Micro-Climate Engineering for Climate Change Adaptation in Agriculture

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January, 2017

Abstract

Can farmers change micro-climates around their crops as an adaptation to climate change? We present a novel adaptation technique for pistachio growers in California, meant to deal with warm winters. A kaolin clay mud is sprayed on dormant trees, blocking sunlight and lowering tree bud temperatures, preventing adverse yield effects of low chill. Climate predictions for California suggest that within 25 years, roughly one out of three winters will have low enough chill to greatly harm pistachio crops. Simulating market conditions, we estimate the mean welfare gains of this technique on a low chill year to be $554 Million. We expect more micro-climate engineering solutions, some based on existing technologies, to start playing a major role in climate change adaptation.

1. Introduction

Much of the recent climate change literature in agricultural economics is focused on estimating yield responses to extremely hot temperatures (Carleton and Hsiang 2016). The adaptation literature identifies several strategies – including innovation, adaptation crop selection and migration (Zilberman, Zhao and Heiman 2012). For example, Olmstead and Rhode (2011) describe how the introduction of new grain varieties made western migration of US farmers possible in the 19th century. Feng *et al* (2012) observe climate change driven internal migration in the US in the past four decades.

In this paper, we consider the role of an innovative adaptation strategy, engineering the micro-calimte experienced by plants. As a case study, we explore a particular technology for dealing with the threat of low winter chill on pistachio growers in California. A new treatment, coating dormant trees with a special kaolin mud, lowers the effective temperature and prevents a substantial yield drop. We explore the significance of this new adaptation approach for California pistachio growers and consumers, and find significant gains from it. We believe that there are many potential applications to micro-climate engineering as a new approach for climate change adaptation.

In the following section, we further explain the significance of chill for California agriculture, and specifically for pistachio. Section 3 presents a simple model for evaluating the benefits of micro-climate engineering for the pistachio market. In section 4 we estimate the outcomes from the model by Monte-Carlo simulations. Section 5 concludes.

2. Climate Change, Chill, and Adaptation in California

2.1 Chill Portions and California Agriculture

Chill portions are a well-known temperature metric in plant sciences. This brief explanation of chill is based on Erez (2000). Many fruit and nut trees have a dormancy phase during winter. This phase is an evolutionary adaptation, allowing the tree to “hibernate” and protect sensitive organs in winter, while harsh weather conditions take place and photosynthesis potential is limited. Once the tree has gone into dormancy, it needs to calculate when to optimally "wake up". Blooming too early might expose the foliage to frost. Blooming too late means not taking advantage of available resources (sunlight), and eventually being out-competed.

Temperatures and lengths of daylight affect both entry and exit from dormancy. Agronomists stipulate that, once dormant, tree buds count both chill portions and day lengths, until threshold levels of both are reached. Only then will the buds break and the tree will start blooming. Failure to attain a threshold chill count, which might vary between crops and cultivars, leads to low and non-uniform bud breaking, which is linked to low yields at harvest. Thus chill accumulation is critical for growers, especially in warmer areas where the chill constraint might be binding.

While early chill accumulation models were degree-hour based, the Dynamic Model seems to explain tree phenolgy best, especially in warmer climates (Luedeling and Brown 2011). The Dynamic Model posits that certain temperatures, around 6-8 degrees Celsius, are optimal for the synthesis of an intermediate chemical used as counter by the buds. About 30 hours of such temperature allows the level of this intermediate substance to reach a threshold level, where one chill portion is "banked" for the counting process and the level of intermediate substance is reset. Nevertheless, daytime exposure to higher temperature sets conditions optimal for the decomposition of this intermediate, "setting back the clock" for the current portion. In this way, alternating low night temperatures with higher daytime temperatures can interfere with chill accumulation (for the chemical intuition and mathematical model, see Erez et al. 1987; Erez et al. 1989; Fishman et al. 1987a; Fishman et al. 1987b).

An example of temperatures and chill portion accumulation is presented in figure 1. It shows the winters of 2003 and 2014 in Madera County, California. For pistachio, chill is usually counted November through February (Pope et al. 2015). The figure shows the daily range of temperature, and the cummulative chill at each day. Horizontal lines show the mean temperature for each winter. Note that, while 2003 saw 30% more chill portions accumulated than 2014 (78 compared to 60), its mean winter temperature is higher by almost half a degree: 8.49^oC compared with 8.06^oC. Moreover, the daily minimum temperatures in 2014 were mostly lower than the minimum temperatures in 2013. However, the maximum temperatures in 2014 were also much higher than the ones of 2013 for most of the winter, and the greater diurnal temperature variation reduced chill substantially.

2.2 Pistachio - a Vulnerable Crop

As weather is a direct input in agriculture, many climate change studies focus on the potential yield response to predicted future climate. Most of this literature deals with annuals (e.g. maize, rice, wheat), and eventually uses the metrics of mean daily temperature or degree days (Carleton and Hsiang 2016). The effect of climate change on agriculture through chill has been discussed in the natural sciences (for a review, see Campoy, Ruiz and Egea 2011), but the economic literature seems to have paid less attention to it. We stipulate two main reasons for this. First, staple foods are usually grains. In California, however, fruits and nuts are among the top revenue crops, and grains are secondary in importance. The second reason is technical: estimating yield is harder with perennials. Many other factors influence yield, including spring weather, tree vintage, alternate high and low bearing years, pollination conditions, and more (Pope et al. 2013; Dose and Menzel 2004). Estimating discontinuities or steep yield responses around a hypothesized lower chill boundary is further complicated by selection in orchard location: commercial orchards are planted where environmental conditions are favorable. Nevertheless, there is evidence of low chill in California hurting nut yields (Pope et al. 2015; Doll 2015).

