Unintended Costs of Climate Change Adaptation: Agricultural Wells and Access to Drinking Water*

Ellen Bruno†, Jeffrey Hadachek‡, Nick Hagerty§, and Katrina Jessoe¶

May 27, 2022

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Abstract

Adaptation actions taken to mitigate climate damages may impose negative externalities on vulnerable populations. We study this in the context of groundwater in California and evaluate the effects of annual fluctuations in weather and surface water supplies on agricultural well construction and access to drinking water. Using the population of geocoded wells, we show that farmers respond to extreme heat and surface water scarcity through agricultural well construction. This mitigating behavior by agricultural users imposes costs, as extreme heat and surface water scarcity reduce local groundwater levels and lead to domestic well failures. Our findings demonstrate that an unintended cost of agricultural groundwater extraction is access to drinking water supplies in disadvantaged communities.

*We thank seminar participants at the University of Alabama and UC Davis Water Economics Lab for helpful comments and discussions and Samanatha Poteet for research assistance. Funding for this research came from the Giannini Foundation of Agricultural Economics.

†Department of Agricultural and Resource Economics, University of California, Berkeley. Email: ebruno@berkeley.edu

‡Department of Agricultural and Resource Economics, University of California, Davis. Email: jdhadachek@ucdavis.edu

§Department of Agricultural Economics and Economics, Montana State University. Email: nicholas.hagerty@montana.edu

¶Department of Agricultural and Resource Economics, University of California, Davis. Email: kkjessoe@ucdavis.edu

1 Introduction

The costs of climate change are expected to be broad in reach and disproportionately borne by the poor (Hsiang, Oliva, and Walker, 2019). The latter occurs in part because the magnitude of damages depends on the ability to adapt, and poorer households are less likely to have the means to respond (Burke and Emerick, 2016; Rode et al., 2021; Jessoe, Manning, and Taylor, 2018; Dell, Jones, and Olken, 2014, 2012). Averting actions taken by some to mitigate climate damages may also impose externalities that are disproportionately realized. However, little is known about the extent to which avoidance behaviors taken to reduce climate damages impose costs on those unable to do so.

We study this in the context of groundwater in California, and evaluate the extent to which agricultural well construction compromises access to drinking water sources in vulnerable communities. In California the agricultural costs of climate change vary dramatically across studies, ranging from negligible to up to 15% of profits (Deschênes and Greenstone, 2007; Mendelsohn, Nordhaus, and Shaw, 1994). A challenge with climate change impact assessment for irrigated agriculture is that precipitation no longer measures water availability and temperature indirectly influences water supplies (Deschenes and Kolstad, 2011; Schlenker, Hanemann, and Fisher, 2005, 2007). One consistency across the range of cost estimates is that groundwater extraction, which has been traditionally unregulated, has long operated as an adaptation strategy to mitigate the agricultural costs of surface water reductions and heat (Lund et al., 2018; Hornbeck and Keskin, 2014).[1]

However, this reliance on groundwater reserves for agricultural consumption may compromise access to safe drinking water supplies for surrounding rural communities through increased domestic well failures (Pauloo et al., 2020).[2] This concern is particularly acute in

[1]Climate change is expected to increase the frequency and severity of extreme heat and drought, make precipitation more variable, and reduce soil moisture (Swain et al., 2018). Collectively, these factors will increase agricultural demand for water and introduce large uncertainty into surface water availability for agricultural irrigation. To buffer against surface water curtailments and increased demand, agricultural users have often drawn from non-renewable groundwater reserves.

[2]A large literature focused on the non-renewable nature of most groundwater stocks has quantified the pumping and stock externalities imposed on of current and future agricultural users (Provencher and Burt,

the San Joaquin Valley, an area that is over 50% Latino/a and contains some of the highest rates of poverty and food insecurity in the state. Many rural households rely on private domestic wells for drinking water purposes, and it is expected that approximately 10,500 domestic wells will dry up by 2040 (Pauloo et al., 2020).

This paper will examine the extent to which new groundwater well construction by farmers, in response to annual fluctuations in heat and surface water scarcity, impacts depth to the water table and access to domestic wells. Our conceptual framework posits that surface water curtailments and heat will induce agricultural users to respond on the intensive and extensive margins, extracting more water from existing wells and building new and deeper groundwater wells. These responses will impact access to drinking water supplies through the channels of water quality and water scarcity. We empirically test these hypotheses by first estimating the effects of extreme heat and surface water curtailments on the response of agricultural producers through the drilling of new groundwater wells. We capture the gross effect on agricultural groundwater demand by evaluating how the depth to the water table changes in response to heat and surface water curtailments. Lastly, we evaluate the reduced-form relationship of heat and surface water scarcity on domestic well failures, assuming this operates through the channel of groundwater table depletion.

To empirically measure these impacts, we constructed a district-level panel spanning 30 years on drinking and groundwater access in California. We combined the universe of groundwater wells constructed, data on domestic well failures, groundwater depth data from groundwater monitoring stations, gridded weather data, and annual data on district-level surface water supplies. Information on groundwater well construction and well failures include the location and date of construction, well depth, and well type for over a million wells. Schlenker and Roberts (2009) provide measures of temperature and precipitation derived from PRISM monthly data and daily weather station observations, and data from Hagerty (2020) measures the universe of surface water allocation in California by area and

1993; Roseta-Palma, 2002; Brozović, Sunding, and Zilberman, 2010; Pfeiffer and Lin, 2012; Edwards, 2016; Merrill and Guilfoos, 2017) year from 1993 to 2020. These detailed data allow us to deploy a instrumental variables panel data approach that exploits annual fluctuations in temperature and surface water shocks, and control for a number of factors, such as fixed differences, and annual shocks, such as recessions, that likely impact water access and agricultural producer's decision making in these local areas.

A first central result indicates that farmers are responding to heat and surface water scarcity through the construction of groundwater wells. We estimate that for each acre foot (AF) of reduced surface water allocations for agriculture, the annual rate of agricultural well construction increases by 46%. Using an approximated cost of $75,000 to construct an agricultural well (CVFPB, 2020), this translates to a back-of-the-envelope $37 million dollars invested annually in extensive-margin adaptation behavior by California farmers. This number also provides a lower bound estimate on the avoided damages of well construction to California agriculture.

Our finding that extreme heat will increase groundwater extraction brings a new data point to our understanding of how climate change will influence water resources. While climate projections indicate increased year-to-year variation in rainfall, projections on the amount of precipitation are less clear (Jessoe, Mérel, and Ortiz-Bobea, 2018). Our results highlight that even if water supplies remain unchanged, warmer temperatures will increase demand for groundwater, with an additional harmful degree day increasing well construction by 1.2%. They also offer empirical evidence of (historical) agricultural adaptation to heat, with groundwater extraction serving as a critical buffer to mitigate the costs of extreme heat in California (Burke and Emerick, 2016; Hornbeck and Keskin, 2014; Barreca et al., 2016; Auffhammer and Schlenker, 2014).

