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Analyzing California Climate Change Time Series Data and Its Impact on Crop Production

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ABSTRACT

Climate change has become an increasingly concerning problem in California over the last years, stemming from lack of precipitation and snowfall as well as constantly rising temperatures. Many aspects of Californian life including water availability and crop production have been negatively impacted by this recent trend. Due to the significance of agriculture on California, the farming com- munity within California and its consumers, including both in-state consumers and those who California exports its produce to, are at risk to be harmed by the negative impacts of climate change. Significant changes to the state's temperature, precipitation rate, and water consumption and supply all would have the potential to harm crop production and the agricultural industry. Using the data obtained from various sources for each of these factors, we hope to calculate predicted changes in indemnity losses due to crop production over time. By modeling temperature and precipitation as sinusoidal functions and water consumption as a linear relation to temperature, it becomes possible to predict future indemnity losses based on these factor values using polynomial regression. By passing a moving average filter and eliminating the cyclic nature of the loss function, we were able to deduce that average temperature seemed to increase, average precipitation rate seemed to decrease, and average water consumption also increased. The combination of these factors led to a steady increase in predicted indemnity losses within the next 50 years. As water consumption is the only factor that can be changed through human intervention, it is logical for us to base our recommendations off of it. Agricultural water consumption is the main use of water in the state and a transition into more conservative irrigation methods would allow for a reduction in the net water consumption. Over long periods of time, this would decrease water consumption and therefore indemnity losses based on our models.

Background Information

It is no secret that climate change is becoming an increasingly present factor in our daily lives. Since the beginning of the 20th century, temperatures in California have risen by almost 3 degrees Fahrenheit. In addition to that, the six warmest years on record have all happened since 2014, with new months of record-breaking temperatures constantly occurring [1]. This drastic increase in temperature has had a detrimental effect on California's already severe drought situation, and as a result, the agricultural industry, as farmers struggle to obtain the necessary amounts of water for their crops. Unsurprisingly, most of the California's water comes from precipitation and snowfall, with the latter being from the Sierra Nevada Mountain range in the Eastern portion of the state. This water flows into rivers, reservoirs, and streams, and is commonly referred to as surface water [2]. In the past, surface water has accounted for most of the California's water supply due to its easy availability and relatively high volume. However, as a result of recent decreases in rain and snowfall levels, California has been forced to rely more heavily on groundwater that seeps into tiny spaces between rocks and soil in the ground in order to keep up with the demands of both the civilian population as well as the agricultural necessities of the farmers. These recent conditions have led groundwater to account for around 60 percent of the state's water supply, rather than the usual 40 that is necessary during years of normal precipitation and snowfall [3].

Like many other U.S states, a significant portion of water in California is used for agricultural purposes. Being the top producers in commodities such as almonds, pistachios, and walnuts, California relies heavily on agriculturally based domestic exports in order to fuel its bolstering economy and rising population. In 2019 alone, these exports totaled approximately 21.7 billion dollars, continuing the increasing trend that has developed over past years [4]. If these numbers were to significantly drop as a result of water shortage, it would be severely detrimental to California's residents and economy. With over 400,000 of California's workers being in the agricultural industry as of 2020, increased crop failures could cause widespread unemployment, further damaging the economy [5].

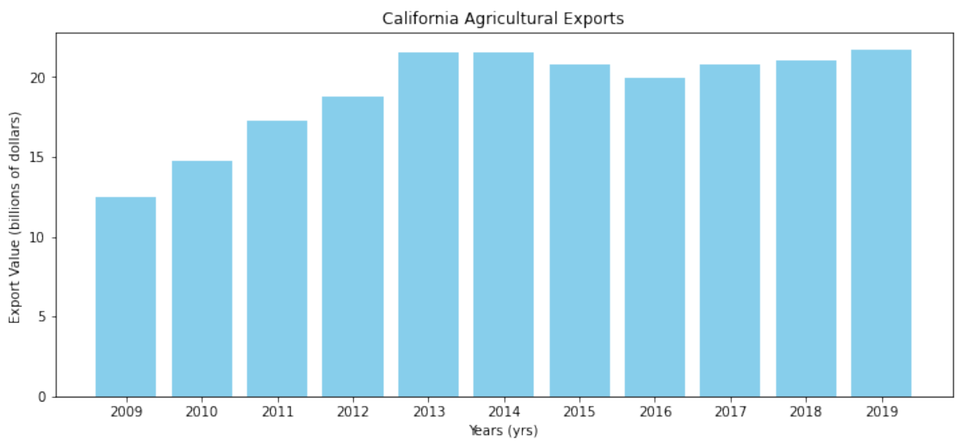

Figure 1. Representing the change in California Agricultural Exports from 2009-2019