Different crops and cultivars may have different chill portion requirement. One of the most chill sensitive crops in California is pistachio (*Pistacia vera*), with most California cultivars requiring at least 54-58 chill portions. For a comparison, most almond cultivars in California only require 22-32 portions (Pope 2015). Introduced to California about 80 years ago, pistachio was the state's 9th leading agricultural product in gross value in 2014, generating a total revenue of $1.65 Billion. California grows virtually all the pistachio crop in the US, and competes internationally with Iran and Turkey (2/3 of revenues are from export). In 2014, five California counties were responsible for a 96.2% of the state's (and national) pistachio crop: Kern (24.3%), Fresno (23.3%), Tulare (22.7%), Madera (17.7%) and Kings (8.2%) (CFDA 2016). Since the year

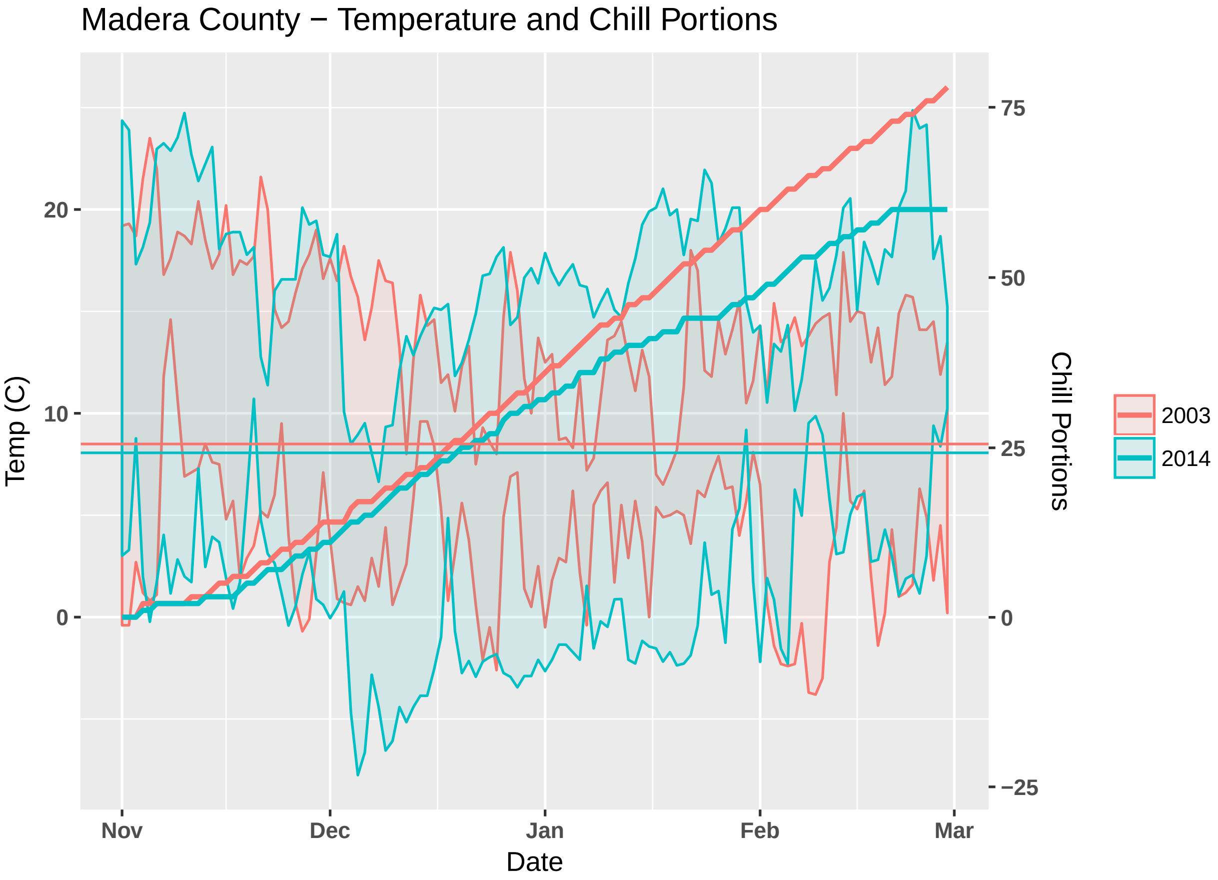

Figure 1: Temperature patterns and chill portion accumulation in Madera County.

