and unmet crop water demand [29]. This water balance model runs on monthly timescales based on plant water demands (ETc) and precipitation and uses a fixed soil water holding capacity of 150 and 50 mm for perennials and annuals, respectively. The soil water holding capacity allows for some carryover of water surplus outside the growing season toward meeting crop water demands in drier periods. This model has been widely used to assess climatic water deficit of ecosystems across many spatial and temporal scales and provides measures of actual evapotranspiration (ET) and climatic water deficit, or the difference between evaporative demand and ET [30, 31]. Herein we use this framework to define crop irrigation demand as the difference between ETc and ET each month. Irrigation practices in California's Central Valley are approximately 80% efficient, with values ranging by crop and management approaches [25]. We do not account for irrigation efficiency explicitly in our estimates and thus assume no changes in such practices under future scenarios.

Observed climate data from gridMET [32], a daily surface meteorological dataset with a horizontal resolution of ~4 km, for the years 1980–2022 is used as our reference data. This data includes the requisite set of meteorological inputs needed for calculating ETo and has been widely used in agricultural analysis in the region [9, 33, 34]. Prior studies have shown widespread positive biases in ETo estimates from gridMET and other gridded meteorological datasets in irrigated lands as the data do not incorporate the land-surface feedback of irrigation, which results in cooling [35]. Herein, we bias correct gridMET ETo by a factor of 0.85 based on biases found between gridMET and *in-situ* weather stations in irrigated lands in the SJV [34].

The standardized Penman–Monteith approach does not account for plant physiological responses to increased CO_2 that drive stomatal closure and increased water use efficiency. Failure to account for this under future climates may thus overestimate potential evapotranspiration [36]. Other plant physiological changes to increased CO_2 such as increased biomass and leaf area index may somewhat offset increased stomatal resistance effects in some vegetation types [37], although such factors may be less evident in annual crops [16]. In developing scenarios of projected changes in ETo with climate change, we use a modified version of Penman–Monteith that accounts for changing stomatal resistance with CO_2 and was designed for use in off-line modeling studies [36].

We adopt a pattern scaling approach to approximate regional changes in ETo with annual Global Mean Temperature (GMT) increases. Pattern scaling is based on linear scaling between local changes in climate responses (e.g. ETo) with changes in GMT [38]. We opted for this approach over a standard approach that uses downscaled climate models due both to the simplicity in application and the ability to more directly link future changes in ETc to changes in GMT with policy-relevant climate goals. The pattern scaling approach also allows for more straightforward scenario planning without having to be explicitly tied to emission scenarios, choice of models, and time periods. Following Dahl *et al* [39] we calculate monthly ETo (using the modified Penman–Monteith approach [36]) from 20 climate models participating in CMIP6 (table S3) covering both the historical forcing experiments (1850–2014) and future moderate emissions pathway SSP2-45 (2015–2100). We repeated this for both monthly temperature and precipitation to best capture seasonal changes in the climate change projections pertinent to phenology and water balance in the region.

Pattern scaling is based on a linear regression between the local change (35–38°N, 119–121°W) in running 31 year monthly climate (i.e. ETo, temperature, precipitation) to the running 31 year average GMT for the period 1980–2080 commensurate with the warming in both observations and model projections. A 31 year centered moving average is applied to increase signal-to-noise ratios and linear least squares fit are used to quantify response patterns. Linear scaling is performed separately for each model and we hereafter use the multi-model median in our sensitivity experiments as in prior work [7]. We additionally perform pattern scaling monthly to capture projected changes in the seasonal cycle of temperature, precipitation, and ETo congruent with increased GMT.

We conducted a sensitivity analysis to isolate the independent and combined effects of climate change applied directly to ETo and precipitation and climate change applied to phenology on crop water needs. The sensitivity runs superimpose scenarios of 1 °C, and 2 °C increases in GMT to the observed climate record (1980–2022). For reference, average GMT during 1980–2022 was approximately 0.7 °C above the 1850–1900 quasi-preindustrial average. Monthly changes in temperature are applied additively from pattern scaling to gridMET temperature, whereas monthly changes in ETo and precipitation are applied multiplicatively. Models are run using both static phenology (i.e., dates for the observed 1980–2022 period) and dynamic phenology driven by warming. By simulating ETc with both dynamic and static phenology we isolate the effects of phenological changes on crop irrigation needs. We first examined such simulations absent changes in evaporative demand and precipitation which uses the observed 1980–2022 data verbatim, herein referred

