UNDERSTANDING CLIMATE CHANGE IMPACTS ON FLORIDA STRAWBERRIES AGRICULTURE

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Environmental Defense Fund

TWO DEGREES adapt

EXECUTIVE SUMMARY

Florida farmers have an opportunity to invest in piloting a broad swath of adaptation approaches to foreseeable climate changes and take a scenario planning approach to make strategic choices based on how strawberry production evolves in California, the dominant US producer.

Climate change is having a real impact on US agriculture by impacting yields, farming practices, and supply security. While the impact of climate change on row crops like corn, wheat, and soybeans has been relatively well studied, agronomic data gathering and yield modeling funding has been limited for fruits and vegetables. As a result, the impact of climate change on fruits and vegetables remains less investigated even though it is an essential component of nutrition and the US agriculture economy.

In this study we illustrate the impacts climate change will have on the fruit industry by modeling the mid-century changes in Florida strawberry yield using downscaled climate models and an innovative process-based crop model developed by researchers at the University of Florida. We demonstrate how climate change induced temperature changes to killing degree days and chilling degree days will shift Hillsborough County, the leading producer of strawberries in Florida, out of the goldilocks zone by 2050. Under this mid-century climate change scenario, strawberry farmers in Hillsborough County will experience decreasing yields (11%) and net income per acre (10%).

Adaptation strategies can offset the negative impacts of climate change. One example is shifting where strawberries are grown to north-central counties such as Marion County, where the mid-century climate will resemble today's climate of Hillsborough County. Besides moving production north, a number of other adaptation options exist including new hybrids, shading, automation, sustainable cooling, and aquifer recharging.

Given the nature of Florida strawberry growers as a price taker and that of California as a price setter, one large unknown is how strawberry production in California would change by 2050 due to climate change. In this study, we have taken a qualitative scenario planning approach to describe four plausible scenarios with varying levels of overall production and winter yield. In a future study, we could quantitatively analyze the impact of climate change on strawberry production in California and Mexico, two competing regions for Florida strawberry growers.

In a future study, our agronomic modeling can get more sophisticated and cover counties beyond Hillsborough, model different planting dates, and additional varieties. In addition to this, a temperature sensitive crop such as tomato can also be studied in depth.

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1. INTRODUCTION

Climate change is having a real impact on US agriculture. Increasing temperatures, water stress, and changes in solar radiation are impacting yields, farming practices, and supply security. The study "Climate-proofing US Agriculture: Four Illustrative Case Studies" illustrated the need for adaptation in the Midwestern US in order to offset climate impacts. The study found without coordinated action, warming temperatures, increased water demand, and an intensified hydrologic cycle will stagnate the long-term increase in crop production. In this study we complete a similar analysis of fruit and vegetable production in Florida.

Fruits and vegetables are an important component of nutrition and the US agriculture industry, however, the impacts of climate change on this industry has been minimally studied until now.

Florida and California are two of the leading producers of fruit and vegetables in the US. Crop agriculture in Florida is dominated by fruits and vegetables. Of the top seven crop commodities, six are fruit and vegetables and account for $1.9 billion in revenue as of 2021 (see Table 1).[1]

TABLE 1

Florida agricultural production as reported in USDA 2021 State Agriculture Overview

Crop	Value of Production (millions US $)	Acres Harvested
Oranges	708	343,000
Strawberries	399	10,400
Tomatoes	323	21,000
Sweet Corn	208	32,600
Watermelons	208	26,400
Bell Peppers	152	10,800
Peanuts	130	158,000

Fruits and vegetables have a much higher value per acre compared to row crops. Notwithstanding their value, it has been difficult to gather production data for fruits and vegetables and develop agronomic models due to the fact that this market is distributed into a much larger number of commodities compared to the row crop market, which is dominated by three crops. In this study, we assess why agronomic models are developed for certain specialty crops, what determines the choice of crops by researchers, and to what extent funding and understanding of growth biology plays a role. We focus on five specialty crops critical to Florida: strawberries, tomatoes, watermelons, bell peppers, and peanuts.[2]

1 USDA Florida State Profile 2021
2 See Appendix A for a summary of the literature we reviewed on each specialty crop.

Of these five crops, Strawberry is the most well studied. Researchers in multiple geographies such as Florida, California, Spain, and Virginia have developed both statistical and process based yield models. Therefore, the second objective of this study is to assess the impact of climate change on strawberry production and economics in Florida (see Figure 1 for an example of Florida strawberry production). Towards this end, we have curated projections of key climate variables: both basic and derived e.g. temperature, precipitation, killing degree days, and chilling degree days. We then use these climate projections to estimate the impact of climate change on strawberry yield and profitability.

