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ADAPTATION IN CALIFORNIA AGRICULTURE: WHAT HAVE WE BEEN ASSESSING FOR TWO AND A HALF DECADES?

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Following the release of the IPCC Fifth Assessment Report, and realizing the likely impact on California water and agricultural sectors, we review key concepts in the climate change lexicon in the context of California agriculture. There are a range of modeling approaches used to study the benefits of water basin- and/or farm-level adaptations, including hydrological, crop simulation, economic programming, and econometric models. Given the central role of farmer and institutional responsiveness, how do recent agro-economic assessments suggest that specific adaptations may improve economic welfare and reduce vulnerability? What is economically efficient adaptation in the short and long-run? What are the limits to the agricultural sector's adaptive capacity?

Keywords: Adaptation; adaptive capacity; vulnerability; climate change; agro-economic models; California.

1. Introduction

Twenty-five years after the publication of the first IPCC Assessment Report, it is instructive to step back and ask what we have learned about the economic impacts of climate change to the agricultural sector, not just from a technical standpoint, but from a conceptual one. California is an ideal focus for such an analysis both because of its strong agricultural sector and proactive climate policy. After passing the 2006 Global

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Warming Solutions Act, the state has sponsored research to complete three climate change assessments, with the fourth assessment report in progress at the time of submitting this paper. This effort to study adaptation appears to be relatively more prolific than in many other global sub-regions, particularly over the past decade (Romero-Lankao *et al.*, 2014).

Assessing adaptation potential — the institutional, technological, and management instruments for adjusting to actual or expected climatic change and its effects (IPCC, 2014) — represents an important turning point in the climate impacts literature. The important role of *responsive* decision-making by farmers and institutions is recognized for the first time as the key ingredient to dampening the effects of climate change (Walthall *et al.*, 2012). Adaptation was simply mentioned as an optimistic afterthought in earlier studies, which suggested that agriculture would fully or mostly adjust in the long term — although there was sparse detail on how it would do so (Lewandrowski and Schimmelpfennig, 1999; Adams *et al.*, 1990; Adams, 1989). When adaptation was directly included in the modeling framework, economists found that the estimated welfare damages from climate change documented in previous studies declined (Smit and Skinner, 2002; Adams *et al.*, 1999; Segerson and Dixon, 1999; Mendelsohn *et al.*, 1994). In colloquial terms, this is a shift from modeling the "dumb" farmer to modeling one with reasonable economic agency.

There are four key concepts linked to the idea of adaptation: vulnerability, adaptive capacity, economic welfare, and economic efficiency. In the IPCC literature, adaptation is connected to the foundational concept of vulnerability, defined as the propensity for agricultural systems to be affected by future climatic changes (IPCC, 2014). Vulnerability can also be defined endogenously as the ability of farmers and institutions to respond and adapt to, and recover from such changes (Kelly and Adger, 2000). This latter definition is synonymous with the concept of adaptive capacity, or the ability of a system to moderate potential damages and take advantage of adaptation and mitigation opportunities to reduce vulnerability of the system to climatic changes (Walthall *et al.*, 2012; IPCC, 2007). Economic welfare is the sum of producer and consumer surplus in the agricultural sector. Adaptation dampens welfare losses caused by climate change. The relationship of adaptation with vulnerability is more complex, and better represented as that of trade-offs. For example, changing the crop mix in favor of high value crops may reduce vulnerability to water scarcity, but it may increase vulnerability to heat tolerance. Finally, the concept of efficient adaptation has been defined as a situation where the costs of effort to reduce climate-induced damages is less than the resulting benefits from adapting (Mendelsohn, 2000). Given the central role of farmer and institutional responsiveness, how do recent agro-economic assessments suggest that specific adaptations may improve economic welfare and reduce vulnerability? What is economically efficient adaptation in the short and long-run? What are the limits to the agricultural sector's adaptive capacity?

This is certainly not the first review of climate impact assessments to California agriculture. Smith and Mendelsohn (2006) highlighted the importance of regional climatic impacts to several economic sectors in California (timber, agriculture, energy), integrating across range of modeling approaches (crop, hydrological, programming, and econometric models). The agricultural impacts are calculated by the Statewide Agricultural Production (SWAP) model under wet (Hadley) and dry (PCM) scenarios. The results echo those of more recent SWAP studies, suggesting that field crop usage will decline by the end of the century under a dry scenario, though the decline in revenues will be partially offset by increased production of high-value crops. Prior to Smith and Mendelsohn (2006), several notable studies examined the state of the knowledge of climate assessments at the US level (Lewandrowski and Schimmelpfennig, 1999; Mendelsohn and Neumann, 1999). In particular, Lewandrowski and Schimmelpfennig (1999) integrate the knowledge from both programming and econometric studies of the agricultural sector. Other reviews have focused on the technical details of the different modeling approaches without discussing the results of the various studies (Iglesias *et al.*, 2011).