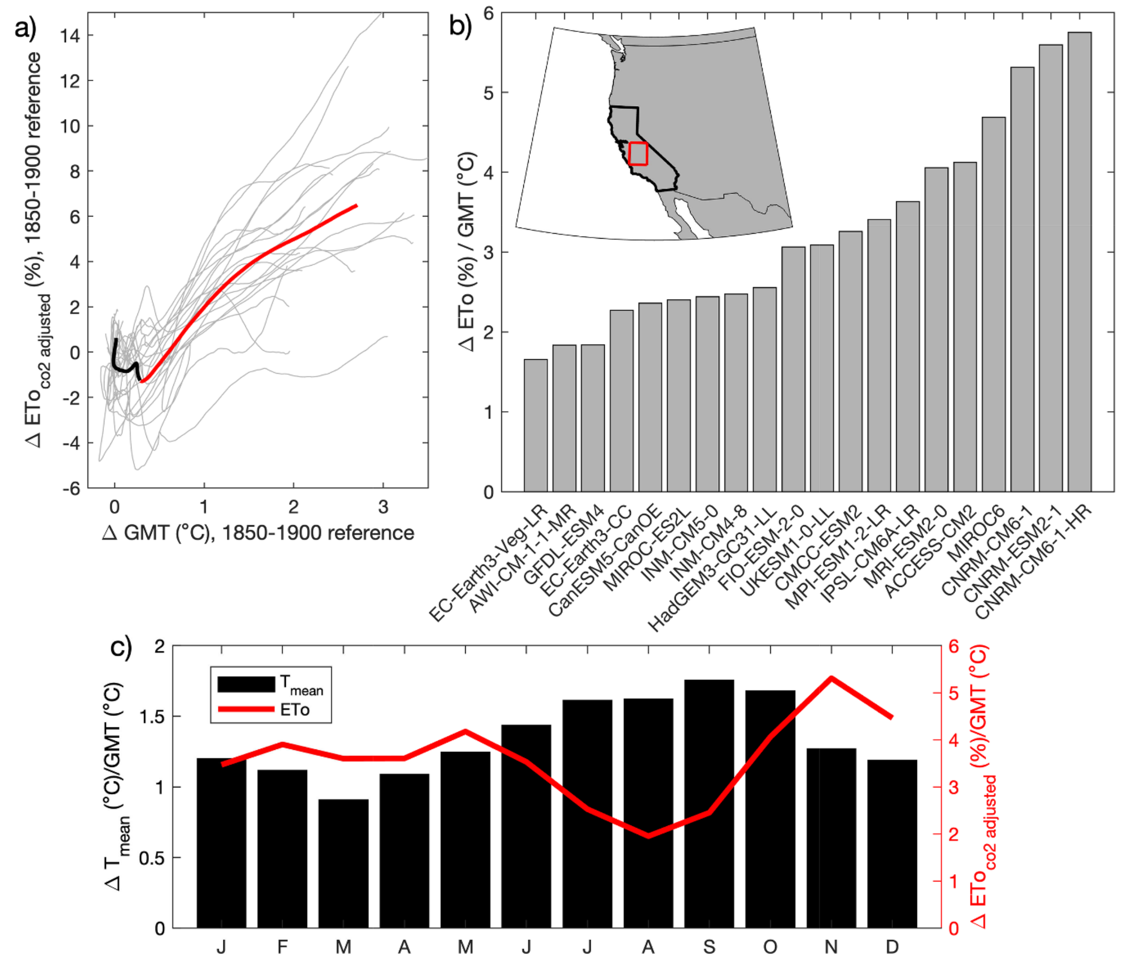

Figure 1. (a) Scatterplot of moving 31 year Global Mean Temperature (GMT) anomalies (relative to 1851–1900) versus 31 year moving average April–October ETo anomalies for central California (relative to 1851–1900) for each model. Thin grey lines show the results of individual models, while the bold black and red lines shown the 20-model average during 1850–1979 and 1980–2100, respectively. (b) Model spread of the pattern scaling of April–October ETo in central California (inset red box). (c) Multi-model median linear relationship between monthly change in ETo and mean temperature in central California to GMT. We use the Yang *et al* (2019) method in calculating ETo that accounts for dynamic CO_2 concentrations.

to as static climate, Next, we introduced the climate change impact in evaporative demand and precipitation, herein referred to as dynamic climate. Coupled phenology and water balance models are run for each crop for three experiments: (i) static climate and dynamic phenology, (ii) dynamic climate and static phenology, and (iii) dynamic climate and dynamic phenology. The difference between the latter two results yields a potential water savings arising from phenological adjustments with warming.