Overall, key factors including temperature, precipitation, and water consumption appear to contribute heavily to California's agricultural production and general welfare. However, drastic changes in recent years due to climate change threaten to put the state at risk. Therefore, our aim is to utilize climate change factors such as temperature, precipitation, and water consumption in order to be able to better understand future agricultural losses for California.

Data Methodology

Data Sources

USA Facts Temperature and Precipitation - USA Facts.org has com- piled data sets for both temperature and precipitation. These data sets consist of the average monthly precipitation and temperature for each of the 58 California counties over the past 100 years, which is sufficient to determine historical trends. The purpose of this data will be to predict future values and how said values will affect agricultural loss. The calculated average values are consistent with results from government sources, making the data reliable and trustworthy for us to use [6]. 2. California State Water Resources Control Board Water Consumption Data - Provides average monthly residential gallons per capita daily for each of the 58 counties in California from 2014-2021. This data is collected from a .gov website (CA.gov), meaning that it is owned by an official government organization. Data from .gov sources are both reliable and accurate, making them ideal choices to use in our model [7]. 3. USDA Southwest Climate Hub Indemnity Loss Data - This data provides agricultural indemnity loss data so that we can see the effect that climate change has had on California's agricultural industry. Many individual factors are included, such as drought, frost, and excess moisture, to determine which has the strongest correlation with loss. Data from this source is directly collected from the USDA Risk Management Agency cause of loss files, a government regulated website that has been providing reliable information since 1996. Like our water consumption data that was also gathered from a .gov source, the loss values that we collect are credible and can therefore be used for modeling [8].

Data Pre-Processing

The first step in preparing our temperature and precipitation data was to down- load all of the data sets for each of the 58 counties, as we were interested in the average values for California as a whole, rather than just for an individual county. Then, after removing any undefined values, each of the datasets were iterated through and their corresponding monthly values from that specific county aggregated in order to find average temperature and precipitation values for the entire state every month. The resulting data was then concatenated into an individual data set and sorted by date. The water consumption data was calculated per water supplier and population served. Therefore, before aggregating the total number each month, the amount of water consumed had to first be found via the product of population served and water consumed per capita. The pre-processing for our indemnity loss data was much simpler, as the only issue were empty and non-positive values, since they would not be useful in our model. Overall, most data pre-processing followed a similar algorithm:

Algorithm 1 Data Pre-Processing Algorithm

Remove all n/a values
$n \leftarrow 0$
while $n < DatasetLength$ **do**
    $i \leftarrow CountyDatasetMonth\#$
    $v \leftarrow CountyDatasetValue$ ▷ Temp/Precip/Water Consump Value
    OverallDataset[i] += v
end while

Figure 2. Algorithm used in our model to pre-process the data

Mathematical Modeling

Assumptions

1. Temperature and precipitation are cyclical events and can therefore be modeled using sinusoids.
2. Temperature and precipitation will be considered as independent factors or variables in both our analysis and predictions.
3. Any positive R-squared coefficient is considered to represent a correlation in our regression. Although this may be considered a weak relationship, most of the predicted output indemnity loss data will be calculated as an estimate interval that will cover at least 90 percent of the data.

Temperature Forecasting

Using monthly average temperatures since 1895, we noticed that temperature followed a monthly cycle pattern repeated for about every 12 months. Thus, we propose that temperature can be modeled using a simple sinusoidal curve that can be represented by:

$$T(x) = a\sin(bx + c) + d + ex$$

with x representing the month number, a representing the maximum change in temperature, b representing the frequency, c representing the phase shift, d representing the offset or mean temperature, and e representing a parameter that attempts to linearly introduce non stationarity into the sinusoid. The parameters were first guessed using approximations for phase shift (multiples of π/4) and frequency(2π/12). The approximated offset was calculated by taking the average of the y-values, and the approximated amplitude was calculated by taking the difference between the average of the data peaks and the offset. The peak average was calculated via an iterative peak-finding algorithm:

$$f(x) = \sum_{i=1}^{n} T(t_i)$$

for a total n of peaks $T(t_i)$ that satisfies:
$T(ti-1), T(ti+1) < T(t)$ $T(ti) > M$ (4) where M is a manually inputted lower bound for peaks in order to to reduce noise and disregard higher frequency low peaks.