Following the pioneering work of Smith and Mendelsohn (2006), this paper also focuses on California. The state is a leader in agricultural production, with $53.5 billion in sector cash receipts in 2014. California accounts for roughly 2/3 of US fruit/nut production, and 1/3 of US vegetable production (CDFA, 2015). Roughly 1/3 of California cropland, or 9 million acres, is irrigated (DWR, 2013; Thompson, 2009), making the state's agricultural sector highly vulnerable to changes in groundwater and surface water supply (Jackson *et al.*, 2012). Several programming and econometric studies have been published after Smith and Mendelsohn (2006), that operationalize the concept of adaptation (Table 1). This paper begins with a review of regional impacts of climate change to California agriculture. It is followed by a review of the results from recent programming and econometric studies. The final section synthesizes the results from these studies, addressing lessons learned about vulnerability,

Table 1. Adaptation strategies included in California agro-economic assessments.

Adaptation feature	Study	Details
Technological development that increases future crop yields	Medellin-Azuara *et al.*, 2011; Medellin-Azuara *et al.*, 2009; Medellin-Azuara *et al.*, 2008	Follows from the work of Brunke *et al.* (2004), who create a statewide yield index for 30 California crops using historical data. They find that the mean rate of growth for the index over the historical study period (1960–2002) is 1.42% annually. Some studies have accounted for carbon fixation as a limiting factor for photosynthetic development, and thus reduce annual yield growth during the latter part of the study period.

Table 1. (*Continued*)

Adaptation feature	Study	Details
Irrigation technology change	Joyce *et al.*, 2011	Gradual improvements in irrigation efficiency until 2050. Specifically, they assume that most crops (excluding rice) will make a gradual shift to drip irrigation. That is, orchards, vineyards, and row crops entirely irrigated w/ drip. Field crops would only incorporate half of their irrigated land to drip.
Crop mix changes	Dale *et al.*, 2013; Frisvold and Konyar, 2012; Joyce *et al.*, 2011; Medellin-Azuara *et al.*, 2009; Medellin-Azuara *et al.*, 2008	Programming models focus on the change in regional crop mix. Indeed crop acreage is the central decision variable, and thus changes in crop acreage drive much of the analysis. Dale *et al.* (2013) and Joyce *et al.* (2011) relate the share of crops in a given region to water supply conditions at the time of planting, through a multinomial logit analysis. Thus water supply conditions drive crop mix rather than the relative profitability of a given set of crops.
Crop variety changes	Lobell and Field, 2011	Explore how different almond varieties may react to winter warming.
Land fallowing	Dale *et al.*, 2013; Frisvold and Konyar, 2012; Joyce *et al.*, 2011; Medellin-Azuara *et al.*, 2009; Medellin-Azuara *et al.*, 2008	
Urbanization of ag land	Medellin-Azuara *et al.*, 2011; Medellin-Azuara *et al.*, 2009; Medellin-Azuara *et al.*, 2008	Agricultural land is converted to urban use using projections from a spatial-statistical model of urban growth for California's 38 urban counties (Landis and Reilly, 2002).
Deficit irrigation	Frisvold and Konyar, 2012	
Adjusting labor	Frisvold and Konyar, 2012; Medellin-Azuara *et al.*, 2009; Medellin-Azuara *et al.*, 2008	
Adjusting other inputs (fertilizer, chemicals, other)	Frisvold and Konyar, 2012; Medellin-Azuara *et al.*, 2011; Medellin-Azuara *et al.*, 2009; Medellin-Azuara *et al.*, 2008	

Table 1. (*Continued*)

Adaptation feature	Study	Details
Adjusting capital	Frisvold and Konyar, 2012	Note they allow for changes in capital quantity, but not type (i.e., no shifts between irrigation technologies)
Crop Insurance	Lobell and Field, 2011	
Adjusting irrigation scheduling	Lee *et al.*, 2011; Jackson *et al.*, 2011	
Water portfolio	Mukherjee and Schwabe, 2014	
Participation in federal commodity programs (i.e., marketing loan; counter-cyclical payments)	Frisvold and Konyar, 2012	
Water market transfers; urban water conservation; waste water treatment and reuse; seawater desalination; conjunctive use of groundwater and surface water	Frisvold and Konyar, 2012; Medellin-Azuara *et al.*, 2011; Medellin-Azuara *et al.*, 2009; Medellin-Azuara *et al.*, 2008	

adaptation, and adaptive capacity; and how these relate to economic welfare and efficiency.

2. Impacts of Climate Change in California

Observational studies indicate that average daily temperature and daily minimum temperatures, particularly during the winter season, have increased in California (Hoerling *et al.*, 2013; Barnett *et al.*, 2008). Average daily temperature in the US Southwest for the previous decade (2001–2010) has been higher than any decade observed in the previous century (Hoerling *et al.*, 2013). Barnett *et al.* (2008) find that daily minimum temperatures in winter (January–March) have increased between 0.28–0.43°C per decade from 1950–1999. Not just magnitude, but an increased rate of warming has been observed. Karl *et al.* (2009) suggest that the US Southwest has experienced the most rapid rate of warming in the nation.