We present our results in more detail (e.g. all warming scenarios, sensitivity tests) for a representative location near Kerman, CA (36.7°N, 120°W) located in the middle of the SJV where most of the five representative crops are grown. We then examine changes across the extent of the SJV agricultural landscape for a +2 °C warming scenario. For the latter, we use estimates of 2018 crop distribution and areal extent [40] to provide an estimate of how phenological shifts might impact regional crop water use, both with and without dynamic phenology.

3. Results

Climate models project a quasi-linear increase in ETo for central California including the SJV with rising global temperature through 2 C above pre-industrial GMT (figure 1(a)). This relationship is most apparent from 1980 onward, with multi-model analyses revealing an average rise of 3.1% in Apr-Oct ETo per °C increase in GMT albeit with inter-model spread (figure 1(b)). A distinct annual cycle in both regional temperature and ETo scaling factors per degree warming in GMT was found (figure 1(c)). Specifically, we found accentuated warming in late summer (⩾1.2 °C/°C) with slightly subdued relative increases in ETo (∼2%/°C) during the summer months. Yet, ETo has a strong seasonal cycle with the highest ETo during the summer resulting in the largest absolute increases in ETo during the growing season. Pattern scaling of monthly precipitation showed minor increases in mid-winter with minor decreases in spring and fall and thus do not