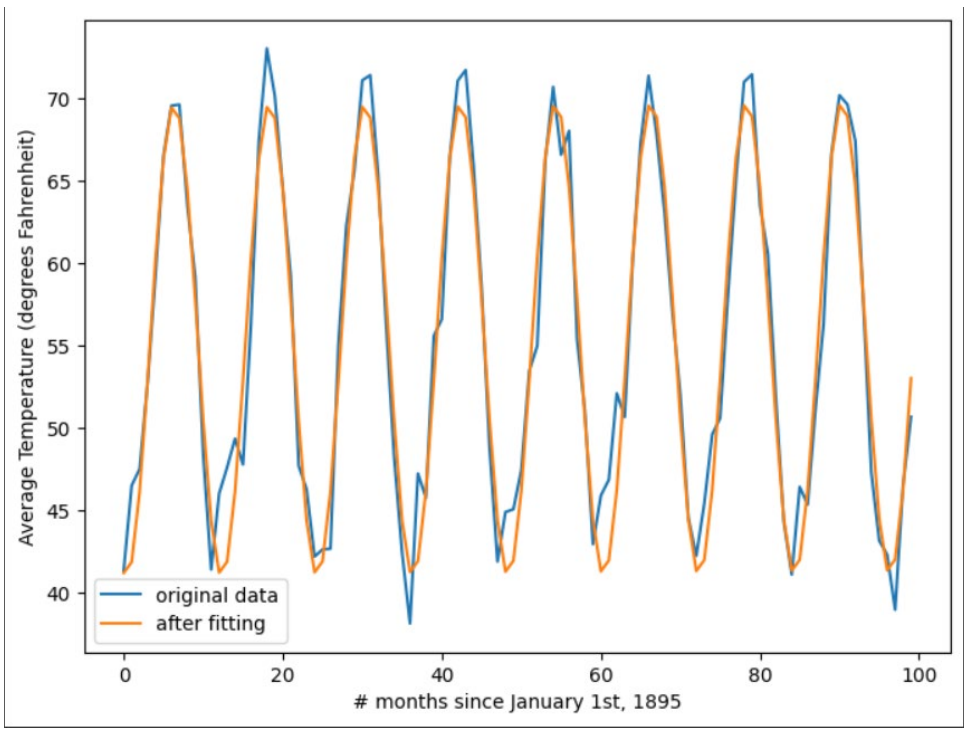

Figure 3: Sinusoidal Temperature Model Over Time1

After using SciPy's non-linear least squares curve fit regression that both used the function template and first guess parameters, the fitted parameters were calculated to be:

$$T(x) = 14.309\sin(0.523x + 4.539) + 55.327 + 0.00167x$$

The mean temperature was calculated to be around 55 degrees Fahrenheit. There was a 14-degree amplitude or variation, and the period was approximately 12 months. The e parameter was positive, indicating an average increase in temperature over time possibly due to climate change.

Precipitation Forecasting

Like temperature, the precipitation data also contained monthly values since 1895. We therefore decided to use another sinusoidal function mentioned in Gazi University Journal of Science that modeled monthly precipitation based on a combination of a sine and cosine function [9]:

$$P(x) = a\sin(bx) + \cos(dx) + e + fx$$

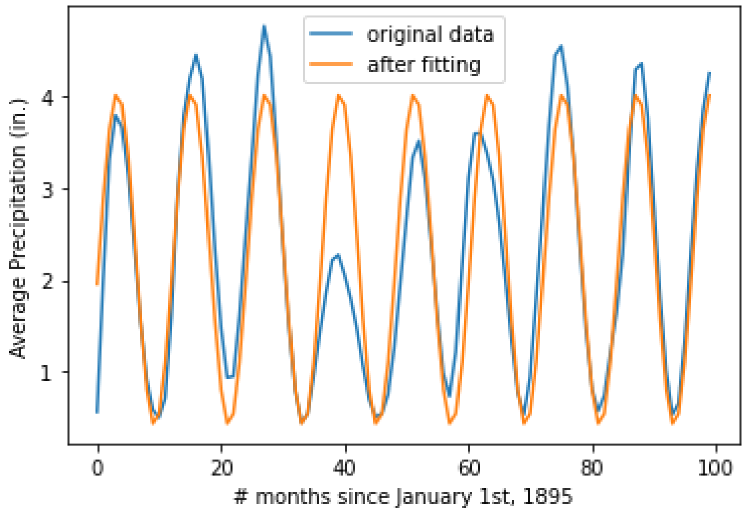

Figure 4. Sinusoidal Precipitation Model Over Time

Using the same SciPy curve fit regression as well as parameter estimation method, the parameters were calculated to be:

$$P(x) = 1.786\sin(0.524x) - 0.270\cos(0.524x) + 2.227 - 0.0000202x$$

The average monthly precipitation seems to be around 2 inches, with 1.5 - 2-inch amplitudes. The negative value of the f parameter indicates that precipitation rates are slowly decreasing over time.

Water Consumption Forecasting

Due to the relatively small amount of water consumption data, a curve fit using regression based on a time series seemed unlikely to work. However, a simple linear regression between temperature and water consumption yielded a linear function with an R-squared value of 0.88:

$$W(x) = 0.0631T(x) + 0.528$$

where W(x) is measured in billions of gallons.

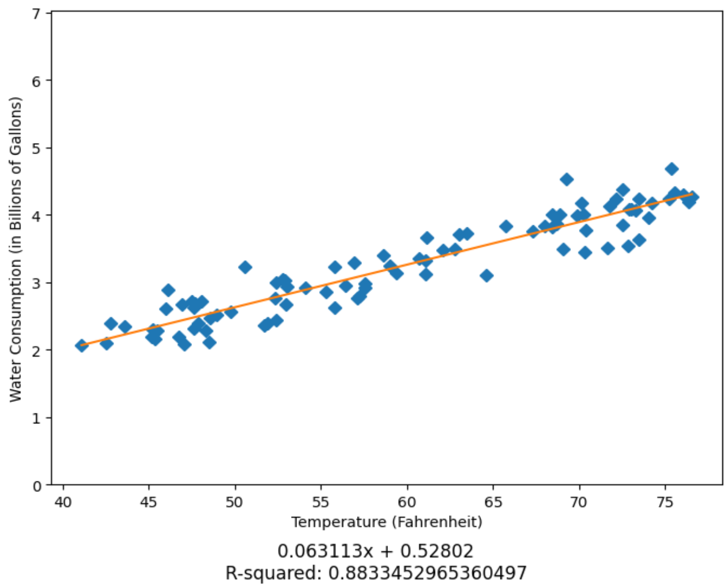

Figure 5. Linear Regression Model of Temperature vs Water Consumption

Indemnity Regression Model

After creating forecasting functions for temperature, precipitation, and water consumption, a regression model is necessary to relate it to the indemnity model. These indemnity losses were split between different factors. As a result, we identified ten possible candidate causes of loss that would be impacted by our forecasting functions. We constructed scatter plots between each variable factor and indemnity loss factor. Subsequently, we constructed polynomial regressive functions of orders 1, 2, and 3. These factors were often manipulated with natural logarithms on both axes in order to eliminate data skewing. The data was then fit using SciPy's curve fit function as well as stochastic differential evolution in order to discern the parameters. After determining the function with the best fit (lower order functions that would offer a clearer trend were prioritized), the regressive function was then surrounded with a 90% confidence interval. The lower bound of this 90% confidence interval gives us the lower bound of 95% of the data, making it reasonably accurate.