Observed precipitation patterns are fundamentally more complex and variable than temperature, exhibiting a high degree of variability across space and time. Trenberth *et al.* (2007) indicate that annual precipitation has decreased in the southwestern United States for the period 1901–2005. Consistent with scientific theory, empirical research suggests that warmer climates, such as those projected for the Southwest, will lead to more extreme precipitation intensity and frequency (Allan and Soden, 2008; Trenberth *et al.*, 2007), particularly during the winter season (Dominguez *et al.*, 2012; Maurer, 2007; Maurer *et al.*, 2007). Since annual precipitation is projected to decline (Trenberth *et al.*, 2007), more extreme events do not translate into higher total rainfall for a given year. Instead, it is projected that light precipitation — an important source for soil moisture and groundwater recharge — will concomitantly decline. Between 1901 and 2010, the areal extent of drought increased in the southwestern United State (Hoerling *et al.*, 2013). Some have attributed the increasing expanse of drought, particularly in the previous decade, to warmer temperatures (Dai, 2011). Others have suggested that it is due to changes in atmospheric circulation (McCabe *et al.*, 2004; Hoerling and Kumar, 2003).

In addition to temperature and precipitation, CO_2 fertilization is another climate change pathway affecting agriculture. Increased atmospheric carbon dioxide stimulates photosynthesis, leading to increased plant productivity and decreased water and nutrient use (Tubiello *et al.*, 2007). Benefits from elevated CO_2 concentrations depend upon plant type and irrigation level. C3 photosynthetic plants (e.g., wheat, potatoes, soybeans) will benefit more than C4 plants (e.g., corn, sorghum) (Stockle *et al.*, 2010), and dryland cropping systems will benefit more than irrigated systems (Easterling *et al.*, 2007). The extent to which CO_2 fertilization mitigates climate-induced water scarcity in the field still lacks scientific consensus, and there is debate on the extent to which simulating CO_2 effects actually reproduces the results in free air carbon dioxide enrichment (FACE) experiments (Tubiello *et al.*, 2007; Long *et al.*, 2006).

Agricultural impacts from climate change are rooted in complex pathways. Assessments of crop impacts due to climatic change fall under two, broad categories: (i) process-based and (ii) statistical models. Process-based models simulate physiological development, growth and yield of a crop on the basis of interaction between environmental variables (e.g., soil, climate) and plant physiological processes (e.g., photosynthesis, respiration, transpiration). Statistical crop models impute a relationship between historic crop yield and climate variables, often in order to project the impact on yield under future climate scenarios. Process-based models remain the gold standard in crop modeling as one is able to study the relationship between weather and all phases of crop growth in a range of weather possibilities, even those lying outside the historical record (Yin, 2013; Lobell and Field, 2011; Adams *et al.*, 2006).

California field crops have been modeled using DAYCENT (Lee *et al.*, 2011; Jackson *et al.*, 2011). Both studies highlight resilience of alfalfa yield under A2 scenario by end of the century, whereas 5 other crops exhibit a decline. Jackson *et al.* (2011) also find alfalfa yield to be particularly resilient to early and repeated heat waves during May–July. Lee *et al.* (2011) also run climate projections with and without a CO_2 fertilization effect on seven field crops in the Central Valley of California. They assume a CO_2 increase of 350 ppmv (parts per million by volume) from 1990 levels enhances net primary production by 10% for all crops except alfalfa and maize. They find that CO_2 fertilization increases crop yields 2–16% above the model without CO_2 effects under the high-emissions scenario by the end of the 21st century. There is a much smaller yield increase (1–8%) under the low-emissions scenario. Lobell and Field (2011) use two estimation methods (least absolute selection and shrinkage; and regression tree analysis) in studying the effects of temperature and precipitation on perennial crop yields. Their model includes 72 potential weather predictor variables for each crop, such as monthly averages for max and min temperature and their corresponding squares. They find that cherries and almonds are harmed by future warming out of a set of 20 perennial crops in their analysis.

Crop-level adaptations — such as adjusting the planting and harvesting date (Lee *et al.*, 2011), and substituting between different crop varieties (Lobell and Field, 2011) — have been included to a limited extent in crop models. However, these cannot account for the broad range of decision making at the farm-level under which many of the negative effects of climate change could be partially offset with input and output substitutions, improving information, and effective water institutions. Thus, economic models are necessary to capture a broader range of responsive decision-making as the climate changes.