FIGURE 1.

Florida strawberries growing in raised beds with plastic mulching.

Although strawberry production in Florida is a $400 million industry, it is a much smaller producer given California's nearly 10x larger production which sets the market price. As a price-taker, Florida Strawberry farmers have developed unique strategies. We have developed four scenarios to qualitatively assess how strawberry production in California may be affected by mid-century climate change and how Florida farmers should respond.

Given the long timeline and uncertainty in competing geographies, we recommend that Florida strawberry farmers invest in piloting a broad swath of adaptation technologies spanning heat tolerant varieties, operational efficiencies, and ecosystem improvements. For each of the technology sectors we have identified four to five technology providers.

2. FLORIDA CLIMATE IN 2050

For this study, we considered climate simulations following RCP4.5, a middle-of-the-road scenario where global GHG emissions peak before mid-century and then slowly decline. RCP4.5 results in a global average warming of about 2.4°C (4.3°F). To focus on Florida strawberry growing, we extracted data for strawberry-specific growing regions of Florida from a high resolution historic dataset (gridMET) and a collection of 20 downscaled climate model simulations (MACA) following RCP4.5 (see Appendix B for details).

A summary of mid century climate changes for Hillsborough strawberry growing areas is shown in Table 2. We focus on October-April, the time when strawberries are commercially grown and harvested in Florida. Hillsborough County gets significantly warmer by mid century, with afternoon highs and overnight lows warming about one degree Celsius. While humidity and rainfall increase, vapor pressure deficit (the difference between how much water vapor the air is holding and how much it can hold) also increases, which can lead to increased water needs for plants. Since most rainfall in this area falls in the summer months it is not surprising that changes to strawberry season hydroclimate are relatively small.

TABLE 2

Hillsborough County historical (gridMET) and mid-century change (MACA)

Strawberry Growing Season (October - April)	Historical average gridMET	Mid-century change MACA	Mid-century % change MACA
Total precipitation	**46.8cm**	**2.59cm**	**+5.5%**
Daily maximum temperature	25.9°C	+1.0°C	+4.0%
Daily minimum temperature	13.3°C	+1.1°C	8.1%
Daily average specific humidity	0.0104 kg/kg	+0.00067 kg/kg	+6.5%
Daily average vapor pressure deficit	0.847 kPa	+0.066 kPa	+7.4%
Daily average wind speed	3.84 m/s	-0.02 m/s	-0.66%
Daily average downwelling solar radiation at the surface	191 W/m2	+2.4 W/m2	+1.3%

The expected changes to Hillsborough County are further explored in Figure 2. This graphic shows observed and modeled past and future changes to average temperature during the strawberry growing months. Warming is expected to be steady and relentless: each decade warms approximately 0.22°C (0.4°F).