A second set of results indicates that extreme heat and reductions in agricultural surface water supplies lower the depth to the groundwater table. A 1-AF of reduced agricultural surface water allocation to every California cropland acre, lowers local groundwater levels by an additional 4 feet. An additional harmful degree day reduces groundwater levels by 0.5 inches. Declining water tables suggest that the costs of climate change may be larger in the long-run if farmers cannot avail themselves on groundwater resources (Hornbeck and Keskin, 2014; Auffhammer, 2018).

Extreme heat and surface water scarcity also lead to domestic well failures, with a 1 AF decrease in surface water supplies and an extra HDD increasing failures by 5 and 0.2 percentage points, respectively. These results are consistent with a theoretical framework and computational hydrology model in which increased groundwater consumption among agricultural users comes at the cost of drinking water supplies through the channel of a declining water table (Pauloo et al., 2020). More broadly, our work adds a new dimension to our understanding about inequities in exposure to environmental costs (Banzhaf, Ma, and Timmins, 2019). A recent literature documents the unequal rate at which disadvantaged communities are exposed to pollution and the relative health costs, as well as the distributional implications of environmental regulations intended to reduce exposure (Currie, 2011; Hernandez-Cortes and Meng, 2020; Bento, Freedman, and Lang, 2015). Our work implies inequities that arise from the absence of regulation, specifically that mitigating behaviors by those with access to capital will impose costs on disadvantaged groups. When implementing proactive policy aimed at easing the burden of climate change, policymakers must ensure they are not unintentionally burdening the most vulnerable individuals.

This finding is also informative for the design on drinking water regulations in the United States. Drinking water quality issues impose severe costs in less advantaged communities, and are a growing concern in rural communities in the Southwest (Allaire, Wu, and Lall, 2018; Christensen, Keiser, and Lade, 2021; Marcus, 2021). And drinking water is becoming increasingly expensive, making affordability a growing concern (Cardoso and Wichman, 2022). We find that access to drinking water supplies as measured by domestic well failures and depth to the water table will be exacerbated under climate change, and disproportionately affect disadvantaged communities.

2 Agriculture and Rural Communities in California

California agriculture plays a significant role in the global food value chain. The agricultural industry in California employs over 400,000 people and generates over $50 billion in agricultural sales, the most of any state in the US. California also contributes the entire US supply of some fruits and nuts, like almonds and grapes (CDFA, 2020).

California, and other agricultural land west of the 98th meridian, receives insufficient precipitation for efficient agricultural production. Irrigation availability and technology has played a significant role in the development of the agricultural economy in these states (Hornbeck and Keskin, 2014; Edwards and Smith, 2018). Whereas, agriculture east of the 98th meridian primarily rely on periodic rainfall for crop production. Irrigation in California occurs via surface water and groundwater, with the former accounting for roughly 40% of water supplies (Hrozencik and Aillery, 2022).

Agricultural production in California is heavily concentrated in the San Joaquin Valley (SJV) in central California. The counties that comprise the SJV are largely rural and experience some of the highest poverty rates in the country. Many households in rural areas utilize private domestic wells and depend on groundwater wells for residential use and drinking water supply. The geographic intersection of agricultural groundwater use and groundwater dependant households makes these areas particularly vulnerable to climate change damages.

2.1 Surface Water Irrigation

Summertime surface water availability in California is largely determined by the previous winter's snowfall. As the Sierra Nevada snowpack melts, it is captured in reservoirs and later delivered through a network of canals. Swings between dry and wet winters in California translate to significant variation in surface water supplies from year to year.

Surface water is allocated through a complex first-in-time, first-in-right scheme that

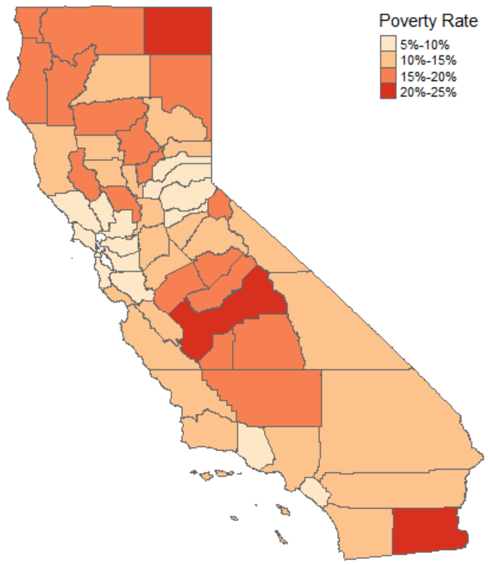


Figure 1: Poverty Rate of California Counties

Note: The figure graphs the percent of the population in poverty by California county. Data come from USDA Economic Research Service.

has persisted since the early 1900s. Most commonly, irrigation districts hold these water rights contracts which translate to an allocation of water in a given year based on predicted supply. Each year, the California Department of Water Resources announces an allocation percentage telling rights holders how much of their contracted water they will receive. It is not uncommon for allocation percentages to be set to 0-10% in drought years. Thus, the impacts of drought manifest through changes in surface water.

Year-to-year fluctuation in surface water allocation are determined by government agencies with algorithms conditional on weather, reservoir levels, and environmental conditions. Allocation is announced prior to the growing season, before producers make input decisions. Actual surface water delivery can differ from allocation in a few ways. Irrigation districts can purchase additional water mid-season on the spot market, pull water from groundwater banks, or reserve water for up to a year in response to environmental conditions. Hence, actual surface water deliveries are potentially endogenous to drought. To control for potential endogeneity in surface water supplies, we instrument deliveries with allocation, similar to Hagerty (2020). We discuss this in further detail in the empirical framework.

2.2 Groundwater Irrigation

Groundwater has traditionally acted as a buffer to fluctuations in surface water supply. Groundwater accounts for 80 percent of water supplies during times of drought. Changes in surface water deliveries are thus correlated with groundwater pumping which affects the water table.

Historically, this sector has been largely unregulated. Owners of land have the right to drill wells and pump groundwater with few restrictions. The open-access nature of groundwater has led to declining groundwater levels, higher costs to pump, and other negative consequences. As a result, a historic groundwater regulation was passed in 2014 – the Sustainable Groundwater Management Act (SGMA) – with the aim to sustainably use and manage groundwater in California by 2042.[3]

The cost of groundwater well construction varies widely based on the completed drilled depth and intended use. Residential domestic wells are typically between 100 and 300 ft deep and cost approximately $10,000. Agricultural wells are drilled between 300 and 500 ft deep on average and cost between $50,000 and $100,000. They are drilled with a wider diameter than residential wells to allow for higher flow rates. New wells are required to be reported to the DWR and are typically constructed by a well professionals in under a week (CVFPB, 2020).

2.3 Drinking Water in Rural Communities

Most individuals in California receive residential and drinking water from community water systems regulated by the Safe Drinking Water Act (SDWA)[4]. However, many individuals

[3]Most SGMA sustainability plans were developed and will be enforced by local groundwater sustainability agencies (GSA) starting in 2022, after our sample of study. There remains no direct restrictions on the drilling of groundwater wells in these plans.

[4]Community water systems are public water systems with over 15 connections and serve greater than 25 people.

outside of community water system boundaries, like households in rural areas, rely on groundwater wells for their domestic water supply. Deteriorating drinking water quality is pervasive for many of these users, especially since these water sources are outside the jurisdiction of the SDWA. Declining groundwater tables also threaten safe and affordable access to residential water for this subset of the population.