3. Programming Models

Recently, adaptations specific to California agriculture have been studied using three economic programming models: the Statewide Agricultural Production (SWAP) model, Central Valley Production Model (CVPM), and the US Agricultural Resources Model (USARM). Capturing the decision-making process is an important part of modeling. In programming models, the farmer's decision is captured by the objective function. The main decision variable in these models is acres of land allocated to a region-specific crop mix. The farmer responds to reductions in water availability and yield by adjusting crop acreage. Exogenous adaptations include institutional (e.g., water markets/transfers, fallowing incentive programs), socioeconomic (e.g., population growth, increase in real income, urbanization), and technological change (e.g., availability of yield-enhancing production methods). Calibration through positive mathematical programming (PMP) also captures decision-making by preserving observed crop mix allocation decisions (Merel and Howitt, 2014; Howitt, 1995). SWAP employs a PMP cost function to the capture the decision of bringing an additional unit of land into production (Medellin-Azuara *et al.*, 2011). Both CVPM and USARM have also been calibrated using PMP (Dale *et al.*, 2013; Frisvold and Konyar, 2012; Joyce *et al.*, 2011). CVPM studies have also generated synthetic crop share data from Monte Carlo runs using a base water supply and groundwater depth with random perturbations. Crop adaptation equations are then derived from a multinomial logit regression of this CVPM-generated synthetic crop share data (Dale *et al.*, 2013; Joyce *et al.*, 2011).

In order to represent climate-induced changes in water supply, many mathematical programming models are linked to hydrological management models, such as the

California Value Integrated Network (CALVIN), Water Evaluation and Planning (WEAP), CalSim-II, and C2VSim. CALVIN is a generalized network flow-based optimization model that minimizes economic operating and scarcity costs of water supply, subject to water balance, capacity, and environmental constraints for a range of operational and hydrologic conditions (Tanaka *et al.*, 2006). CALVIN has the potential to incorporate several basin-level adaptations to water allocation rules such as contract changes, markets and exchanges, water rights, pricing, and water scarcity levels. However, it has limited ability to represent important physical phenomena, such as stream-aquifer interactions and groundwater flow dynamics under different climate and water management scenarios (Tanaka *et al.*, 2006; Draper *et al.*, 2003). WEAP has many of the same water management features as CALVIN and CalSim-II. WEAP includes demand priorities and supply preferences in a linear programming framework to solve the water allocation problem as an alternative to multi-criteria weighting or rule-based logic. It is different because analysis in the WEAP framework comes directly from the future climate scenarios and not from a perturbation of historical hydrology as with the other models. Unlike CALVIN and CalSim-II, WEAP only has a simplified representation of the rules guiding the State Water Project and Central Valley Project systems (Joyce *et al.*, 2011; Yates *et al.*, 2005). CalSim-II is also very similar to CALVIN and WEAP (Dale *et al.*, 2013). C2VSim is a multi-layer, distributed integrated hydrologic model that could represent pumping from multiple aquifer layers, effects on groundwater flow dynamics, and stream-aquifer interaction (Dale *et al.*, 2013).

Recent programming studies focus on how certain adaptations (i.e., changes in crop acreage, water markets/transfer, groundwater usage, and drip irrigation) may affect costs under relatively extreme cases of water scarcity. These studies thus assess how these adaptations may offset costs under worst-case-scenarios of water supply reductions. Given that reduction in statewide agricultural water use due to the current drought is estimated at 6% (Howitt *et al.*, 2014), studies on 40–70% flow reduction should be interpreted with caution. The subsequent studies are organized according to magnitude of water supply/flow reduction.

Studies on 5–6% reduction in water supply reveal the heavy fallowing and groundwater use (Howitt *et al.*, 2014; Frisvold and Konyar, 2012). Howitt *et al.* (2014) find that a 6.6 maf deficit in surface water caused by the current drought is largely substituted by 5.1 maf of additional groundwater. This is estimated to cost an additional $454 million in pumping. In addition to over-pumping groundwater, farmers adjust by fallowing crop land. The overwhelming majority (96%) of the 428,000 acres estimated fallowed in 2014 are in the Central Valley, where the majority of fallowed acres belong to field crops. However, they project that fallowing will decrease by 43% by 2016, suggesting a trend toward stabilization. Frisvold and Konyar (2012) use USARM to examine the effects of a 5% reduction in irrigation water supply from the Colorado River on agricultural production in southern California. In particular, they are able to compare the potential value-added of additional adaptations that include changing the crop mix, deficit irrigation, and input substitution to a "fallowing only" model. They find that these additional adaptations have the potential to reduce costs of water shortages to producers by 66% compared to the "fallowing only" model.[1]

Medellin-Azuara *et al.* (2008) examine the extent to which more flexible[2] versions of California water markets could reduce water scarcity costs under a 27% statewide reduction in annual streamflow. They compare agricultural water scarcity in the year 2050 under two scenarios: 1. Baseline: population growth and resulting levels of agriculture to urban land transfer, 2. Warm-dry: includes population pressure and climatic changes under GFDL CM2.1 A2). Under the warm-dry scenario, even with optimized operations, water scarcity and total operational costs increase by $490 million/year, and statewide agricultural water scarcity increases by 22%. If water markets are restricted to operate only within (rather than between) the four CALVIN sub-regions, statewide water scarcity costs increase by 45% and 70% for the baseline and warm-dry scenarios, respectively. Marginal opportunity costs of environmental flows increase under the warm-dry scenario, with particularly large percentage increases for the Delta Outflow and American River. Medellin-Azuara *et al.* (2009) conduct a similar analysis, adding the comparison with a warm-only 2050 scenario. The agricultural sector water scarcity costs rise by 3% from the baseline to warm-only scenario, versus an increase of 302% from the baseline to the warm-dry scenario.[3] Indeed the greater hydrological impact of the warm-dry scenario results in significantly greater scarcity costs than the warm-only scenario.