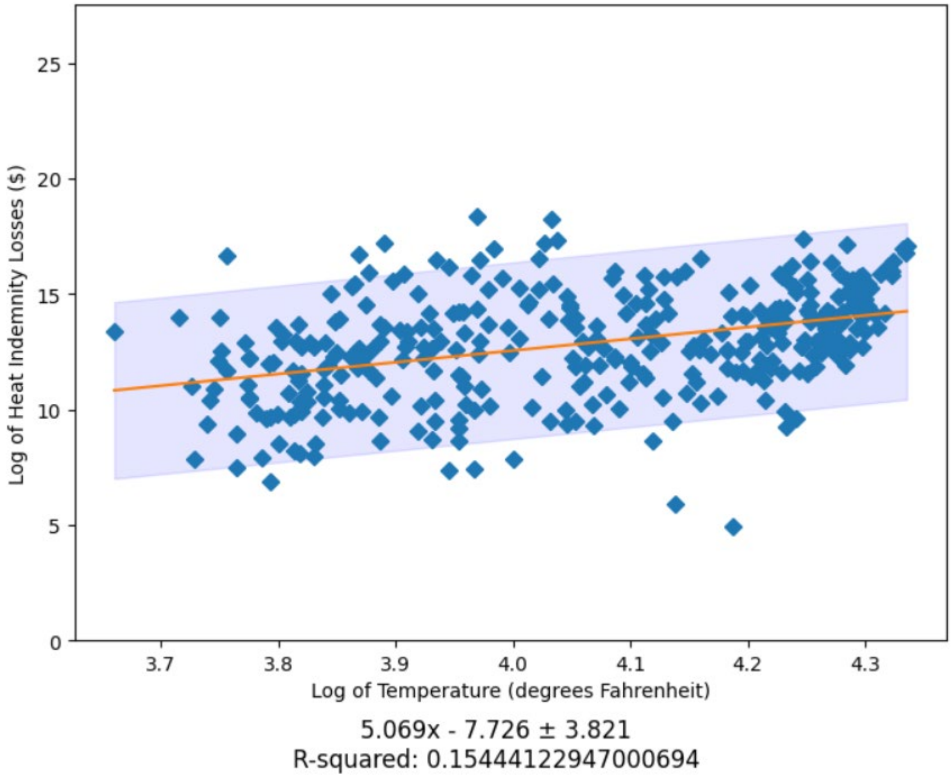

Figure 6. Note that the plus/minus value is meant to represent the bounds for the confidence interval.

A total of 30 possible regression functions were considered (temperature, precipitation, and water consumption factors were all matched against the 10-indemnity factor causes). The usability of the regressive functions was determined both by its R-squared value as well as the logicality of the trend shown. Out of the 30, 12 were eventually considered to be viable.

Table 1. Comparing the viabilities of each factor compared to each indemnity factor

Indemnity Factor	Temperature	Precipitation	Water Consumption
Indemnity Factor	Temperature	Precipitation	Water Consumption

The regressive function could then be built by taking the average of each indemnity factor between the three input factors and aggregating each indemnity factor into a total indemnity loss. The function can therefore be modeled as: n∑ k=1 I(k) (9) for a total n indemnity factors where each indemnity loss function I(k) is represented as the average of the 3 regressive functions:

$$\frac{\left(R_T\left(T(x)\right) + R_P\left(P(x)\right) + R_W\left(W(x)\right)\right)}{3}$$

Modeling Results

After the predictor models and regression models were obtained for each factor, the losses were then predicted starting at 1989 and continuing until 2021.

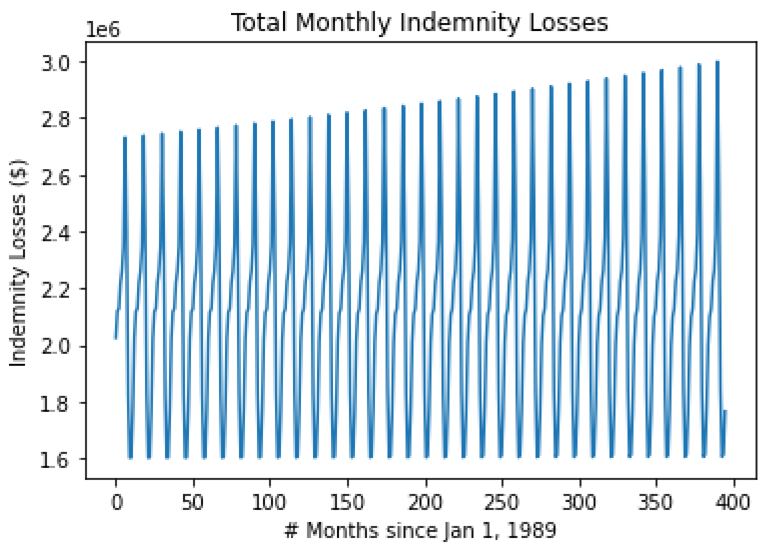

Figure 7. Predicted Monthly Indemnity Losses Over Time

Interestingly, the average minimum value for indemnity seems to remain relatively constant, while the upper bound seems to steadily increase over time. This seems to imply that the indemnity loss cycles are not fixed by a certain amplitude but rather increase in volatility over time. Next, both the separate indemnity factors as well as the aggregated total were predicted for the next 50 years. Due to the cyclical nature of the graph, a moving average filter for 12 months was passed through the data in order to better analyze trends hidden by the seasonality.