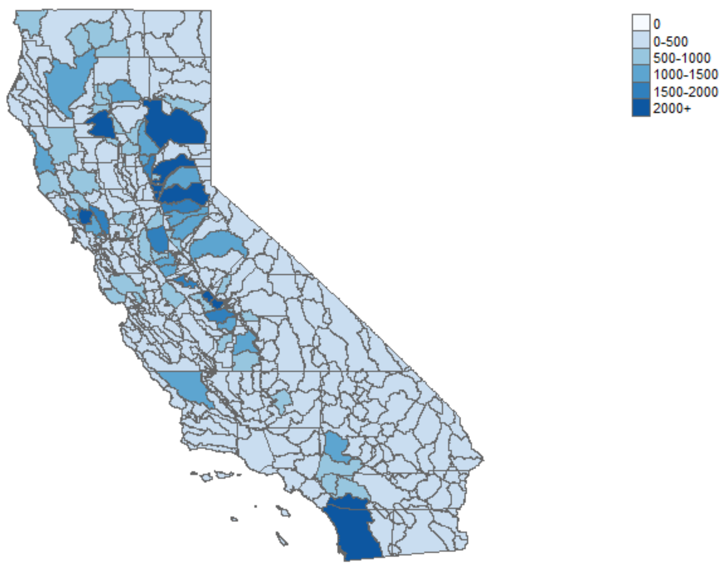


Figure 2: Total Domestic Wells Constructed from 1993-2020

Note: The figure shows a count of the number of domestic groundwater wells constructed from 1993 to 2020 by Detailed Analysis Unit by County, the smallest water management planning unit defined by the California Department of Water Resources (DWR). Data are from DWR.

These counties experience some of the highest poverty rates in the country and a large percent Latino/a populations (Huang and London, 2012). Many of these individuals are also employed by the prosperous local agriculture industry (Martin and Taylor, 1998). This "poverty amidst prosperity" relationship is further perpetuated through increasing environmental vulnerability as a result of climate change in these communities.

3 Data

Panel data on surface water deliveries and allocations, groundwater levels and well construction and failures form the primary dataset for this analysis. We supplement these data with additional information on local weather.

Unit of Observation

Due to the nature of several of our variables, it is necessary to define a geographic unit of aggregation for several variables. When necessary to aggregate to the Detailed Analysis Unit by County (DAU by Co or DAUCO) boundaries for aggregation. DAUs divide California's hydrologic regions and planning areas into smaller geographic areas for agricultural land use and water balance analysis by California's Department of Water Resources (DWR). Historically, DAUs followed the United States Geological Service's watershed boundaries (HUC-8). As additional water infrastructure was added to California, DAUs were updated to account for water district boundaries so that water accounting could be completed more accurately. At present, DAUs are a combination of watershed and water district boundaries. DAUs often overlap counties. In these cases, we further disaggregate the unit into DAU by County – the smallest geographic unit of aggregation used by DWR. We use these boundaries to define the count of new agricultural wells annually and the agricultural surface water delivered. We weight each of our regressions by the number of crop acres in a DAUCO to reflect the differing agricultural intensities between DAUCOs.

Well Construction

Our first outcome measures the extensive-margin adaptation to surface water scarcity and extreme heat through the metric of new agricultural well construction. We use the universe of Well Completion Reports from Department of Water Resources (DWR), which reports each well's location, the depth of the well, intended use, and other characteristics. To measure adaptive response, we count the total number of new agricultural irrigation wells per DAUCO

	Unit	Count	Mean	s.d.	Min	Max
Outcomes:						
New Ag Wells	DAUCO	10416	11.116	19.428	0	316
Depth to Groundwater (ft)	Monitoring Well	575410	62.882	80.419	0	2714.08
ΔDTW	Monitoring Well	575399	0.299	6.068	-58.7	56.3
Probability of Domestic Well Failures	Domestic Well	473940	0.025	0.157	0	1
Independent Variables:						
Ag SW Allocation per crop acre (AF)	DAUCO	9660	2.333	2.043	0	10
Ag SW Deliveries per crop acre (AF)	DAUCO	10416	2.233	1.914	0	10
Harmful Degree Days	DAUCO	9996	97.235	86.881	0	622.3141
Growing Degree Days	DAUCO	9996	3535.366	659.927	632.4846	5813.042
Annual Precipitation	DAUCO	9996	350.267	233.430	11.40778	4668.895
Crop Acres	DAUCO	10416	169741.485	131332.890	.2222608	502692.3

Mean and s.d. statistics are weighted by crop acres.

Table 1: Summary Statistics

per year.

Figure 3 maps new agricultural well construction for the same years as figure 4. The Central Valley of California experiences the most severe shocks to agricultural surface water curtailment, and these areas appear to respond the most in scarce water years by constructing new agricultural wells.

Groundwater Elevation

We use groundwater monitoring wells from groundwater basins across the state to measure groundwater elevation (depth to water table (DTW)). We compile these measures from two sources: 1) The State Water Resources Control Board (SWRCB) Groundwater Information System and 2) DWR's Periodic Groundwater Level data. We append these two datasets and select a single annual measurement for each monitoring well prior to the start of next year's growing season. For example, we assign the groundwater depth of 2015 as the observed groundwater depth nearest to March 15, 2016. This ensures that we realize the cumulative effects of groundwater pumping throughout the current year and prior to the water intensive months of next year. [5] We take the first difference of groundwater elevation as our final outcome variable to estimate the year-to-year changes in the groundwater table as a result

[5] March is also conceivably the point in the year where groundwater levels are most stable in California on a year-to-year basis.