Using the CALVIN model runs from Medellin-Azuara *et al.* (2009), Medellin-Azuara *et al.* (2011) analyze adaptations at the farm-level, including adjustments in crop acreage (decision variable), and to a more limited extent, yield-enhancing technology (exogenous). Similar to the 2008 paper, the model compares economic losses (this time in the form of loss in agricultural revenue) between a baseline scenario (2050 with the same assumptions about urban population growth) and a warm-dry scenario (2050 with 21% average water reduction for agricultural regions). Results reveal an anticipated decline in acreage of low-value crops (corn, grain, and pasture), which is particularly severe due to the large reduction in water availability. For example, pasture acreage is reduced by 90% across 3 out of 4 agricultural regions. The results also suggest that statewide agricultural revenues decline (between the two scenarios) at a proportionately lower level (11%) than the reduction in water availability (21%). Their model also captures the complexity between crop demand and climate-induced supply reduction. Although the demand for high-valued orchard crop increases, production decreases due to the negative impact on yield from temperature increases.

[1]This is the percent reduction for the entire southwest region (Arizona, California, Colorado, Nevada, New Mexico, and Utah) since they do not calculate results for individual states.

[2]CALVIN is only constrained by infrastructure and physical constraints. Existing institutional constraints, such as limited water markets, are largely unrepresented (Medellin-Azuara *et al.*, 2008).

[3]Note that the assumptions in constructing the warm-dry scenario for Medellin-Azuara *et al.* (2009) are more strict than those for Medellin-Azuara *et al.* (2008), although both papers use GFDL CM2.1 with A2 emissions level.

The resulting price increase cannot compensate for the decrease in supply, and gross revenue still declines.

Two studies examine the impacts of more extreme reductions in water supply (Dale *et al.*, 2013; Harou *et al.*, 2010). Harou *et al.* (2010) construct a synthetic drought (40–60% reduction in mean flows) in 2020 based on the paleo-record, rather than GCM projections. Their results regarding agricultural water scarcity and environmental flows are consistent with other CALVIN-SWAP studies. Environmental flows are also extremely restricted. Marginal opportunity costs of environmental flows rise by one or more orders of magnitude with extreme drought as compared to the historic baseline, with the Trinity, Clear Creek, and Sacramento Rivers experiencing the highest increase. Average agricultural water scarcity increases 3900% across the entire state under extreme drought even under well-functioning water markets, which seems somewhat implausible and may result from an overly restrictive model. Although Dale *et al.* (2013) do not calculate scarcity costs, they find that a 60-year drought with 70% reduction in surface flows only moderately impacts the total amount of irrigated acreage in the Central Valley, which declines from 2.4 million hectares to 2.1 million. This suggests that Central Valley farmers tend to have a relatively inelastic groundwater demand, compensating for the loss in surface water with groundwater rather than fallowing. Within the Valley, they find that Tulare Basin has a greater increase in fallowing than the San Joaquin Basin since the former is historically more dependent on groundwater. Dale *et al.* (2013) are also able to capture the increase in aquifer subsidence due to increased withdrawals during the prolonged drought, suggesting that the quality of the aquifer will decline through time with excessive pumping.

Joyce *et al.* (2011) use WEAP-CVPM to model climatic changes with 6 GCMs (CM3, CM2.1, MIROC 3.2, ECHAM5, CCSM3.0, PCM1) under B1 and A2 scenarios for 2006–2099. Unlike the CALVIN-SWAP studies, they model irrigation efficiency by assuming that vegetable and fruit and nut crops in the Central Valley will be entirely converted to drip irrigation, and half of field crops will be converted by mid-century. They find that these adaptations tend to offset increasing water demands caused by increasing temperatures and periods of drought. The model even projects a reduction in annual groundwater pumping compared to the historical period until mid-century under some scenarios. Unfortunately, this positive effect of switching to drip irrigation is lost toward the end of the century as higher temperatures drive up crop water demands.

4. Econometric Approaches

One of the earliest econometric evaluations on the impacts of human-induced climate change to US agriculture developed out of a reaction to the limited substitution (i.e., adaptation) options in earlier production function models (Mendelsohn *et al.*, 1994). Given long-run production decisions, one could use a cross-section of county farm data to assess how climate could impact agricultural rents. The underlying assumption is that farmers have fully adapted to their environmental circumstances (Mendelsohn, 2000). While one cannot explicitly identify these decisions, these models are an improvement over older models because one could at least measure the consequences of adaptive decision-making (Massetti and Mendelsohn, 2011). Other econometric models are able to capture annual decision-making using panel data. However, these models are unable to capture the idea of adaptation because farmers are very likely unresponsive to changes in weather from one year to the next.