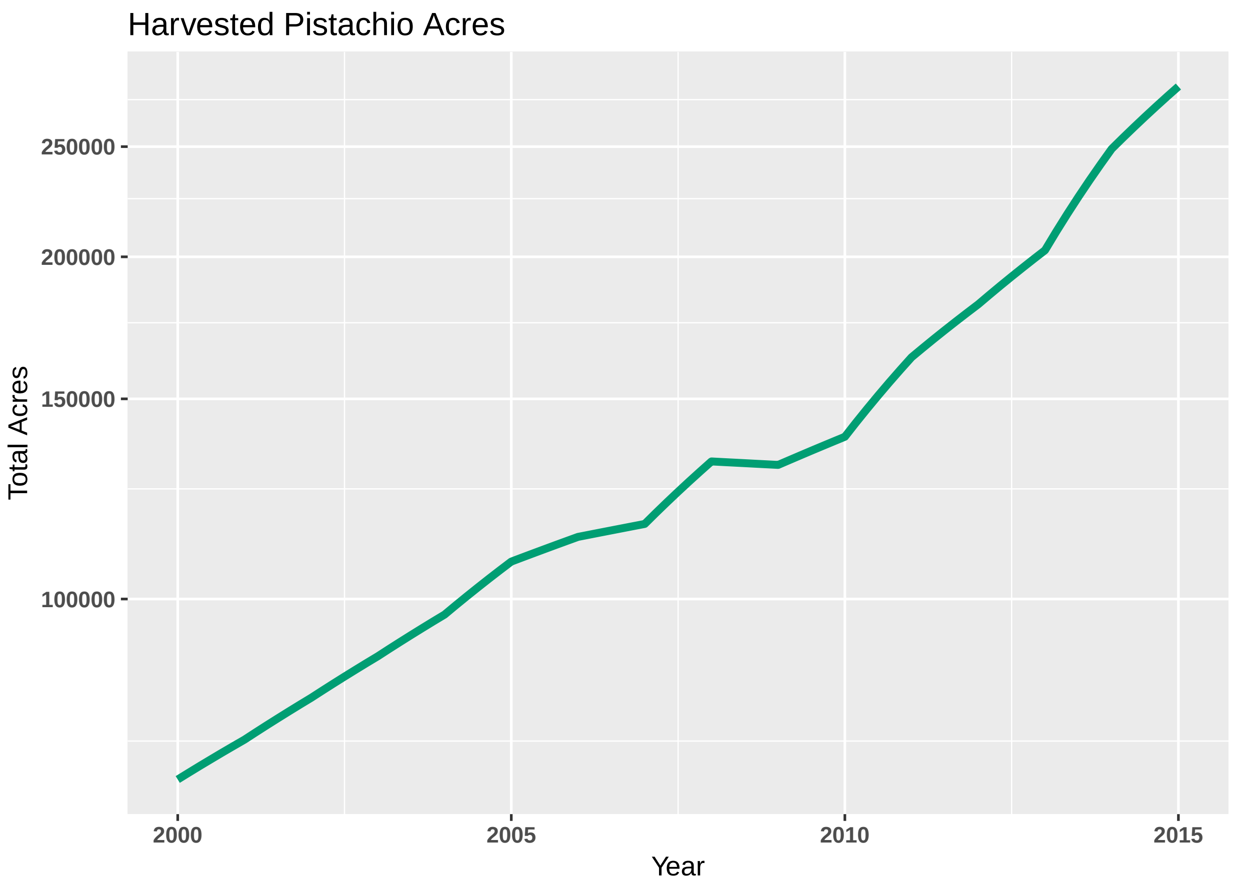

Figure 2: Total pistachio harvested acres in Kern, Kings, Fresno, Madera, and Tulare Counties. Data from yearly county crop reports.

2000, harvested acres in these counties have been increasing by roughly 10% yearly (see figure 2). Each increase represent a 6-7 year old investment decision, as trees need to mature before commercial harvest (CPRB 2009).

With climate change and global warming, chill in California is expected to decrease due to higher winter temperatures. While the mean chill might still remain within an acceptable range for pistachio trees, the concern is with the lower tail of the distribution. The winter of 2013-2014 had an alarmingly low chill, and personal communications with California growers, farm advisers, consultants, and other experts reveal a great worry about changing chill patterns in the southern part of San Joaquin Valley. Chill distribution is predicted to shift down, and extreme low chill winters might become likely. Pistachio growers might soon be facing severe random negative shocks to their production function.

2.3 Micro-Climate Engineering as an Adaptation to Low Chill

On the long run, drastic climate change would require the physical transition of orchards, and/or breeding of new cultivars. These adaptations are costly and slow, and perhaps not economically justifiable if the probability of a low chill year is small enough. 280k acres of pistachio need an adaptation mechanism for low chill years, and researchers with the UC Cooperative Extension might have just found one: spraying the dormant trees with a fine clay mud, protecting them from sunlight and essentially changing the climatic conditions for trees. In an experiment, treated pistachio trees on a low chill year experienced higher chill (measured by attached data-loggers) and significantly higher yields than untreated trees (Doll 2015).

The mud used for this experiment was made from a product commercially known as Surround, a processed kaolin clay used for many other purposes in agriculture. It is used as a non-toxic physical pest repellent, and also to protect fruits from sunburns. The use of kaolin clay for low chill adaptation is, to our knowledge, completely new.

According to Erez (2000), existing techniques for dealing with low chill suffer from many drawbacks. For example, bud breaking can be induced by special chemicals. These can be expensive, toxic to parts of the tree, and sometimes to humans as well. Another solution, reported to be applied commercially in Israel, is physically lowering the temperatures near the buds in winter time by spraying water from the top of the trees using mini sprinklers during daytime. This approach has drawbacks as well: it is quite water intensive (some experiments used about 14 gallons per hour per tree), and this water is not used by the trees for other means as they are dormant. It is also capital intensive, as a watering system needs to be installed with sprinklers on top of trees. Also, as water evaporates, salt accumulates on the tree and harms the buds to a certain extent. Another labor intensive technique uses special pruning to induce bud breaking.

3. Modeling Markets under Low Chill

Using iso-elastic supply and demand functions, we can model a simple pistachio market. In a low chill year, the supply curve shifts, altering eventual price and quantity. A simple sketch is presented in figure 3.