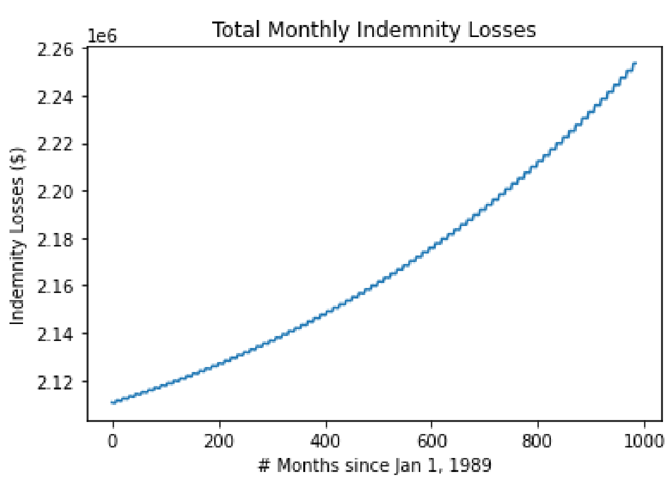

Figure 8. Predicted Monthly Indemnity Losses Over Time with a 12 Month Moving Average Filter

Risk Analysis

Understanding Our Risks

The climate of California and the world is rapidly changing. Climate change is a serious issue that will have dire consequences if not addressed. Multiple products of climate change include increasing temperature and decreasing precipitation. This leads to more frequent droughts and increasing costs for Californians.

Increasing Variability

Additionally, as these trends are allowed to continue, the weather and climate in general becomes more erratic. The indemnity graphs from section 4.5 show that the effects or damages of heat and cold are increasing over time. The reason both of these are increasing is that the temperature is more unpredictable mirroring other climate factors, which is another product of climate change. This affects the way we can respond to natural catastrophes such as droughts due to their increased frequency and size. The drought severity model serves as evidence of this as drought intensity is continuing to increase. Of the two major droughts from 1988 to 2007, they were short in length and only had one peak of drought. Of the droughts after 2007, the size and number of peaks in each were significantly greater [10]. As time goes on, the climate will get harder and harder to respond to, so we will have the most success dealing with these issues in the short term.

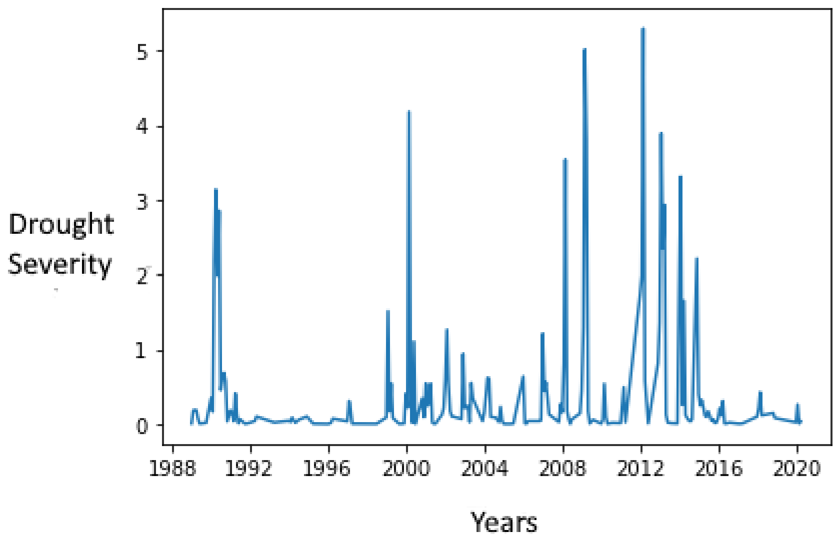

Figure 9. The severity of a drought on a scale of 0-5. 0 signifies little to no drought and 5 signifies an extremely severe drought. These values are based of the Palmer Severity Drought Index.