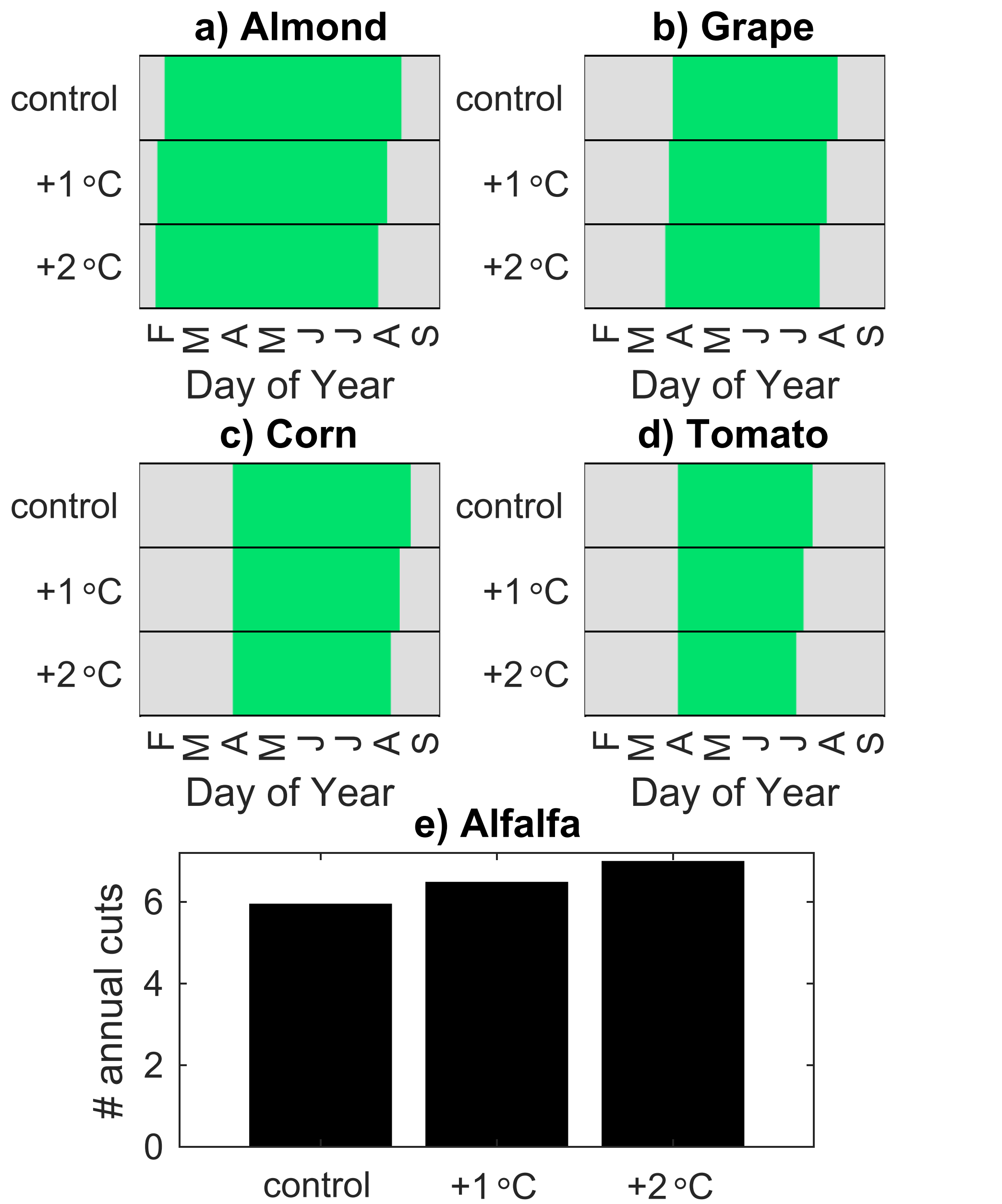

Figure 2. Changes in crop phenology near Kerman, CA (36.7°N, 120°W) using data from 1980–2022 using models for almond, grape, corn, tomato, and alfalfa. Sensitivity experiments are applied to augment local daily temperatures corresponding with +1 °C and +2 °C change in Global Mean Temperature. Colors depict the growing season, for perennials the period between bud burst and harvest, and for annuals the period between planting and harvest. Static 1 Apr planting dates are given for annuals. Alfalfa assumes the growing season commences on 15 Feb and shows the average timing of harvests through October. For alfalfa, the average number of cuttings per year are shown.

strongly factor into projected changes in crop irrigation demand given the region's Mediterranean climate (table S4).

Phenological tests applied near Kerman, California show a shortening of growing seasons for all crops (figure 2). However, changes differ by crop with annuals such as tomatoes and corn showing a clear compression of the growing season (6–7 d per °C warming in GMT), notably truncating the growing season during the seasonal apex in evaporative demand. Both almonds and grapes show changes in budburst and crop maturation dates leading to a shorter growing season as well. Under elevated warming (+2 °C), almonds show crop maturation 2.5 weeks earlier than in the reference scenario. Alfalfa shows minimal changes in growing periods as it can have multiple cuttings per year and is not limited by freezing events in SJV during February–November. Models suggest more frequent cuts under warmer conditions with approximate one additional cutting per year with +2 °C warming.

Models run with dynamic phenology but static climate showed reduced crop irrigation water demand under warming scenarios for Kerman, California (figure 3(a)). These savings stem from shortened growing seasons induced by warming, with