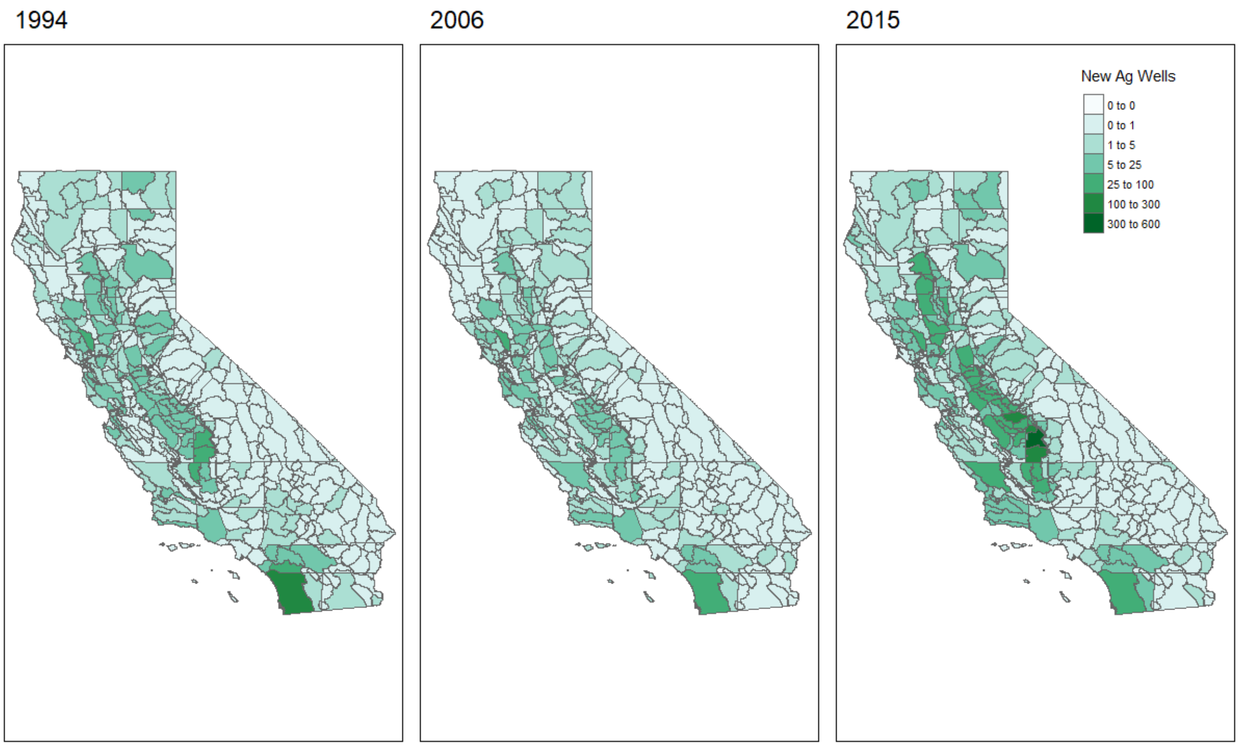


Figure 3: New Agricultural Well Construction

Note: The figure plots the count of new agricultural wells constructed at the DAUCO level for three snapshots in time: 1994, 2006, and 2015. New agricultural well drilling is predominant in the San Joaquin Valley.

of surface water scarcity.

To remove outlier observations of groundwater elevation, we exclude observations that are more than 1.5 times the inner decile range of all other changes in groundwater levels reported from monitoring wells in the DAUCO over our sample. This rule removes observations that observe drastically different changes in groundwater levels than other local groundwater measures.[6]

We study the outcome of changes in groundwater elevations at the monitoring well level, where all monitoring wells in a DAUCO are assigned the same volume of surface water allocation and delivery in a given year. Therefore, we cluster our standard errors at the DAUCO level.

Well Failures

Beginning in 2014, DWR created a system to households to report domestic well failures. These data are now publicly available and regularly updated. These data contain the coordinates for the reported dry well, the date the issue started, and if the issue was resolved. We create a panel of all domestic wells in California from the Well Completion Reports. We geographically match the reported failures to the domestic wells from the Well Completion Reports. The final dataset for the analysis on well failures spans from 2014-2021, where *failure=1* for a domestic well in a given year if it is reported in the well failure database. For all other years, we assume *failure=0*. Hence, our primary analysis of the externality created from agricultural adaptation is the linear probability of domestic well failure as a function of surface water and extreme heat. However, this under counts the true number of domestic well failures since reporting of well failures is voluntary by the household.

[6]Some of these outlier observations are the result of a misplaced decimal, while other errors could occur from monitor errors. We cannot easily identify the source of measurement error in these data in order to assign accurate values, and therefore, remove these observations to reduce measurement error in our point estimates.

Surface Water Allocations and Deliveries

We use spatial and temporal variation in agricultural surface water allocations and deliveries throughout California from Hagerty (2020) as the primary measures of water scarcity. These annual data measure the volume of water allocations and the volume that is actually delivered from the Central Valley Project (CVP), State Water Project (SWP), the Lower Colorado Project, and water rights from 1993-2020[7]. We spatially aggregate these volumes to the DAUCO level. Because the place of use may differ from the point of delivery, this variable is subject to a greater degree of measurement error as the geographic unit of analysis becomes smaller. We transform total water allocations and deliveries by dividing by cropland acres in each DAUCO. Our final measure of surface water supplies captures the volume of surface water delivered in acre feet (AF) per cropland acre in the DAUCO. Because there are a number of inflated values, likely due to measurement error, we Winsorize this variable at 10 AF per acre.

Figure 4 displays the variation across DAUCO areas within a given year and the locations most impacted by curtailments in drought years, 1994 and 2015.

To account for potential endogeneity in surface water supplies, we follow Hagerty (2020) and use allocations as an instrument for deliveries. Results from the first-stage are presented in table 2 and show that allocations are a strong instrument for deliveries. We present both the reduced-form (outcome regressed on allocations) and the instrumental variable (either two-stage least squares or control function) results for each set of results. Deliveries are the better measure of actual surface water supply and scarcity; therefore, the primary regressor of interest for water scarcity is agricultural deliveries.

[7] All months of 2021 were not yet reported at the time these analyses were performed. The partial-year data for 2021 is included in the dataset, but we exclude 2021 in the estimation. Including partial 2021 data does not change point estimates, but standard errors do increase because of this discrepancy.

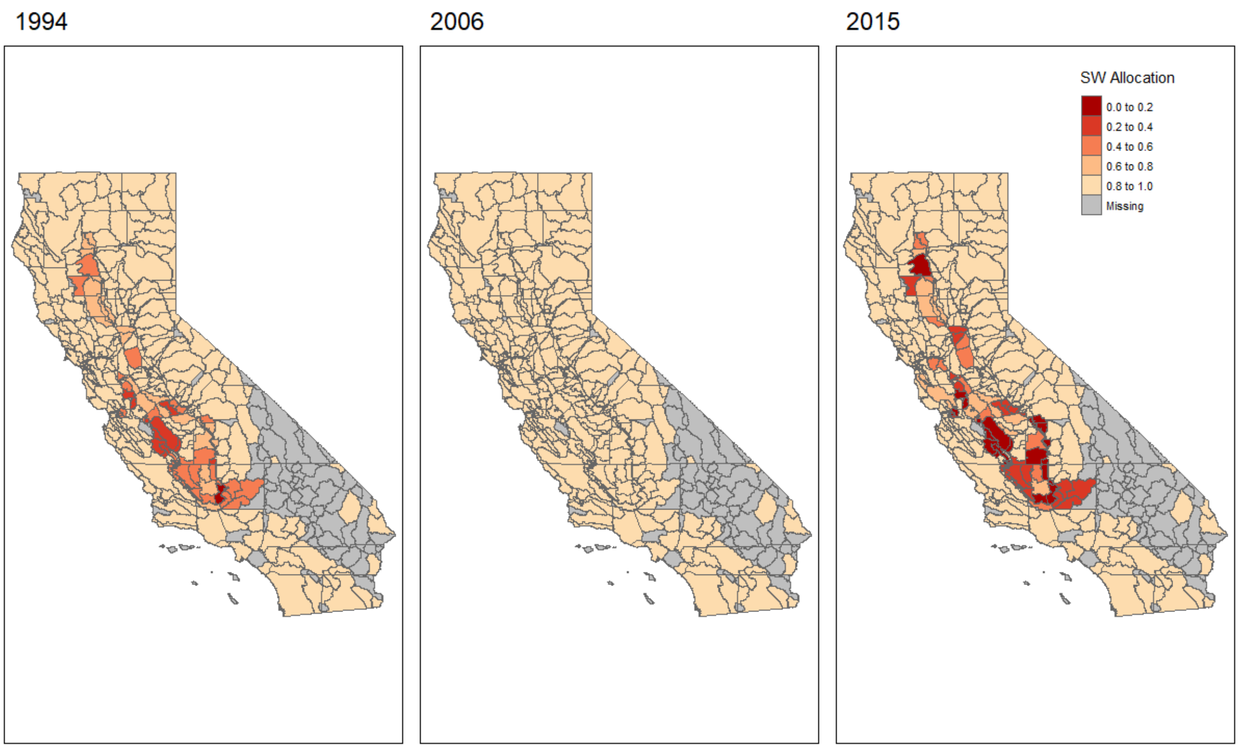


Figure 4: Agricultural Surface Water Allocation Percentages

Note: The figure graphs the fraction of agricultural water entitlements to be received by irrigation districts at the DAUCO level for three years: 1994, 2006, and 2015. Allocation percentages, which are announced by the state prior to the growing season based on environmental conditions, vary over space and time.