3.1 A Normal Chill Year

In a normal chill year, where chill is sufficient everywhere, price and quantities are determined by iso-elastic supply and demand functions

$$Q_d = A_D \cdot P^{\varepsilon_d} = A_s \cdot P^{\varepsilon_s} = Q_s$$

3.2 Low Chill Year - no kaolin use

Because of geographic spread of current pistachio growers, and the fact that some counties have higher chill than others, we assume heterogeneity among growers. In a low chill year, there are two groups of growers: the ones affected by low chill, and the ones who still have enough chill for a successful crop. An important assumption is that, in a normal year, both groups have a supply function that is a share of the original one. A share $(1-\alpha)$ is unaffected, and has a supply function of

$$(1-\alpha) \cdot A_S \cdot p^{\varepsilon_S}$$

A share of α is affected, and its supply drops by $1/(1+dL)$ for some parameter $L = 1,2,3,4$ (loss of 50%, 67%, 75%, 80%). This assumes that the two groups, affected and unaffected, have the same elasticity of supply. The total supply function is now:

$$Q_s(P) = (1-\alpha) \cdot A_s \cdot P^{\varepsilon} + \frac{\alpha}{1+dL} \cdot A_s \cdot P^{\varepsilon}$$

This can be equated with the normal demand function, and solved for P (given the other parameters, which will be simulated). Then, the quantity can be recovered, and welfare and profits can be calculated.

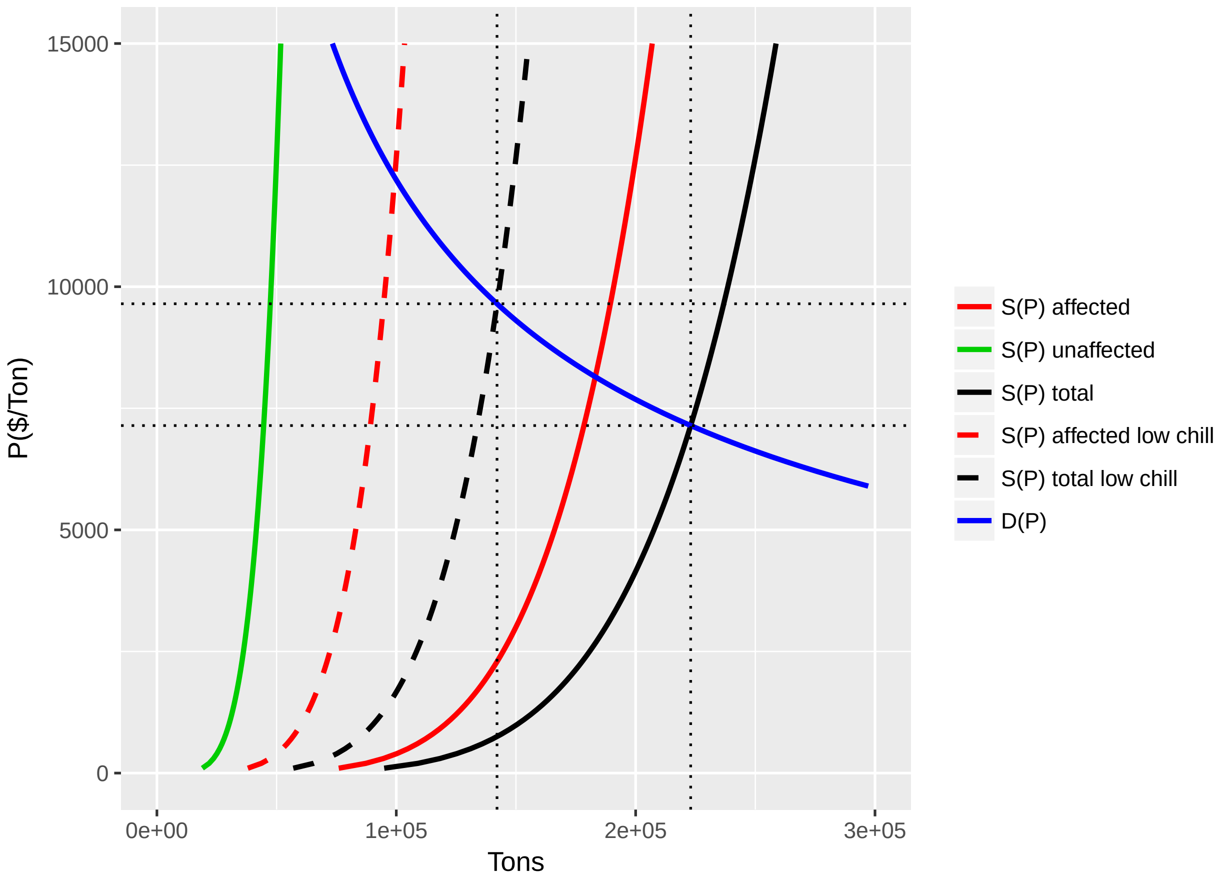

Figure 3: Market for pistachio in regular and low chill year

3.3 Low Chill Year - kaolin Option

In a low chill year, the affected growers face a decision: should they apply the kaolin or not? If they don't, their supply falls, and with it the whole market supply. Prices should be higher. Thus, an inelastic residual demand will make them not use the kaolin. If they do use it, their supply function is the original, but they have to pay the cost of kaolin application (assumed to be fixed per ton grown). Choosing this option, the market price should increase slightly, their quantity sold somewhat reduced, but now they have to bear the extra cost of production. Essentially, to make this decision, the affected grower needs to compare two potential profits.