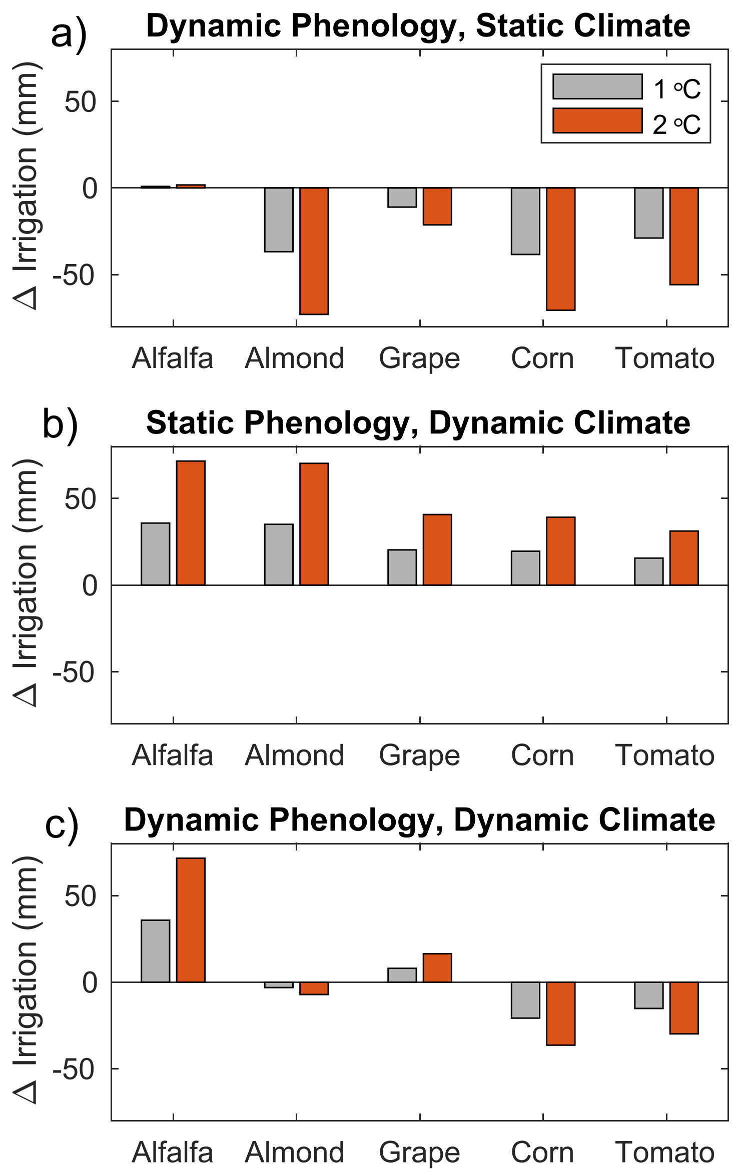

Figure 3. Changes in annual irrigation demand for five crops near Kerman, CA (36.7°N, 120°W) with varying levels of warming applied. Panel (a) shows changes using dynamic phenology and static climate. Panel (b) shows changes using static phenology and dynamic climate. Panel (c) shows results using dynamic phenology and dynamic climate. All differences are shown relative to the 1980–2022 reference period.

reductions ranging from 8.1% (73 mm) for almonds to 15.9% (56 mm) for tomatoes under a +2 °C warming scenario (figure S1). Results were quasi-linear with warming. Tomatoes saw the largest reductions in crop water need due both to their shorter growing season and the curtailment of K_c values entering the seasonal windows when ETo is highest (figure S2). Corn showed slightly less water savings than tomato with warming. Alfalfa, conversely, displayed no change in irrigation demand as its growing season remains static—although more overall cuttings (and potential yield) occur with increased thermal time.

Simulations using dynamic climate but static phenology revealed significant increase in crop irrigation water demands across all crops with warming, mirroring the rise in ETo (figure 3(b)). This effect was particularly pronounced for higher water use crops like alfalfa and almonds, with their longer growing seasons under a +2 °C warming scenario leading to additional crop irrigation demands of 71 and 70 mm, respectively. Relative increases in crop water needs were consistent across crops with 7.5%–9.5% increase with a 2 °C warming (figure S1).

Simulations using dynamic phenology and dynamic climate showed mixed results for perennials and annuals under warming scenarios (figure 3(c)). Relatively little difference crop irrigation water was seen for perennials such as almonds (−7 mm, −0.8%) and grapes (+17 mm, +3.9%) with 2 °C warming. By contrast, annuals like tomatoes (−30 mm, −8.4%) and corn (−36 mm, −6.9%) saw reduced supplemental crop water needs with +2 °C warming. Experiments that moved the planting date for annuals up by 2 weeks saw additional minor reductions in