	(1)	(2)
Ag SW Allocation per crop acre (AF)	0.588***	0.531***
	(0.0460)	(0.0540)
Harmful Degree Days		-0.000353
		(0.00172)
Growing Degree Days		0.000184***
		(0.0000432)
Annual Precipitation		-0.000461*
		(0.000202)
Observations	9660	9240
N Cluster	345	330
F Stat	163.6	79.07
Weights	Crop Acres	Crop Acres
Cluster	DAUCO	DAUCO
Time FE	X	X
Unit FE	X	X

Note: Dependant variable is Ag SW deliveries per crop acre in levels from 1993-2020. All regressions are weighted by the DAUCO crop acres and include year and DAUCO fixed effects. Standard errors are clustered at the DAUCO level and are reported in parentheses.

* $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$

Table 2: Agricultural SW Deliveries: First Stage Results

Weather

We measure extreme heat and precipitation using weather observations from Schlenker and Roberts (2009) and PRISM climate data. We measure extreme heat through "harmful degree day"(degree days over 32 degrees Celsius) and "growing degree days" (degree days over 8 and below 32 degrees Celsius). We also control for local annual precipitation reported in millimeters. Schlenker and Roberts (2009) data, which are derived from PRISM weather station observations, ends in 2019. Therefore, we supplement weather observations from the raw PRISM data for 2020 and 2021.

4 Empirical Model

California presents a rich context to study climate change adaptation strategies and the subsequent externalities from adaptation. Our empirical framework uses annual fluctuations in weather, surface water supplies, agricultural well construction, groundwater elevation, and domestic well failures from 1993-2020 to measure three reduced-form effects. First, we attempt to estimate the casual relationship between extreme heat and surface water scarcity on new agricultural well construction by farmers. These estimates capture direct evidence of adaptation behavior by California farmers to the impacts of climate change. Second, we measure the year-to-year changes in groundwater elevation as a result of heat and reduced water supplies. These estimates show that farmers pump more groundwater in response to both heat and less surface water. These results also capture the externality imposed on other users (and future users) of groundwater. Lastly, we estimate the reduced form effect of surface water scarcity and heat on domestic well-failure. All together, these estimates uncover a chain of climate change-induced impacts displayed in Figure 5 that measure the extent of adaptation in California agriculture and the maladaptation externalities.

Outcome 1: Agricultural Well Construction

To estimate the effects of drought and surface water curtailment on agricultural well construction, we estimate two different specifications. First, using OLS and two-way fixed effect, we estimate equation 1. Our panel is constructed at the Detailed Analysis Unit by County (DAUCO) and annual level. The variable Y_{it} measures the count of new agricultural wells where i signifies the DAUCO and t denotes the year between 1993 and 2020. The independent variable, SWD_{it}, are surface water deliveries and $SDWA_{it}$ allocations in AF per acre. HDD_{it} reports the number of harmful degree days in DAUCO i in year t. The vector $\boldsymbol{X}_{it}$ controls for other localized weather shocks. Annual fixed effects, λ_t, control for statewide dynamic shocks, like statewide policy or state-level drought. DAUCO fixed effects control for time-invariant factors, like area size and location. All regressions are weighted by crop

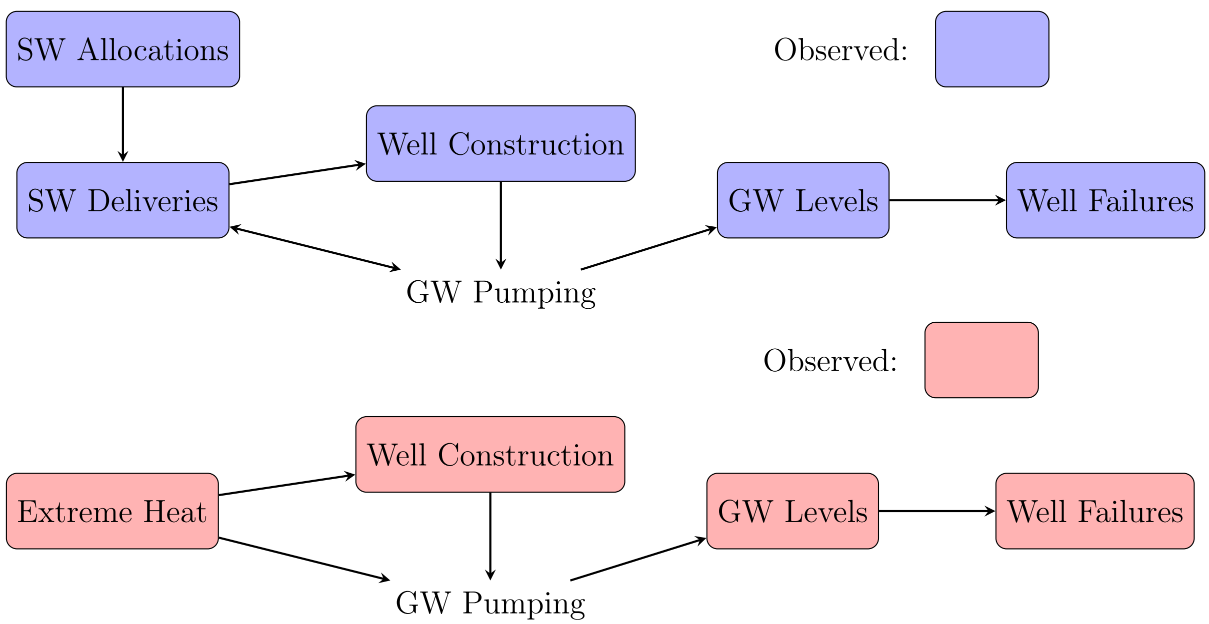


Figure 5: Causal Empirical Chain

Note: The figure charts a conceptual framework for the empirical relationships from water scarcity to domestic well failures on the top panel and extreme heat to domestic well failures on the bottom panel. Groundwater pumping is unobserved.

acres, which identifies the weighted average treatment effect across California crop acres.