3.3.1 Profits When Not Applying Kaolin

If they choose not to apply kaolin, the market clears by equating:

$$A_d \cdot P^{\varepsilon_d} = (1-\alpha) \cdot A_s \cdot P^{\varepsilon_s} + \frac{\alpha}{1+dL} \cdot A_s \cdot P^{\varepsilon_s}$$

Solving for P, we get the equilibrium price P^*, and then we can calculate the quantity supplied by the affected growers:

$$Q_a^* = \frac{\alpha}{1+dL} \cdot A_s \cdot (P^*)^{\varepsilon_s}$$

The profit of affected growers is:

$$\begin{aligned}
\Pi_{affected} = P^* \cdot Q_a^* - \int_0^{Q_a^*} P(Q)\, dQ &= P^* \cdot Q_a^* - \int_0^{Q_a^*} \left(\frac{1+dL}{\alpha \cdot A_s} \cdot Q\right)^{1/\varepsilon_s} dQ \\
&= P^* \cdot Q_a^* - \left(\frac{1+dL}{\alpha \cdot A_s}\right)^{1/\varepsilon_s} \cdot \int_0^{Q_a^*} Q^{1/\varepsilon_s} \\
&= P^* \cdot Q_a^* - \left(\frac{1+dL}{\alpha \cdot A_s}\right)^{1/\varepsilon_s} \cdot \left[\frac{Q^{1+1/\varepsilon_s}}{1+1/\varepsilon_s}\right]_0^{Q_a^*}
\end{aligned}$$

Note that elasticity of supply is positive, and the integral always works. While the only statistic that matters in this case is the profits for the affected growers, it is instructive to figure out the profits for the unaffected growers and total welfare. The profits of unaffected growers are:

$$\begin{aligned}
\Pi_{unaffected} = P^* \cdot Q_u^* - \int_0^{Q_u^*} P(Q)\, dQ &= P^* \cdot Q_u^* - \int_0^{Q_u^*} \left(\frac{1}{(1-\alpha) \cdot A_s} \cdot Q\right)^{1/\varepsilon_s} dQ \\
&= P^* \cdot Q_u^* - \left(\frac{1}{(1-\alpha) \cdot A_s}\right)^{1/\varepsilon_s} \cdot \left[\frac{Q^{1+1/\varepsilon_s}}{1+1/\varepsilon_s}\right]_0^{Q_u^*}
\end{aligned}$$

Where Q_u^* is the quantity grown at market price by the unaffected growers:

$$Q_u^* = (1-\alpha) \cdot A_s \cdot (P^*)^{\varepsilon_s}$$

The total welfare in this outcome is:

$$W = \int_0^{Q_a^*+Q_U^*} P_d(Q)\, dQ + \Pi_a + \Pi_u = \left(\frac{1}{A_d}\right)^{1/\varepsilon_d} \cdot \left[\frac{Q^{1+1/\varepsilon_d}}{1+1/\varepsilon_d}\right]_0^{Q_a^*+Q_U^*} + \Pi_a + \Pi_u$$

There are two technical notes to bear in mind here with respect to the elasticity of demand. First, when the elasticity of demand is $\varepsilon_d = -1$, the integral is a log rather than the exponential. Second, for inelastic demand the integral from zero quantity diverges to infinity. We assume out inelastic demand, as exports currently generate 2/3 of pistachio revenue in California. Nevertheless, we start integrating from $Q = 100$ for welfare and $Q = 50$ for each of the profit integrals.

3.3.2 Profits When Applying Kaolin

This time, the market price is set by solving:

$$A_d \cdot P^{\varepsilon_d} = (1-\alpha) \cdot A_s \cdot P^{\varepsilon_s} + \alpha \cdot A_s \cdot (P - P_K)^{\varepsilon_s}$$

where P_K is the per-ton price of kaolin application. Solving and calculating the quantity for affected growers, we get:

$$Q_a^* = \alpha \cdot A_s \cdot (P^* - P_K)^{\varepsilon_s}$$

And we can calculate again the affected growers' profit:

$$\begin{aligned}\Pi_{affected} = P^* \cdot Q_a^* - \int_0^{Q_a^*} P(Q)\,dQ &= (P^* - P_K) \cdot Q_a^* - \int_0^{Q_a^*} \left(\frac{1}{\alpha \cdot A_s} \cdot Q\right)^{1/\varepsilon_s} dQ \\ &= (P^* - P_K) \cdot Q_a^* - \left(\frac{1}{\alpha \cdot A_s}\right)^{1/\varepsilon_s} \cdot \int_0^{Q_a^*} Q^{1/\varepsilon_s} \\ &= (P^* - P_K) \cdot Q_a^* - \left(\frac{1}{\alpha \cdot A_s}\right)^{1/\varepsilon_s} \cdot \left[\frac{Q^{1+1/\varepsilon_s}}{1+1/\varepsilon_s}\right]_0^{Q_a^*}\end{aligned}$$

For the profits of the unaffected growers and the welfare, we need to calculate,

$$Q_u^* = (1-\alpha) \cdot\ A_s \cdot (P^*)^{\varepsilon_s}$$

and then follow the steps from the previous case.

4. Simulations

With uncertainty regarding some of the parameters in the model, we follow Zilberman *et al* (1991) and Hueth and Zilberman (1998) in estimating a distribution of outcomes by Monte-Carlo simulations. Namely, we define a distribution for each parameter and run the simulation drawing from the multivariate distribution. Calculating market outcomes first, we can then calculate the outcomes in terms of profits and welfare when affected growers use or don't use kaolin on a low chill year.