In their classic paper, Mendelsohn *et al.* (1994) evaluate the impact of climate variables (temperature and precipitation) on the expected present value of future rents in US agriculture, which they assume is proportional to farm land value under a few simplifying assumptions.[4] They regress farm land values on climate, soil, and socioeconomic variables using cross-sectional data for 2933 US counties. Their results reveal the seasonality and nonlinearity in the relationship between climate variables and farm land value. Beyond this, both the direction and magnitude of their estimated climate parameters have been criticized and subsequently revised (Deschenes and Kolstad, 2011; Schlenker *et al.*, 2006; Darwin, 1999; Fisher and Hanemann, 1998; Mendelsohn *et al.*, 1996; Cline, 1996).

One criticism with the original model, now obvious with hindsight, is the omission of ground and surface irrigation variables (Fisher and Hanemann, 1998). Indeed, the negative effect of summer precipitation on land value in Mendelsohn *et al.* (1994) is potential evidence of omitted variable bias and, as Schlenker *et al.* (2005) suggest, misspecification. In response, Mendelsohn and Dinar (2003) include a surface water variable interacting it with annual temperature and precipitation. They find that the former is positive while the latter is negative, suggesting that counties with more surface water can tolerate higher annual temperatures and lower annual precipitation. Schlenker *et al.* (2005) indicate that dryland and irrigated counties require two separate estimation equations, unlike the single estimation equation in Mendelsohn and Dinar (2003). A single equation erroneously implies that dryland farms requiring irrigation in the future will have access to analogous large-scale water projects peculiar to the western US at a given point in history. In testing the null hypothesis that each of the 16 climate variables in the original analysis are individually the same in the dryland ($n = 2197$) and irrigated ($n = 514$) farm sub-groups, they find that between 4 and 6 coefficients are significantly different from 0, depending on the weighting method. Even though Schlenker *et al.* (2005) did not have access to water data on irrigated counties at the time, their F-test was still able to provide sufficient proof of the bias in pooling dryland and irrigated counties into one model.

After studying climate impacts to dryland agriculture in the US (Schlenker *et al.*, 2006), Schlenker *et al.* (2007) study the impact of water availability (surface and groundwater) and degree days on California farmland values. Their cross-sectional

[4]They assume the interest rate, rate of capital gains, and capital per acre are equal to the land rent.

dataset represents individual farms, rather than county aggregates.[5] Including groundwater and surface water supply corrects for the omitted irrigation variable bias in Mendelsohn *et al*. (1994). Importantly, Schlenker *et al.* (2007) include a nonlinear measure of temperature effects on crop growth known as degree days.[6] Their results suggest a positive relationship between the long-run annual availability of surface water and farmland value (for farms less than $15,000/acre). They find that the coefficient on surface water is sensitive to water price: as water price per acre-foot increases, this coefficient decreases. They also find that the coefficient on degree days is positive and statistically significant, while degree days squared is negative and statistically significant. They do not use these relationships to estimate impact to farmland value under future climate scenarios. A criticism of degree days, as used in Schlenker *et al.* (2007), is that it is a measure of weather not climate (Dinar and Mendelsohn, 2011).

In contrast to cross-sectional analysis, Deschenes and Greenstone (2007) estimate the impact of yearly fluctuations in weather on annual farm profits using US county-level panel data (n =2262), under 3 climate scenarios: uniform, Hadley II (2020-49), and Hadley II (2070-99). When they account for county and year effects, the results from all three models show a negative impact on profits. With the addition of state-by-year fixed effects, all three models show a positive impact on annual profits. Fisher *et al.* (2012) find data and coding errors in the Deschenes and Greenstone (2007) model, biasing the original results in the positive direction. Specifically, the climate variable on the average number of degree days (1970–2000) has a zero value for several (163) counties, and climate projections varied by state while their historic climate data varied by county. Both of these errors tend to result in a regression toward the mean effect, with warm counties projected to get cooler, and vice versa. In response, Deschenes and Greenstone (2012) acknowledge the data and coding errors, and find that the $1.3 billion benefit in annual profits under Hadley II (2070-99) is actually a $4.5 billion loss.[7] However, Deschenes and Greenstone (2012) disagree that state-by year fixed effects are misspecified. Like Fisher *et al.* (2012), they find that state-by-year fixed effects tend to absorb most of the weather variability, resulting in a positive (or less negative) impact on profits. Their purpose in including state-by-year fixed effects is to control for state-level shocks in prices and productivity. To test for this, Deschenes and Greenstone (2012) include two additional specifications of year

[5]They use geo-referenced data on individual farms from the USDA June Agricultural Survey. Since this data presents information on several farms for any given level latitude/longitude, the authors use random effects to allow farmland with identical latitude/longitude pairs to be correlated.