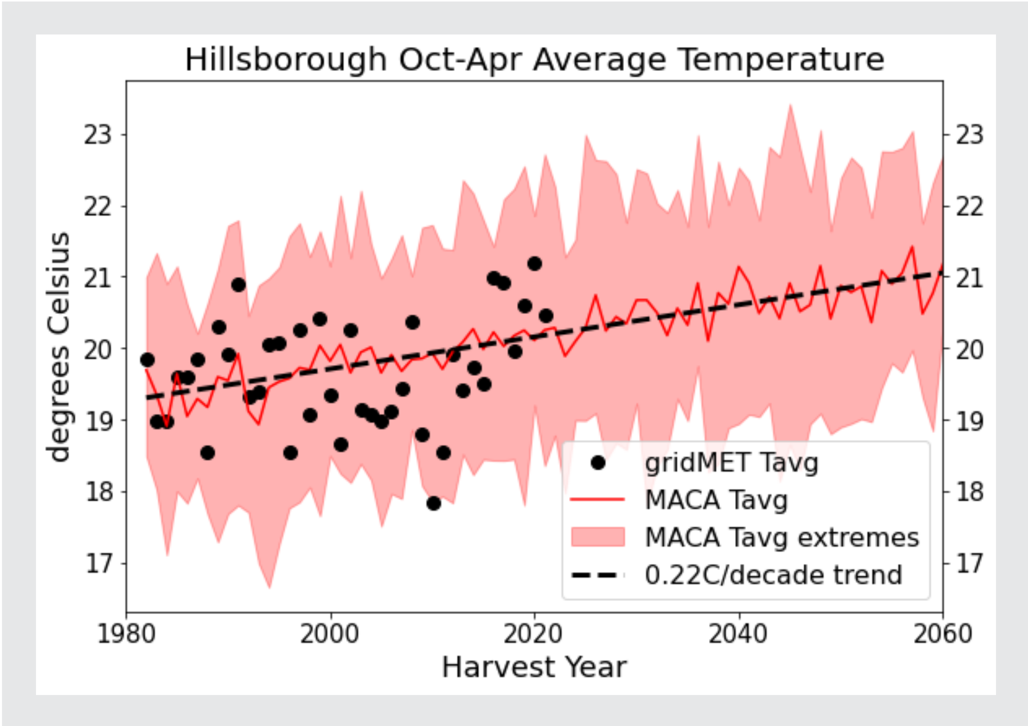

FIGURE 2.

Hillsborough County strawberry growing season average temperature

Black dots show historic (measured) temperatures. The area shaded in red shows climate model predictions of temperature by year across a range of models. The red line shows the average temperature predicted across all of the models; note that the model-predicted temperatures are a good fit to the historic (measured) temperatures. The dashed black line shows the average trend in temperatures across historic and predicted future data, and shows a steady increase in average temperature of 0.22oC per decade.

Comparison to Other Strawberry Growing Regions

To see whether other counties may fare differently under global warming we compare the above changes to Hillsborough strawberry farms to two other strawberry growing counties: Manatee County and Marion County. Since they are very close neighbors Manatee County experiences very similar climate changes to Hillsborough (see Appendix B). Changes to Marion County are more significant, as detailed in Table 3 and Figure 3 below.

TABLE 3

Marion County historical climate (gridMET) and mid-century change (MACA)

Strawberry Growing Season (October - April)	Historical average gridMET	Mid-century change MACA	Mid-century % change MACA
Total precipitation	**52.3cm**	**2.12cm**	**+4.0%**
Daily maximum temperature	24.5°C	1.1°C	+4.4%
Daily minimum temperature	11.3°C	1.1°C	+9.9%
Daily average specific humidity	0.0090kg/kg	0.0005 kg/kg	+6.6%
Daily average vapor pressure deficit	0.856kPa	0.071kPa	+7.9%
Daily average wind speed	3.65m/s	-0.02m/s	-0.69%
Daily average downwelling solar radiation at the surface	184W/m2	3.0W/m2	+1.64%

Marion County warms at the same rate as Hillsborough but starts from a cooler historic baseline. By 2060 Marion's October-April average temperature will be similar to Hillsborough County's historic average (comparison of black trend line and red climate baseline in Figure 3).