4.1 Parameters

The following parameters are drawn from uniform distributions. The ranges were determined according to existing literature, our experience, and consulting other experts.

- Elasticity of demand: $\varepsilon_d \sim U[-2, -1.01]$. These estimates reflect, on one hand, an elastic demand as international markets play a significant role in pistachio. Moreover, pistachio is not an indispensable, staple crop. On the other hand, pistachio has a unique taste and no real close substitutes. Hence we cap the elasticity at -2. This range was used by Gray *et al* (2005) when analyzing regulation outcomes. Zheng *et al* (2012) estimate a demand elasticity of -1.8.
- Elasticity of supply: $\varepsilon_s \sim [0.1, 0.3]$. Many agricultural goods, especially on the short run, are inelastic, reflecting the fact that much of the stock largely exists when markets clear.
- Loss parameter: $dL \sim U[1, 4] \implies$ 50 - 80% crop loss on affected growers.
- Function parameters: A_d and A_s calculated with ε_d, ε_s, and 2014 price and quantity.
- Price of kaolin per ton pistachio: $p_k \sim U[215, 430]$ up to twice current per ton.

4.2 Probability of Low Chill and Percent Grower Affected

Chill portions in pistachio growing counties are predicted to decrease over the years. Luedeling *et al* (2009) estimate the bottom 10% chill in the South San Joaquin Valley, where the large pistachio growing counties are, at 50.6 ± 3.8 by the years 2041-2060 in a medium emissions scenario. That is roughly 10-15 portions decrease from the current 10% percentile chill in pistachio counties for the winters of 2000-2016 (authors calculation, data from CIMIS 2016). Assuming the whole chill distribution will shift by a similar amount, we use current chill distribution for counties to try and estimate the probability of low chill winters in the future. Deducting 12 portions from 2000 - 2016 winter data, we show the shifted 17 year distribution on figure 4. Sampling many times with replacement, we can get the probability of any county hitting a low chill threshold, which we set at 53 (following Pope 2015). That would be the expected probability of a low chill year in California, which we find to be 0.36.

Furthermore, we use this re-sampling method to bootstrap the joint low-chill event probability distribution for all counties, conditional on a low chill event in any county. Multiplying by the shares in pistachio production in each county, we simulate α - the share of affected growers in a low chill year.

4.3 Simulation Results

Running 10,000 simulations with randomly drawn parameters, we get distributions for the market outcomes and the potential gains of kaolin use on a low chill year. Figure 5 shows the market outcomes, in terms of price and quantity. The mean price increase in a low chill year is of 39% (sd 38%), and the mean output decrease of 32% (sd 22%).

Would the affected growers choose to use kaolin on a low chill year? That would depend on the marginal demand curve they see. It turns out that, within the parameter ranges we specified, affected growers always “chose” to increase their production - profits when using kaolin were higher. Only when setting the initial demand price elasticity at very inelastic values, e.g. -0.3, do we see that the affected growers are better off by letting their supply curve drop.

Once we have the new prices and quantities, we can calculate the profit welfare effects. Their distributions are presented in figure 6. The mean profit gain of kaolin use, for growers affected by low chill, is \$276 Million. This is offset by a loss of the unaffected growers, as kaolin use prevents the fall of their competition that year. The mean of this loss is \$149 Million. A net total industry profit is, on average, \$127 Million (sd \$125 Million). Gains in consumer surplus are \$426 Million on average, and the total welfare gain from kaolin use is averaged at \$554 Million.

Multiplying these numbers by the probability of a low chill year in California, which we estimated at 0.36, we can get the potential gains from the option to use kaolin. This is \$46 Million in total profits, and \$153 Million in consumer surplus, and \$199 Million in welfare. Chill variance is naturally high, and an exact interpolation