[6]Degree days capture the number of days within a given growing season that are either below, above, or within a certain temperature threshold (8-32 C). For this analysis, the authors use the 30-year average (representing a climate normal) daily temperature for 1960–1989 for the April–September growing season.

[7]Following criticism from Fisher *et al*. (2012), they also include a lagged temperature variable to account for production that is stored as inventory in any given year. They find that the lagged temperature variables tend to have the opposite sign compared to the annual temperature variables, though the magnitude is generally smaller. This is consistent with economic theory that farmers use inventory management to compensate for annual shocks in production.

fixed effects: varying according to 9 USDA Farm Resource Regions, and varying according to 9 US Census Divisions. The results from an F-test reject the null hypothesis of zero local shocks. Just as excluding all year effects, as in Fisher *et al.* (2012), may bias the results downward, including fixed effects at the state level may be too strict, biasing the results upwards. The two intermediate cases of region-by-year fixed effects may present a "happy medium" to this problem.

Schlenker and Roberts (2009) use panel data to study yield impacts to cotton in the western US.[8] Constructing a dataset that incorporates the entire distribution of temperatures within a day, and across all days of the growing season, they find that the level of yield decline is greater under nonlinear temperature effects than linear ones. Even under a moderate emissions scenario (Hadley III, B1), cotton yields decline across the western US by approximately 30%. Their approach is analogous to statistical crop studies discussed in the Impacts of Climate Change to California section (Lobell and Field, 2011). Massetti and Mendelsohn (2011) test the use of panel data on a Ricardian model using the same Agricultural Census data ($n = 2914$) as Deschenes and Greenstone (2007). They test the stability of climate variables (seasonal/annual temperature and precipitation) using two panel data approaches (pooled and two-stage) against a repeated cross-section Ricardian model. Both panel models have relatively stable climate variables (i.e., same sign and order of magnitude) across the six Census years tested. There are $15 billion in welfare gains for a uniform 2.7°C warming and 8% precipitation increase for both panel models, although this ignores distributional welfare impacts. In contrast, the climate variables of a repeated cross-section Ricardian model vary through time. As a result, the welfare calculations also vary through time.

Deschenes and Kolstad (2011) use panel data on aggregate county-level farm profits to study the differential effects of climate (cross-sectional county data) and yearly fluctuations in weather (times series within each county). Their climate variables include a 5-year moving-average of the annual degree days and precipitation, while weather variables are represented by annual degree days and precipitation. While none of the coefficients on annual degrees days (represented through climate and weather variables) are statistically significant with either the historical or CCSM (B1 and A2) models, their study is instructive in finding that the climate variable has a greater magnitude than the weather variable both in the baseline and climate change scenarios. This corroborates the theory that long-term changes in weather (as represented by the climate variable) are more costly for some farmers than short-run fluctuations. They tease out which farmers may be most affected by changes in climate by analyzing 15 of the largest crops (based on production values and yields). They find that certain crop revenues respond positively to degree days (e.g., table grapes), while others respond negatively (e.g., wine grapes).

A few econometric approaches study specific adaptations. Mukherjee and Schwabe (2015) evaluate the benefits of access to multiple water sources for irrigated agriculture

[8] Their analysis of corn and soybeans is limited to counties east of the 100th meridian.

in California. Using a hedonic property value approach, they find that the marginal value of average water supplies from the Central Valley Project or State Water Project decreases as access to other sources increases. Lobell and Field (2011) study the use of federal crop insurance and emergency payments/loans in California from 1993–2007. They find that the most common cause of insurance and disaster payments during this period is excess moisture. Cold spells and heat waves are also important causes.

5. What Have We Been Assessing?

We return to the question posed in the title. What have we been assessing with respect to the human and institutional responsiveness known as adaptation to climatic change in more recent studies on the topic? Several sub-questions are subsequently discussed. To what extent have study results identified economically efficient adaptations? To what extent have economically efficient adaptations reduced vulnerability to climatic changes and/or welfare losses? Have these studies identified limits to adaptive capacity in the agricultural sector, tempering the optimism of earlier studies?

We have examined both normative (mathematical programming) and positive (econometric) approaches to studying adaptation. Normative approaches have provided insight into *which* adaptations may be economically efficient equating this with the optimal solution to the farmer's objective function. There are two such adaptations explicitly represented in the CALVIN/SWAP models: changes to crop mix and water transfers/markets.[9] As water resources decline, the resulting crop mix will reflect a decline in field crop acreage, with relatively less change for specialty crops (Frisvold and Konyar, 2012; Medellin-Azuara *et al.*, 2011). CALVIN includes water markets as an institutional adaptation. Under climate-induced water reduction scenarios, water is transferred from low-value to high-value use. Implicit in this is the transfer of land from agricultural to urban uses, though this is not directly modeled in these studies. In the WEAP-CVPM framework, Joyce *et al.* (2011) implicitly model the potential for converting to drip irrigation, particularly for thirsty field crops.