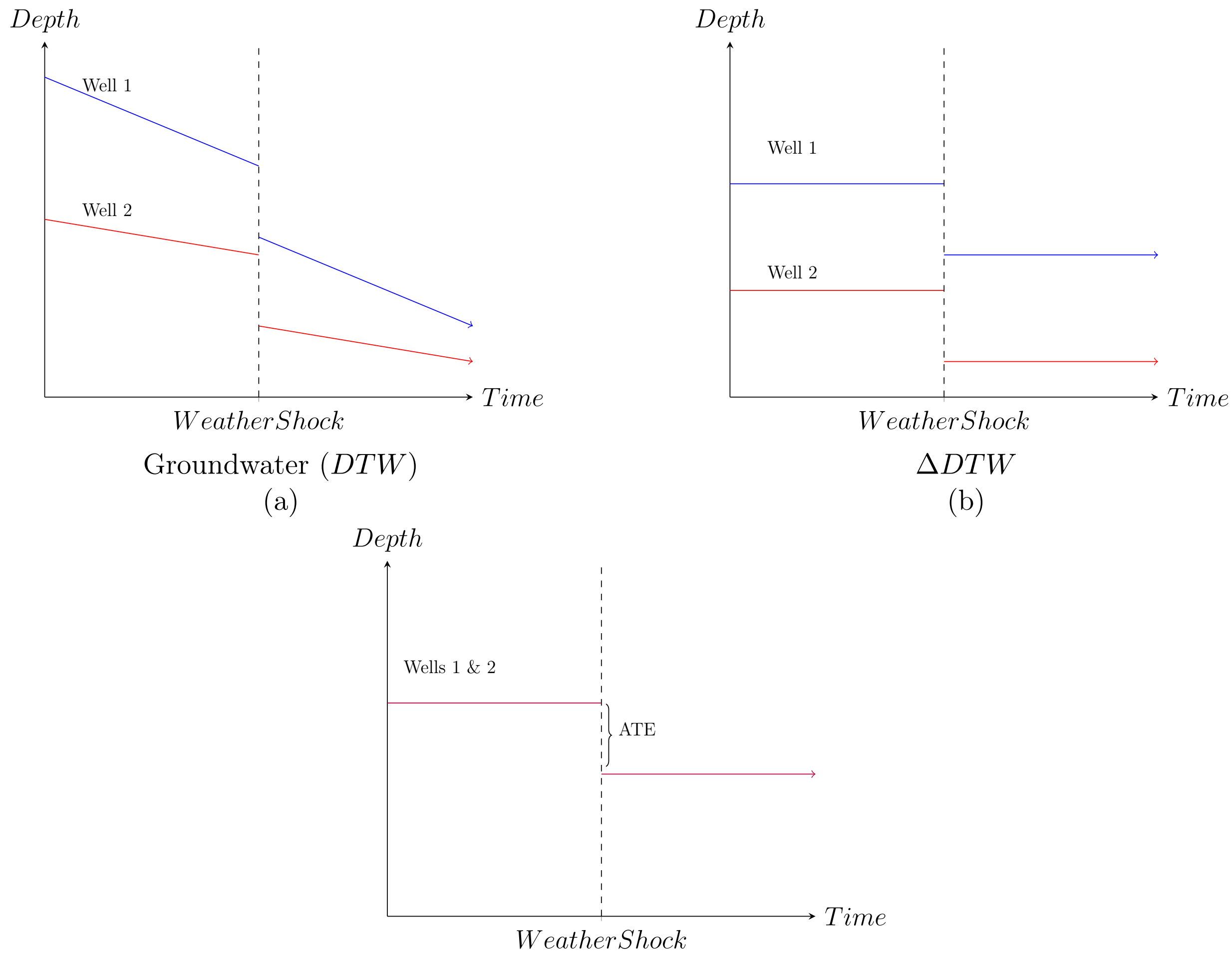
$$\begin{aligned} Y_{it} &= \beta_1 S\hat{W}D_{it} + \beta_2 HDD_{it} + \boldsymbol{B}'\boldsymbol{X}_{it} + \lambda_t + \alpha_i + \varepsilon_{it} \\ SWD_{it} &= \gamma_1 SDA_{it} + +\gamma_2 HDD_{it} + \boldsymbol{\Gamma}'\boldsymbol{X}_{it} + \alpha_i + \lambda_t + \mu_{it} \end{aligned} \tag{1}$$

Second, Y_{it} reports the non-negative count of new agricultural wells and suffers from overdispersion; therefore, we estimate a Psuedo-Poisson Maximum Likelihood via a control function approach with fixed effects as our preferred specification (Wooldridge, 2015). We estimate the Poisson model with equation 2. This method also allows us to test for endogeneity of the regressor by including $\hat{\mu_{it}}$ in the second-stage. The coefficient on $S\hat{W}D_{it}$ indicates that for every one AF decrease in surface water deliveries, the number of new agricultural wells will change by $e^{\beta_1} - 1$ percent. Similarly, for every additional harmful degree day, $e^{\beta_1} - 1$ percent more agricultural wells will be constructed.

$$\begin{aligned} E[Y_{it}|SWD_{it}, \mathbf{X}_{it}, \alpha_i, \lambda_t] &= \exp\{\beta_1 S\hat{W}D_{it} + \phi\hat{\mu_{it}} + \mathbf{B'X}_{it} + \alpha_i + \lambda_t\} \\ SWD_{it} &= \gamma_1 SDA_{it} + +\gamma_2 HDD_{it} + \boldsymbol{\Gamma}'\boldsymbol{X}_{it} + \alpha_i + \lambda_t + \mu_{it} \end{aligned} \tag{2}$$

Outcome 2: Changes in Groundwater Elevation

Annual groundwater elevation, or depth to the water table (DTW), observations measure the stock of groundwater availability, which represent the cumulative outcome of annual groundwater pumping and recharge. We take the first-difference of groundwater elevation levels so that our outcome measures the annual flow to the underlying stock. Fixed effects absorb well-level differential trends over time, allowing for each well to have different linear temporal trends all else equal. Again, we estimate equation 3 in two stages, using surface water allocations as an instrument for surface water deliveries. The coefficients β_1 and β_2 in this equation measure the annual marginal change in groundwater elevation for a unit change in surface water and harmful degrees days, respectively.



Groundwater (DTW)
(a)

ΔDTW
(b)

ΔDTW + FE
(c)

Figure 6: Difference-in-Differential Trends Framework
Note:

$$
\begin{aligned}
\Delta DTW_{it} &= \beta_1 S\hat{W}D_{it} + \beta_2 HDD_{it} + \boldsymbol{B}'\boldsymbol{X}_{it} + \lambda_t + \alpha_i + \varepsilon_{it} \\
SWD_{it} &= \gamma_1 SDA_{it} + +\gamma_2 HDD_{it} + \boldsymbol{\Gamma}'\boldsymbol{X}_{it} + \alpha_i + \lambda_t + \mu_{it}
\end{aligned}
\tag{3}
$$

Outcome 3: Domestic Well Failures

Lastly, our estimation of domestic well failures similarly to equation 1, where Y_{it} is binary outcome indicating a reported well failure. The coefficient estimates from this equation represent the the change in likelihood that a domestic well fails in a given year when surface water availability and extreme heat changes.