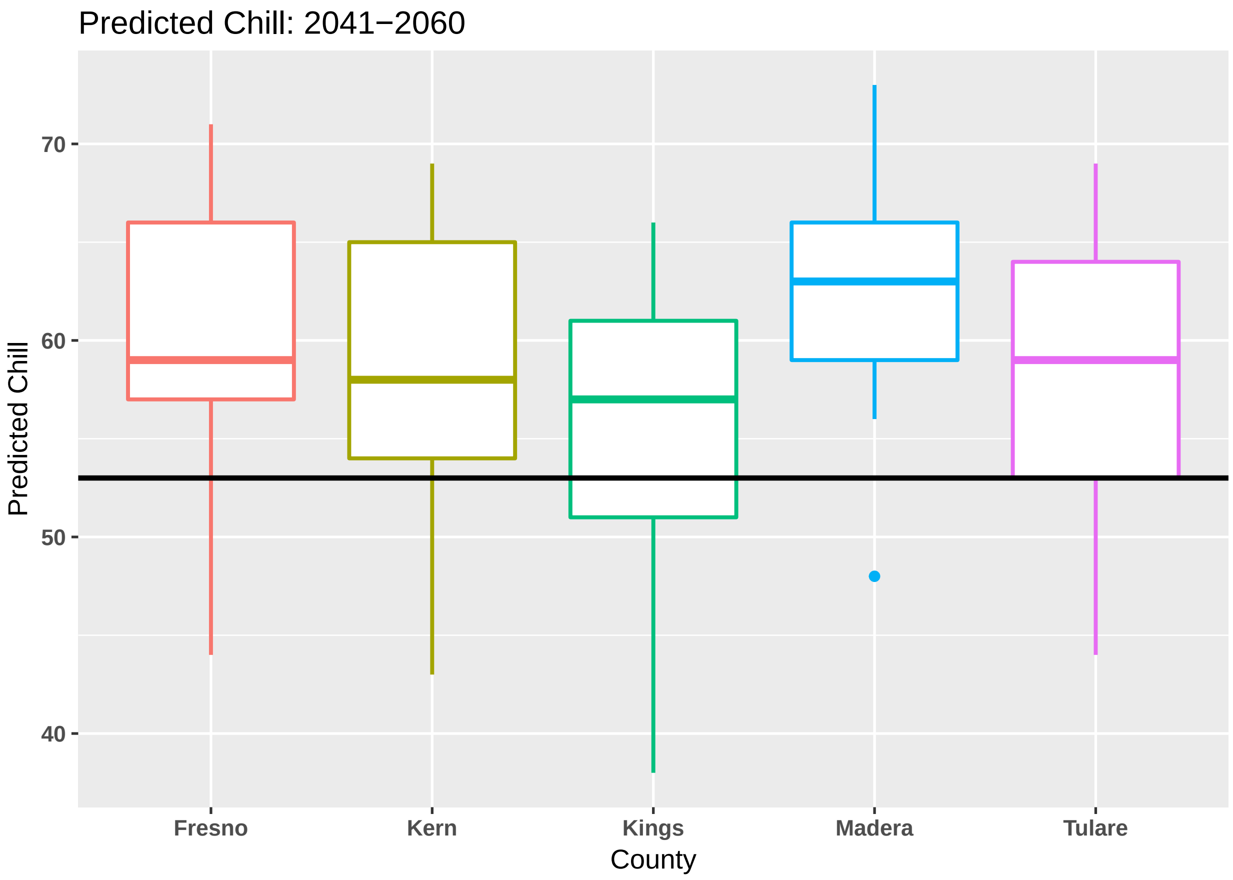

Figure 4: Predicted future chill distributions in pistachio growing counties in California. These are the 2000-2016 distributions shifted down by 12 portions.

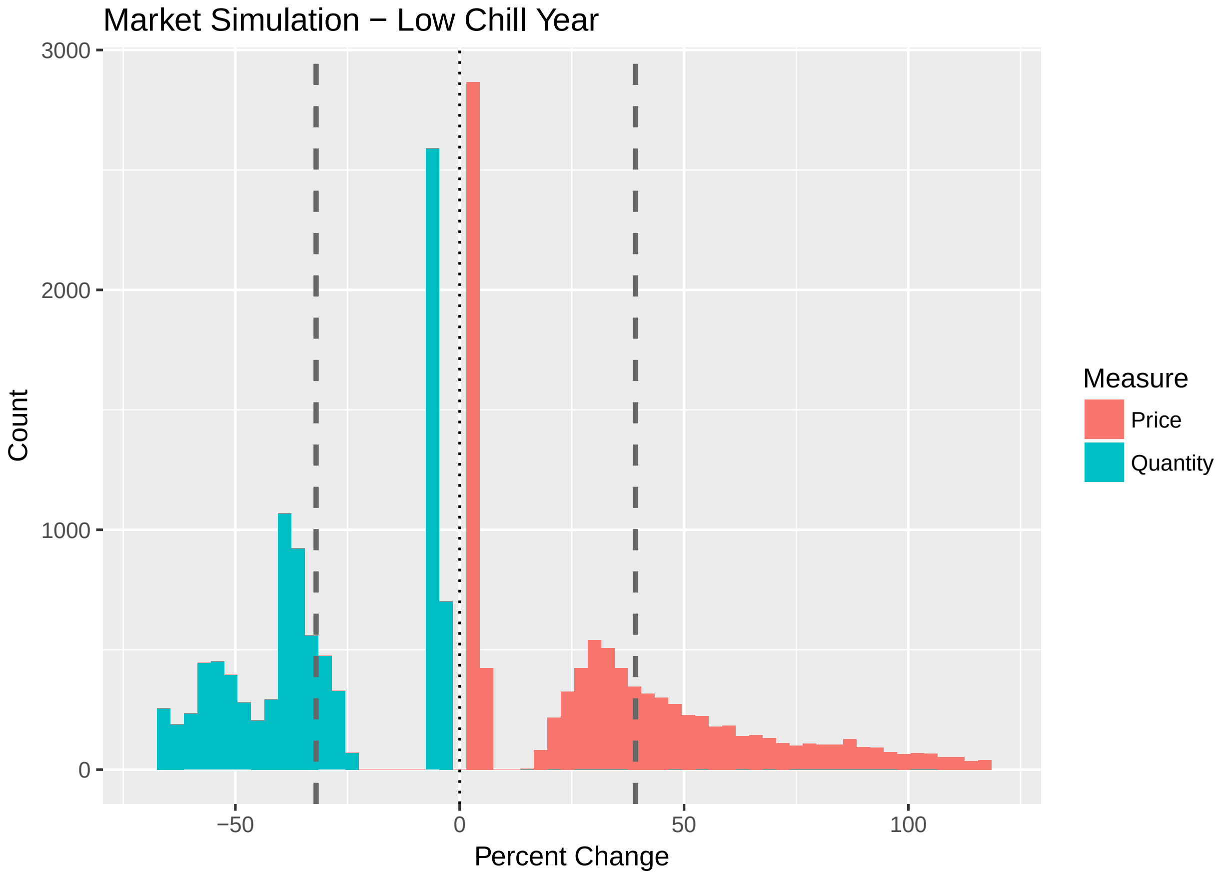

Figure 5: Price and quantity change for pistachio on a low chill year - distribution of 10,000 simulation outcomes.

of low chill chances before 2041 is beyond the scope of this paper. It seems very likely, however, that the value of the kaolin option would be in the tens of millions within a decade or so.