By contrast, economically efficient adaptation is assumed, rather than modeled, in positive approaches, such as Ricardian models. Ricardian approaches have thus studied how climatic change will impact agriculture in the presence of long-run economically efficient adaptations. Without knowing the actual adaptations undertaken, this approach provides limited analysis on economic efficiency. Hanemann (2000) argues that Ricardian models may not even capture long-run efficiency because economic agents do not behave optimally even in the long run. Studies of both short-run and mid-to-long run suggest that farmers with access to groundwater will tend to increase pumping, increasing the likelihood of aquifer subsidence, to compensate for losses in surface water or increases in crop water demands (Howitt *et al.*, 2014; Dale *et al.*,

[9] Harou *et al.* (2010) also find that wastewater reuse increases by 40% under their extreme drought scenario as compared to their optimized historic scenario. It is unclear the extent to which wastewater is being used by agriculture as opposed to other sectors.

2013; Jackson *et al.*, 2012; Joyce *et al.*, 2011). Based on definitions in the latest IPCC report, this is maladaptation more than it is efficient adaptation. Schlenker and Roberts (2009) suggest that there is minimal adaptation even in the long run when they find that the results of their isolated time series are similar to those of the isolated cross-section. Suffice it to say, that Ricardian approaches are capturing some level of adaptation, but it is likely not economically efficient. Panel data studies on farm profits (Deschenes and Kolstad, 2011; Deschenes and Greenstone, 2007) are not able to capture adaptation even implicitly.

In both programming and econometric approaches, vulnerability is measured as loss in economic welfare (or increase in scarcity costs), which is perhaps the greatest limitation of comparative static approaches. Unlike economic welfare, vulnerability is a dynamic concept. For example, the move from field (e.g., pasture, alfalfa, cotton) to high-value (e.g., tomatoes, almonds) crops dampens the economic welfare decline caused by a warm-dry climate mid-to-late century. That is, the percentage loss in farm revenue is less than the decline in farm acreage. Water markets are also likely to dampen the welfare loss associated with climate change (Medellin-Azuara *et al.*, 2011; Medellin-Azuara *et al.*, 2008). However, these high-value crops tend to have lower heat tolerance as temperature increases (Lobell and Field, 2011; Medellin-Azuara *et al.*, 2011). Further, field crops are generally regarded as more secure assets with lower associated production costs, than vegetable or tree crops. The concept of vulnerability is able to capture this insecurity. Vulnerability to overall profit loss may be reduced by the crop mix change, but the increased variability in farm income will also increase vulnerability to temperature increases. Medellin-Azuara *et al.* (2011) illustrate this with high-value orchard crops, where the gross revenue declines even as prices increase. Econometric approaches illustrate that California agricultural land value may be particularly vulnerable to changes in surface water supply and nonlinear temperature effects (Schlenker and Roberts, 2009; Schlenker *et al.*, 2007). Deschenes and Kolstad (2011) also illustrate that farm profits may be more responsive to climate (as represented by a 5-year moving average) than annual fluctuations in temperature and precipitation.

Several analyses illuminate our understanding of adaptive capacity. The overarching focus for many CALVIN-SWAP studies is to start with a worst-case scenario approach and see how well we fare even with some of the best-case farmer and institutional responses (ideal water markets, minimal adjustment costs in changing crop acreage or switching technology). Joyce *et al.* (2011) also illustrate an example of adaptive capacity through time. Assuming drip irrigation is more widely adopted in the Central Valley by mid-century, they find that groundwater pumping declines. However, as the climate continues to warm towards the end of the century, the positive effects of drip irrigation are eliminated. Beyond this, a discussion of adaptive capacity is lacking.

We have moved ahead in the past 15–20 years from the early agro-economic assessments of the early/mid-1990s, but it appears that we are also standing still. This review has illustrated the various ways comparative static approaches have incorporated adaptive actions to illuminate our understanding of climatic impacts to California agriculture. But, as critics suggest (Hanemann, 2000), questions of when and how much farmers and institutions will adapt are left unanswered. *Responsiveness* — the key characteristic of decision-making — is only vaguely addressed, and, important distributional consequences of climate impacts to agriculture while alluded to, are not identified. Lack of responsiveness and distributional consequences is mostly due to a dearth of individual farm-level data, rather than the incapacity of programming and econometric approaches to accommodate a more specific analysis. Using the same county-level data with more innovations (e.g., population projections, advanced climate models, temperature-yield adjustments, panel data) in a comparative static framework could only take programming and econometric approaches so far. There is also a degree of comfort with identifying the primary barrier to moving forward as uncertainty in climate projections. While vulnerability arises out of biophysical processes, it is critical to understand that it is imposed on a pre-existing, dynamic socioeconomic structure (Kelly and Adger, 2000). It is important that our economic models do more to capture this structure.

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