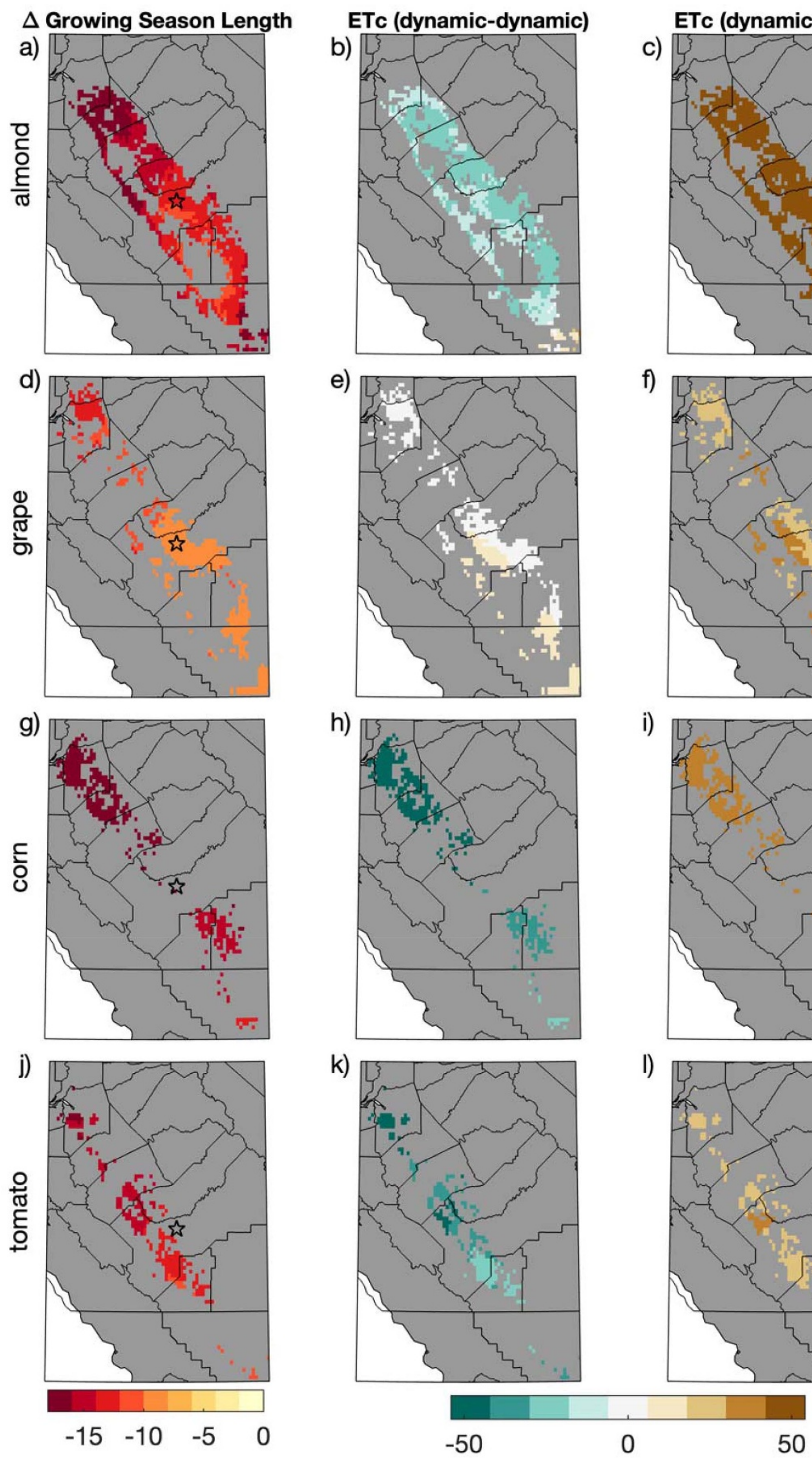

Figure 4. Mapped changes in growing season length, irrigation demand for dynamic climate and dynamic phenology (mm), and irrigation demand for dynamic climate and static phenology (mm) with the +2 °C sensitivity experiment relative to the control. Results are shown for (a)–(c) almond, (d)–(f) grape, (g)–(i) corn, and (j)–(l) tomato and plotted where 2018 crop density exceeds 5%. Kerman, California is denoted by the star in the left-hand column of each plot. County outlines are provided for reference.

supplemental water needs (<2% for +2 °C warming, not shown). Alfalfa saw similar additional crop water needs with dynamic phenology and evaporative demand to those with static phenology and evaporative demand as more cuttings occurred with warming. However, when viewed on a per-cut basis, there was net reduced water needs. These findings highlight the crucial role of phenological response in mitigating the impact of climate change on crop water demands. For perennials like grapes and almonds, dynamic phenology offset 60% and all the ETo-driven increase in irrigation needs, respectively. For annuals, the rapid maturation truncated the growing season to avoid the time of the year with the highest ETo, leading to overall reductions in supplemental crop water needs.