Data Trends

The trends shown in our data clearly reflect the effects of global warming. As shown by our temperature and precipitation forecasting, the temperature of California is rising at deceptively slow rate of 0.02 degrees Fahrenheit per year (1.002 degrees Fahrenheit in 50 years). The precipitation of California is decreasing at a rate of 0.0002424 inches per year (0.01212 inches in 50 years). These seemingly small changes actually lead to massive jumps in accumulated heat which leads to glacier melting and habitat destruction. These trends, however, lead to more rapid, pressing, and economic problems for Californians. We have shown that temperature is linearly proportional to water consumption through the following equation. $W(x) = 0.0631T(x) + 0.528$ (11) Given this equation from our data, we can see that the number of gallons consumed changes by 63,100,000 gallons of water for every increase of one degrees Fahrenheit. Compared with our time-series temperature model, we can see that the amount of water consumption increases at a rate of 1,264,524 gallons per year with x as the number of years. $\Delta W(x) = 0.0012645 \cdot \Delta x$ (12) This increase in water consumption is not sustainable and should be curbed given California's history of droughts. Building on that, the additional cost due to water consumption is rapidly increasing. According to the graph right under section 4.5 of total indemnity loss per month over time due to climate factors changed from 2.7 million dollars to 3 million dollars (a change of 300,000 dollars) over the course of nearly 33 years (1989 to 2022) and this rate of increase is accelerating. Since indemnity cost represents the amount of losses in property one loses, Californians are losing at the minimum an extra 300,000 dollars each month due to climate factors now than they were in 1989.

Risk Conclusions

Over time, the issue of climate change has become more of an issue. There are rising temperatures, precipitation volatility, and other signs of a changing world. We must focus on the products of climate change, rising costs and water consumption that are easier to solve and more damaging to us in the short term. The indemnity costs due to the climate are progressively increasing at an alarming rate. Water consumption is also predicted to increase progressively, which may threaten California's water reserves in the future. Left unchecked, these issues will continue to cause tremendous damage to California's crops. Crop loss will then cause a trickle-down effect with both the farmers and consumers being affected. Agricultural insurance companies will also face rising indemnity costs. Overall, California's climate change predicament will have long-lasting consequences as a result of the possible far-reaching effects of agricultural loss in the state's economy.

Recommendations

Agricultural Water Conservation

As the agricultural industry is a major consumer of California's water, and will therefore be drastically affected by a shortage, increasing efficiency and decreasing waste in this area would greatly mitigate loss. A starting point for this would be to look in to California's irrigation system. Currently California utilizes four distinct methods of irrigation: surface, sprinkler, drip, and subsurface, with sur- face causing the most water waste due to evaporation and subsurface being the least commonly used [11]. However, California's large scale agricultural production makes surface the most popular method in the state, due to its efficiency and low energy consumption. In order to utilize surface irrigation to its greatest degree, farmers plant their crops on downward slopes and use the natural pull of gravity to water all crops in a respective field after essentially flooding the highest point. The upsides of this practice are easily apparent, as farmers have to do a minimal amount of work for a high crop yield with relatively efficient water usage. The downside is that because of the large amounts of farmland in California, the seemingly small amount of water lost in each field from evaporation becomes a glaring concern. In order to mitigate this issue, we recommend that California farmers transition to drip irrigation, a change that is already occurring but at quite a slow rate. Drip irrigation is said to have upward of a 90% efficiency rate in terms of a plants ability to absorb the water provided to it, compared to the respective60% for surface and 75% for sprinkler, as shown in the figure below [12].