5 Results

The reduced form results from equation 1 are presented in table 3. The full PPML model in column 4 implies that a one AF decline per crop acre in California, all else equal, leads to approximately 24.2% increase in the annual number of new agricultural wells drilled. While every additional harmful degree day causes an approximate .9% annual increase in new agricultural wells. Additionally, Table 9 column 3 in the appendix shows that new agricultural wells are drilled about 53 feet deeper for a one acre foot reduction in surface water allocation.

	OLS		PPML	
	(1)	(2)	(3)	(4)
Ag SW Allocation per crop acre (AF)	-7.180**	-6.581*	-0.333*	-0.278*
	(2.665)	(2.596)	(0.131)	(0.124)
Harmful Degree Days		0.115**		0.00897***
		(0.0390)		(0.00202)
Growing Degree Days		-0.00283		-0.000354
		(0.00575)		(0.000469)
Annual Precipitation		0.00409		0.000411*
		(0.00438)		(0.000209)
Observations	9660	9240	8568	8400
N Cluster	345	330	306	300
Weights	Crop Acres	Crop Acres	Crop Acres	Crop Acres
Cluster	DAUCO	DAUCO	DAUCO	DAUCO
Time FE	X	X	X	X
Unit FE	X	X	X	X

Note: Dependant variable is the count of new agricultural wells per DAUCO from 1993-2020. Columns (1) and (2) report the coefficients for the OLS model. Columns (3) and (4) report coefficients from a psuedo-poisson maximum likelihood model. All regressions are weighted by the DAUCO crop acres and include year and DAUCO fixed effects. Standard errors are clustered at the DAUCO level and are reported in parentheses.

* $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$

Table 3: Construction of New Agricultural Wells: Reduced-Form

While table 3 displays the adaptive response to an exogenous surface water allocation shock, surface water allocations may not represent actual scarcity. Producers and irrigation district may choose to receive more or less surface water throughout the year. This endogenous choice may bias the estimates in table 3 towards zero of the true estimate of extensive-adaption to surface water scarcity.

Table 4 reports the estimates of new agricultural well construction on surface water deliveries, where surface water deliveries are instrumented by allocation and local precipitation. Columns 3 and 4 are estimated using a control function approach with a linear first stage and PPML in the second stage. As expected, the estimate on surface water deliveries is larger than allocations and imply that the extensive-adaptation response is approximately 46.2% increase in new agricultural wells.

We also see that this adaptive response is primarily isolated to the agricultural sector. Table 8 shows the corresponding results for new domestic well construction. While the point estimates are in the expected direction for water scarcity, they are smaller in magnitude and not statistically significant. This is indicative that farmers have the capital to invest in climate adaptation strategies, but individual households in those areas do not respond in the same manner, or alternatively, it may be too costly for individual households to respond.

Second, to measure the deterioration of groundwater resources as a result of agricultural surface water scarcity and extreme heat, we estimate estimate both the reduced form and IV versions of 3. The results in table 5 imply that a one AF reduction in SW deliveries leads to 3.75 ft decline in the groundwater levels. Groundwater depth is also responsive to extreme heat. For every additional harmful degree day, groundwater levels decline by 0.04 ft.

The degradation of a common pool resource, like groundwater, creates externalities for other users of that resource. In this context, the externalities from the intensive adaptation of groundwater pumping are borne by all other users of the local groundwater. This externality disproportionately puts household users of groundwater at risk since domestic wells are drilled shallower on average and are more susceptible to well failure.

Pauloo et al. (2020) estimates that for a 10 ft decline in groundwater, cumulatively,

	2SLS		CF/PPML	
	(1)	(2)	(3)	(4)
Ag SW Deliveries per crop acre (AF)	-13.06**	-12.38**	-0.690**	-0.620*
	(4.584)	(4.750)	(0.262)	(0.262)
Harmful Degree Days		0.111***		0.0128***
		(0.0329)		(0.00261)
Growing Degree Days		-0.000551		-0.000493
		(0.00593)		(0.000488)
Annual Precipitation		-0.00162		0.0000120
		(0.00743)		(0.000376)
$\hat{\mu}$			0.732*	0.767*
			(0.346)	(0.347)
Observations	9660	9240	8568	8400
N Groups	345	330	306	300
Weights	Crop Acres	Crop Acres	Crop Acres	Crop Acres
Cluster	DAUCO	DAUCO	DAUCO	DAUCO
Time FE	X	X	X	X
Unit FE	X	X	X	X

Note: Dependant variable is the count of new agricultural wells per DAUCO from 1993-2020. All regressions are weighted by the DAUCO crop acres and include year and DAUCO fixed effects. Standard errors are clustered at the DAUCO level and are reported in parentheses. Columns (3) and (4) standard errors are calculated using 500 bootstrap simulations, clustered at the DAUCO level.

* $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$

Table 4: Construction of New Agricultural Wells: 2SLS and Control Function

6.7% - 10.5% of wells will fail in California. Pairing these predictions with our estimates, this implies that a 1 AF reduction in surface water will cause between a cumulative 4.8% and 7.7% of wells in California to fail or approximately $80 million in damages from agricultural surface water scarcity and farmer's adaptive behavior.

Lastly, we estimate a panel linear probability model, where *failure* is a $\{0, 1\}$ outcome variable in a given year for all domestic wells in California. Table 6 displays the estimates of this regression. Columns 2 and 4 show the results from using the years 2014-2020. The remaining columns use 2015-2020. The voluntary household system was introduced early in 2014 and may have not been a widely known reporting tool for households across the state.

	Reduced Form		IV	
	(1)	(2)	(3)	(4)
Ag SW Allocation per crop acre (AF)	-2.263**	-1.627*		
	(0.808)	(0.750)		
Ag SW Deliveries per crop acre (AF)			-4.955**	-3.754*
			(1.610)	(1.619)
Harmful Degree Days		0.0482*		0.0373*
		(0.0219)		(0.0169)
Growing Degree Days		0.00330		0.00399
		(0.00291)		(0.00256)
Annual Precipitation (mm)		0.00779*		0.00657*
		(0.00339)		(0.00334)
Observations	575397	575243	561083	560929
N Groups	98096	98076	83782	83762
Weights	Crop Acres	Crop Acres	Crop Acres	Crop Acres
Cluster	DAUCO	DAUCO	DAUCO	DAUCO
Time FE	X	X	X	X
Unit FE	X	X	X	X

Note: Dependant variable is the change in the depth to the groundwater from the surface (ft) from 1994-2020 at the monitoring well level. Columns (1) and (2) report results from the reduced-form OLS model. Columns (3) and (4) report the second-stage IV results, where Ag surface water allocations are used as an instrument. All regressions are weighted by the DAUCO crop acres and include year and DAUCO fixed effects. Standard errors are clustered at the DAUCO level and are reported in parentheses.

* $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$

Table 5: Changes in Groundwater Elevation

This could explain why the point estimates for surface water are smaller in magnitude and insignificant when including 2014.

Across all specifications, extreme heat significantly increases the likelihood that domestic wells fail. Column 6 implies that an additional Harmful Degree Day increases the probability that a well fails by 0.2%. That specification also displays that for a 1 AF reduction in surface water per crop acre increases the likelihood of local domestic well failure by 5%. These estimates are large marginal effects relative to the weighted mean probability of well failure displayed in Table 1.