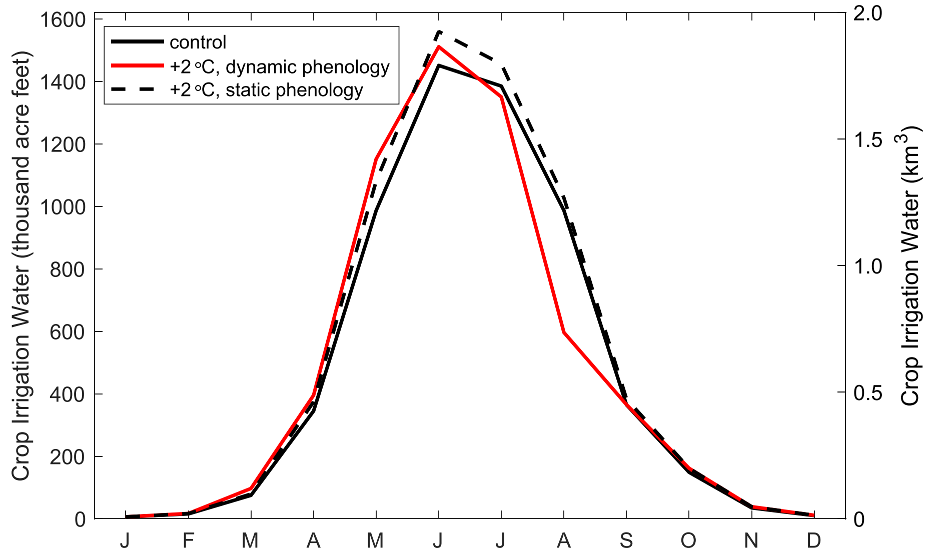

Figure 5. Calculated average monthly crop irrigation demands for the five crops summed across the San Joaquin Valley for the control 1980–2022 climate (black), +2 °C warmer climate that includes dynamic phenological changes (red), and +2 °C warming with static phenology (dashed black).

Simulations applied across the extent of agricultural land in the SJV show similar results to those for the Kerman, California example, including a shorter growing season, and net reduction in supplemental crop water when using dynamic phenological models (figure 4). These results can be leveraged to generate a rough estimate of the differences in supplemental crop water demands across the SJV in a +2 °C warming scenario. When combined with the present-day cultivated area of these five crops, we show a 6.6% annual increase in supplemental crop water demand with warming and static phenology (approximately 385-thousand-acre feet). However, models run using dynamic phenology result in about a 1.6% decrease in supplemental crop water demand (90-thousand-acre feet). In essence, dynamic phenology acts as a buffer, softening the blow of rising evaporative demand under climate change for the SJV's agricultural sector. There is also a shift in the timing of irrigation demand commensurate with phenological shifts. Relative to the control monthly irrigation needs across the region, the +2 °C warming scenario yields increases from March–June and declines in July and August (figure 5).

4. Discussion and conclusions

We show potential for crop phenological changes to partially to fully mitigate the increased evaporative demands under climate change scenarios. The effects of shorter growing seasons have the greatest efficacy at reducing irrigation demand for annual crops where a contracted growing season truncates near the seasonal peak in evaporative demand. Phenological changes partially or fully offset irrigation increases due directly to increased evaporative demand for perennials, although such crops have continued irrigation demands post-harvest despite having reduced crop coefficients. The changes in crop phenology under warming scenarios, with earlier development, maturation, and shorter growing seasons, generally mirror those in previous studies in California and globally [23, 41–43]. A limited set of previous studies have suggested the potential for reduced irrigation demand in annual cropping systems in other Mediterranean climates due to phenological changes [22, 44] and may be particularly advantageous for winter cropping systems [45]. Studies that have used static phenology show significant increases in projected irrigation demands [46]. By contrast, studies that have incorporated both phenology and plant physiological responses to increased CO_2 have shown varied changes in irrigation demand by crop type [23, 47]. Here, we isolate the role that phenology plays in buffering direct climate change effects on crop water demands.

While we examine the potential mitigative effects of phenological response on irrigation demand increases, several areas warrant further investigation. First, as our results are model based, these results are sensitive to model choices. We used simple temperature based phenological models. Such models may overestimate the phenological response to warming given that plant development is regulated by a broader suite of energy and water inputs. For example, models that incorporate photoperiod and degree days show reduced sensitivity to warming [48]. The influences of CO_2 on crop phenology directly are varied [49], highlighting the importance of further phenological studies in constraining the irrigation demands question. While more rapid phenological maturation can mitigate water demands, shorter growing seasons often come at the expense of yield or quality [20, 50, 51]. Impacts to yields may significantly counter some of the moderating effects on irrigation needs and require other adaptation efforts [51]. Further efforts that incorporate these additional considerations can provide a more nuanced understanding of how phenological response shapes agricultural water requirements in the face of climate change [52].