5. Conclusions

Pistachio growers in California are likely to start facing adverse weather conditions every few winters. A new adaptation technique, using kaolin clay mud sprayed on dormant trees and changing the effective micro-climate in orchards, might prevent heavy losses on low chill winters. Our simulations suggest that the gains from this technique are in the hundreds of millions.

This analysis is focused on pistachio, as it is immediately threatened by low chill. Nevertheless, the concept of engineering micro-climates as an adaptation to climate change can be broadened much further. While much of the climate change adaptation literature focused on crop and cultivar selection, this paper emphisized the role of innovative adaptation solutions. We expect to see more and more micro-climate engineering solutions for the challenge of changing climate. While the concept might seem revolutionary on first sight, we see it as a natural extension of existing technologies and conceptual framework in agriculture.

Agriculture is the nurturing of selected beneficial species, while altering and maintaining favorable environmental conditions for them. For millennia, growers have been changing the hydrology, soil composition, and ecology around their plants. More recently, growers are altering localized weather conditions as well. The most common example is the prevalent use of greenhouses for increasing temperature and humidity. These

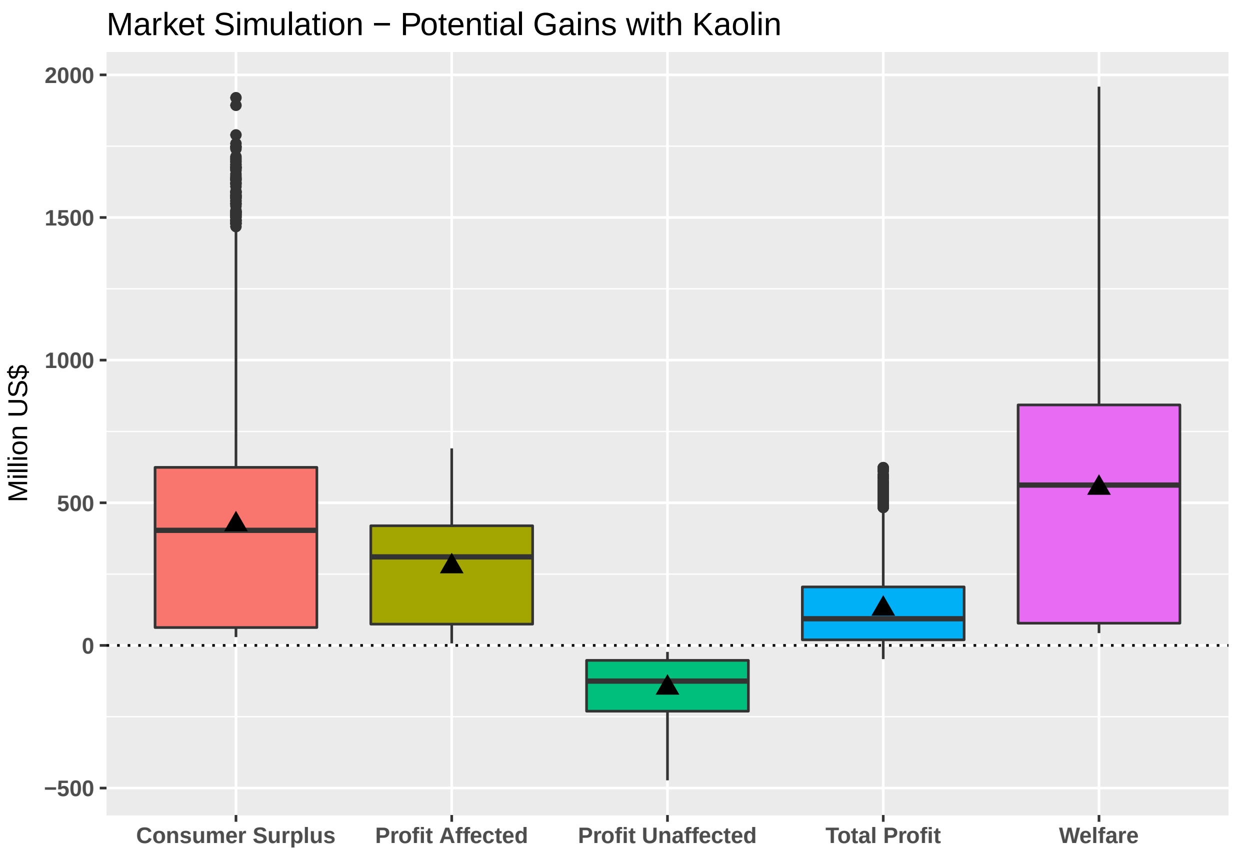

Figure 6: Gains from using kaolin on a low chill year - distribution of 10,000 simulation outcomes.

kind of solutions can and will be implemented for dealing with climate change as well.

Micro-climate engineering in agriculture points us to further research directions in climate change economics. Mainly, the availability of these adaptation techniques would greatly vary among different countries, increasing the already existing heterogeneity in climate change impact incidence. Micro-climate engineering would require high capital investments and a support network for research and implementation of adaptation techniques. These are available for pistachio growers in California, but might not be available in other parts of the world.

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