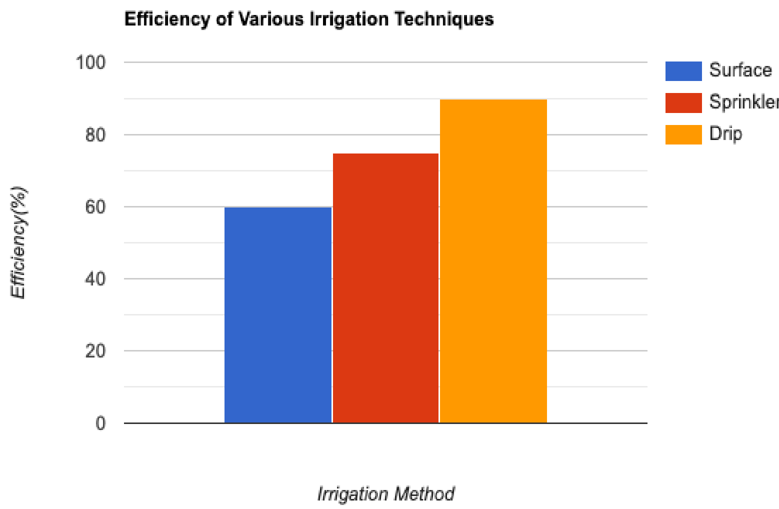

Figure 10. Bar graph of the effectiveness of different irrigation methods

Since drip irrigation supplies water directly to the plant's roots, it decreases chances of evaporation as well as possibility of disease by minimizing contact between the water and the stems, leaves, or fruits of plants. Drip irrigation also requires a minimum amount of labor to operate, and can be utilized even on uneven farmland.[13]. The efficiency of this system will not only decrease the overall cost for farmers in the long run, but will also improve both plant yield and quality, making it a very appealing option during a time of water crisis. In order to provide enough water for their irrigation systems, whether they be drip or surface, farmers often resort to digging wells and pumping groundwater from them. As surface water has become less available in California due to decreased precipitation, many farmers are beginning to dig deeper and deeper wells in order to produce a steady supply of groundwater for their crops. Al- though this may seem like a viable solution to a widespread issue, there are several drawbacks to this practice. The most concerning is the collapse of the ground itself, leading to the destruction of irrigation canals and the decreasing of aquifer capacity [14]. The widespread consequences of over digging pertain to all farmers in the surrounding area, as the land supporting their fields will be negatively affected as well. In order to mitigate this issue, we recommend that the California State Legislature look in to passing a bill that would limit the depth that farmers are allowed to dig to in order to access groundwater. Currently, well digging is a relatively unsupervised practice, resulting in amplified consequences as farmers dig more and more without realizing the severity of what they are doing. Not only would passing a bill protect the land that is being dug on, but it would also aid poorer farmers who do not have enough funds to support deeper digging, yet are still hurt by it.

Urban and Residential Water Conservation

In urban and residential areas, lots of water is used for watering home lawns through the use of sprinklers. However, these sprinklers are often set up and managed very inefficiently, leading to large scale water wastage as sidewalks and driveways end up receiving water that is meant for grass and shrubbery. Along with this, sprinklers are left on during periods of rain, and frequently cross streams and end up watering the same area. Proper planning by homeowners ensuring that their sprinklers are properly spaced to minimize wastage and the investment in to rain sensory sprinklers are minimally costing strategies that can easily be adopted in to the daily lives of millions of California residents. Another option is the investment in turf fields, which do not require watering. However, the cost to not only buy turf but also have it installed is quite high, so this mitigation strategy may not be viable for some. Despite this, it is still a possible option for those who are willing to go an extra step when it comes to water conservation.

Insurance Recommendations

As our model predicts that agricultural loss in California will increase as a whole due to climate change, insurance companies will have to act accordingly to the increased threat of disaster. With crop yields being more likely to fail as a result of rising temperatures and lack of water availability, insurance companies will likely have to increase premiums in order to sustain themselves. As many insurance companies make a profit by reinvesting their earned premiums into other companies, failure to adapt to the increased volatility of crop failure will cause many insurance companies to go under. Another option is for insurance companies to decrease the severity of loss that they are willing to cover. Most yield insurance plans protect against crop loss from a variety of natural disasters, ranging from droughts to floods. However, as the likelihood of loss becomes more frequent, companies may have to start looking in to decreasing the range of disasters that they are willing to insure a farmer for.

Water Supply Recommendations

Another possible, yet more difficult, option to decrease the severity of drought is to increase water supply to the state. As much of California's water is from natural sources like the Sierra Nevada Mountain range or the Colorado River, the increasing severity of the drought will cause these sources to become less reliable when it comes to supplying the state with an ample amount of water for its residents and economy. Since California is a coastal state, distillation of seawater can be used as a last resort if the situation requires it. Despite the massive costs and low efficiency, it is an extremely thorough method that can remove salt and any other contaminating materials from the seawater, providing a new source of freshwater for the state.[15] While costly, it still is a viable option.

Acknowledgments

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