Prior studies have shown that offline models overestimate the impacts of climate change in plant water demand by not incorporating the physiological response of rising CO_2 [53]. Here, we show that the mechanism of phenological changes plays a complementary role in buffering some crop water needs due to climate change. We incorporated an offline approach for incorporating plant physiological responses to elevated atmospheric CO_2 that moderates the direct climate-driven changes in evaporative demand through increased stomatal resistance. While this effect likely holds of annual crops [16], perennial tree crops may exhibit different responses [37]. The details of crop responses to elevated CO_2 and its ramifications for changing evapotranspiration are beyond the scope of this analysis. Models that do not incorporate CO_2 effects on stomatal resistance but do account for phenological change show a 0.9% increase in regional irrigation demand under a +2 °C scenario, well above the nearly 9.4% increase in irrigation demand for fixed phenology (table S5). The large differences in changes in irrigation demand for a +2 °C global warming scenario reflect different mechanisms at play; +9.4% increase due to the direct influence of climate change on ETo and precipitation, reduced to +6.6% increase after incorporating the offline approach for plant physiological response to increased CO_2, further reduced to −1.6% after incorporating changes in crop growing seasons due to warming. While phenological changes may moderate the direct effects of rising ETo on crop water demands in central California for the crops we examined, a more thorough assessment of the effect of phenology across a larger set of crops, uncertainty in climate projections (e.g. figure 1(b)), and relevance across other geographies is needed.

The projected mitigating phenological response to warming from crop irrigation demands does not undermine the broader scale water resource challenges germane to the SJV. While climate projections remain uncertain in terms of overall changes in annual precipitation for the watersheds that procure surface water for agriculture [54], there is robust agreement of declines in mountain snowpack storage and increased occurrence of snow droughts [55] and numerous measures of drought [56] that will strain regional water availability. We show a shift toward increased irrigation demand during March–June with warming and phenological adjustments with decreased irrigation demand in July–August. This shift in irrigation demand is phased with projected advancement in the timing of streamflow from the Sierra Nevada headwaters [57]. Increased evaporative demand in headwater regions may further reduce runoff and overall water resources availability [58]. Lastly, some climate projections for California suggested heightened interannual variability which would facilitate greater reliance on groundwater reserves to meet irrigation demands [59].

While we focused on the phenological responses of crops to climate change, a complex web of management considerations also plays a crucial role in changing crop water demands. First, we assumed full irrigation throughout the growing season; however, deficit irrigation strategies during certain phenostages, already common for crops like grapes, can be more widely adopted to optimize water use and yield [60]. Conversely, we note that evaporative cooling through misting and additional irrigation is a management strategy used to overcome physiological heat stress in wine grapes [61], which may increase under warming scenarios. Second, crop portfolios influence regional agricultural water demand and changes in both crop mix as well as the amount of irrigated cropland given regulatory constraints (i.e. the Sustainable Groundwater Management Act [62]) will factor into future change. Third, shorter growing seasons coupled with longer freeze-free periods might incentivize double cropping systems [63], which would negate any water savings achieved through faster growth. While we show increased crop water demand for alfalfa due to increased cutting frequency with warming, irrigation demands can be curtailed when water resources are scarce or water prices are high and agricultural water markets incentivize flexibility in water reallocation [64]. Lastly, phenological changes as modeled here could disrupt labor patterns and production logistics. These management considerations highlight the need for a multifaceted approach that integrates biophysical responses with practical farming realities to ensure sustainable water use in a changing climate.

Data availability statement

No new data were created or analysed in this study.

Acknowledgments

The authors acknowledge support from USDA National Institute of Food and Agriculture Awards #2021-69012-35916, #2021-68012-35914, #2021-67021-35344; California Department of Food and Agriculture agreement #21-0557-000-SO; California

Natural Resources Agency-California Institute for Energy and Environment subcontract #5CA85; Desert Research Institute Maki Endowment (J.L.H).

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