	Reduced Form			IV		
	(1)	(2)	(3)	(4)	(5)	(6)
Ag SW Allocation per crop acre (AF)	-0.0154*	-0.00851	-0.0278			
	(0.00706)	(0.00535)	(0.0157)			
Ag SW Deliveries per crop acre (AF)				-0.0293**	-0.0165	-0.0555**
				(0.00992)	(0.00906)	(0.0194)
Harmful Degree Days		0.00172*	0.00211*		0.00168*	0.00207*
		(0.000699)	(0.000952)		(0.000681)	(0.000910)
Growing Degree Days		0.000124	0.0000995		0.000128	0.000108
		(0.0000793)	(0.0000639)		(0.0000812)	(0.0000680)
Precipitation (mm)		-0.0000433	-0.0000918		-0.0000486	-0.000117
		(0.0000318)	(0.0000561)		(0.0000328)	(0.0000662)
Observations	473940	552636	473688	473940	552636	473688
N Groups	78990	78948	78948	78990	78948	78948
Years	2015-20	2014-20	2015-20	2015-20	2014-20	2015-20
Weights	Crop Acres	Crop Acres	Crop Acres	Crop Acres	Crop Acres	Crop Acres
Cluster	DAUCO	DAUCO	DAUCO	DAUCO	DAUCO	DAUCO
Time FE	X	X	X	X	X	X
Unit FE	X	X	X	X	X	X

Note: Dependant variable is a {0,1} outcome if a domestic groundwater reported a failure that year. The panel spans from 2014-2020 and is composed of all domestic groundwater wells with unique coordinates in California. Columns (2) and (5) includes reported failures from the first year the reporting system was active, 2014. All other columns exclude 2014. All regressions are weighted by the DAUCO crop acres and include year and DAUCO fixed effects. Standard errors are clustered at the DAUCO level and are reported in parentheses.

* $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$

Table 6: Linear Probability of Reported Well Failure

6 Discussion

The impacts of climate change are dependent on the extent to which individuals adapt. While climate adaptation by some may limit their own potential damages from extreme heat and precipitation variability, these adaptive measures may unintentionally impose costs on others. In this paper, we show that agricultural producers in California significantly adapt to added heat and reduced surface water through the channel of constructing new agricultural wells. We also show that local groundwater levels are responsive these annual fluctuations in weather. These climate-induced changes deplete local groundwater resources, imposing externalities on other users of groundwater. Negative externalities arise for rural communities through the channel of domestic well failures and subsequent reductions in drinking water access.

These findings contribute to the knowledge of the impact of climate change in three ways. First, we show that producers in California spend approximately $37 million annually for every AF per crop acre reduction of surface water availability. While irrigation may mitigate agricultural yield and revenue damages, climate change still imposes a significant annual cost to irrigated agriculture. Second, adaptation strategies contribute additional burden on those less able to engage in adaptive behavior. These externalities of adaption have traditionally been ignored in calculating the economic costs of climate change but should be taken into account for a more complete accounting of climate change damages. Importantly, these externalities are borne in low-socioeconomic communities, increasing environmental inequality. Results are relevant for policymakers seeking to implement environmental regulation.

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7 Appendix

	Reduced Form			IV		
	(1)	(2)	(3)	(4)	(5)	(6)
	Both	Ag	Domestic	Both	Ag	Domestic
Ag SW Allocation per crop acre (AF)	-22.90	-23.14	-8.170			
	(18.16)	(21.67)	(7.699)			
Ag SW Deliveries per crop acre (AF)				-37.03	-34.48	-14.14
				(29.10)	(32.23)	(14.34)
Harmful Degree Days	1.431*	2.592*	0.346	1.340*	2.449*	0.319
	(0.624)	(1.108)	(0.244)	(0.563)	(1.019)	(0.237)
Growing Degree Days	0.0148	-0.00168	0.0424	0.0258	0.0110	0.0455
	(0.0381)	(0.0789)	(0.0276)	(0.0422)	(0.0836)	(0.0286)
Precipitation (mm)	0.0533**	0.0756	0.0402***	0.0455*	0.0668	0.0379***
	(0.0186)	(0.0465)	(0.0103)	(0.0185)	(0.0454)	(0.0104)
Observations	144917	31042	114034	144890	30955	113863
N Groups	337	310	334	328	295	322
Weights	Crop Acres	Crop Acres	Crop Acres	Crop Acres	Crop Acres	Crop Acres
Cluster	DAUCO	DAUCO	DAUCO	DAUCO	DAUCO	DAUCO
Time FE	X	X	X	X	X	X
DAUCO x Type FE	X	X	X	X	X	X

Note: Dependant variable is the depth (ft) of newly constructed wells from 1993-2020 at the well level. Columns (1) and (4) reports results for both agricultural and domestic wells, (2) and (3) for just agricultural wells, and (3) and (6) for just domestic wells. All regressions are weighted by the DAUCO crop acres and include year and DAUCO by well type fixed effects. Standard errors are clustered at the DAUCO level and are reported in parentheses.

* $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$

Table 7: New Constructed Well Depth

	OLS		PPML	
	(1)	(2)	(3)	(4)
Ag SW Allocation per crop acre (AF)	-1.534	-1.021	-0.0657	-0.0128
	(1.582)	(1.535)	(0.0783)	(0.0641)
Harmful Degree Days		0.0774		0.00950*
		(0.0477)		(0.00445)
Growing Degree Days		-0.00782		
		(0.00473)		
Annual Precipitation		0.00734**		0.000417**
		(0.00280)		(0.000139)
Observations	9660	9240	9072	8876
N Cluster	345	330	324	317
Weights	Crop Acres	Crop Acres	Crop Acres	Crop Acres
Cluster	DAUCO	DAUCO	DAUCO	DAUCO
Time FE	X	X	X	X
Unit FE	X	X	X	X

Note: Dependant variable is the count of new domestic wells per DAUCO from 1993-2020. Columns (1) and (2) report the coefficients for the OLS model. Columns (3) and (4) report coefficients from a psuedo-poisson maximum likelihood model. All regressions are weighted by the DAUCO crop acres and include year and DAUCO fixed effects. Standard errors are clustered at the DAUCO level and are reported in parentheses.

* $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$

Table 8: Construction of New Domestic Wells

	OLS		PPML	
	(1)	(2)	(3)	(4)
M&I SW Allocation per Acre	19.71	23.36	1.407	1.459
	(28.88)	(28.91)	(1.300)	(1.257)
Harmful Degree Days		0.115**		0.0143***
		(0.0422)		(0.00287)
Growing Degree Days		0.000191		0.000472
		(0.00839)		(0.000636)
Annual Precipitation		0.00972		0.000757*
		(0.00618)		(0.000357)
Precipitation (mm) (T-1)		0.00229		-0.0000139
		(0.00408)		(0.000347)
Observations	8874	8400	7540	7224
N Cluster	306	300	260	258
Weights	Crop Acres	Crop Acres	Crop Acres	Crop Acres
Cluster	DAUCO	DAUCO	DAUCO	DAUCO
Time FE	X	X	X	X
Unit FE	X	X	X	X

Standard errors in parentheses

* $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$

Table 9: Construction of New Agricultural Wells: Municipal and Industrial Surface Water