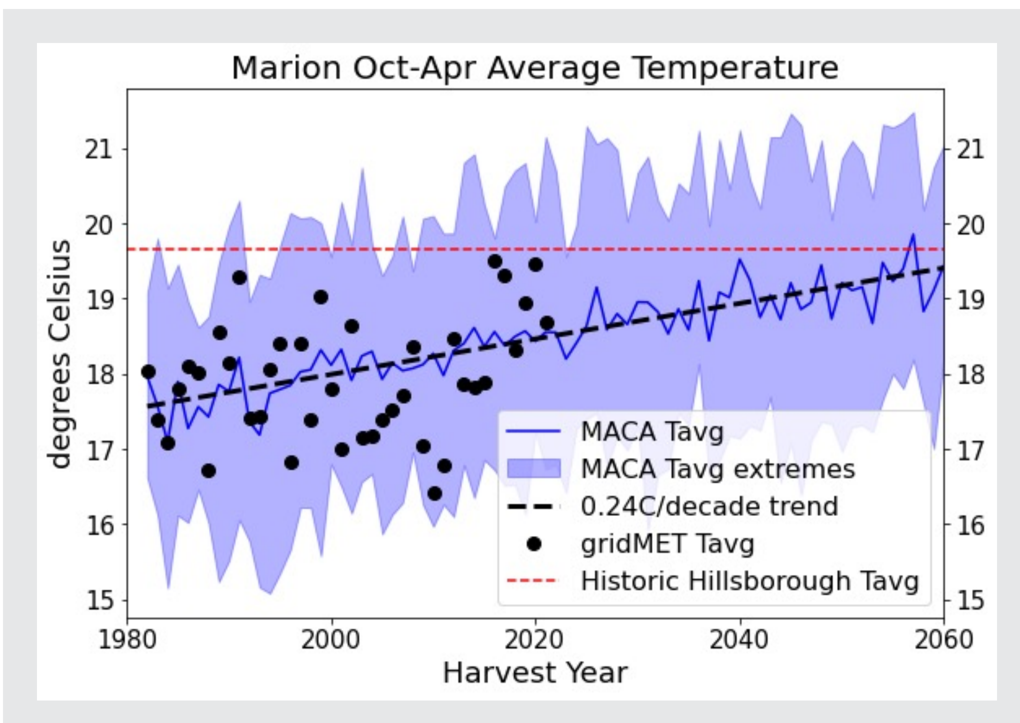

FIGURE 3.

Marion County strawberry growing season average temperature

Dangers of Future Heat to Strawberry Growing

Modest changes in average temperature can lead to significant changes in key crop thresholds, for example temperatures above 85°F damage strawberry plants.[3] In Figures 4 and 5 we show changes in killing degree days, the sum of degrees above 85°F (29.4°C), an approximate measure of heat stress experienced by strawberry plants.

In Hillsborough County killing degree days are expected to increase more than 50% by midcentury. Despite Marion County's average temperature staying below Hillsborough's historic average (Figure 3), by midcentury killing degree days in Marion County are significantly above the historic Hillsborough average (red line in Figure 5). This highlights the difficulties of climate adaptation: while the cooler climate of Marion County may become more suitable for future strawberry growing, damaging warming will likely still harm future yields.

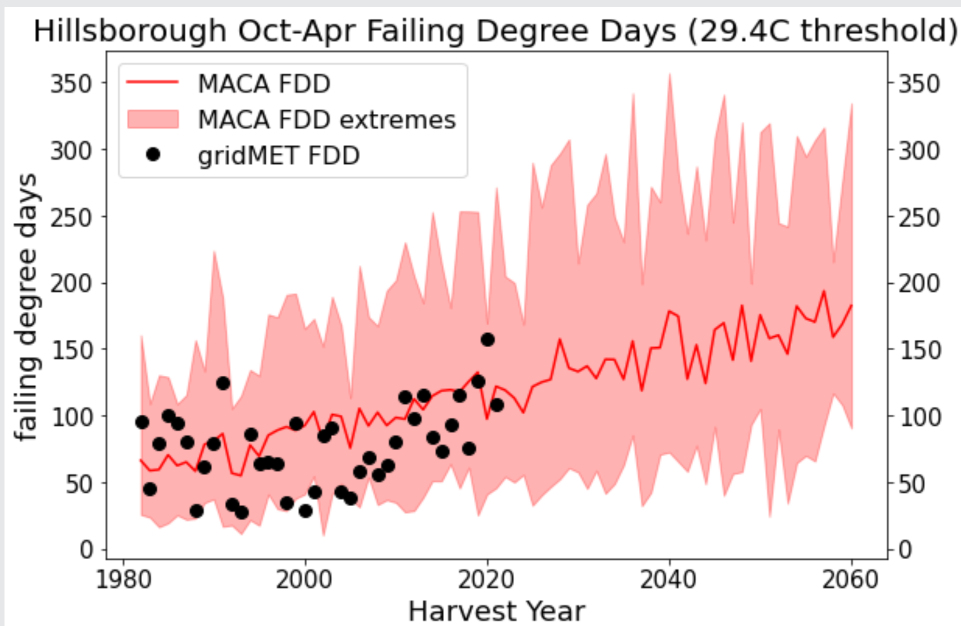

FIGURE 4.

Hillsborough County strawberry growing season killing degree days

3 Morton LW, Peres N, Fraisse C, and Gleason M 2017 Climate, Weather and Strawberries Sociology Technical Report 1047

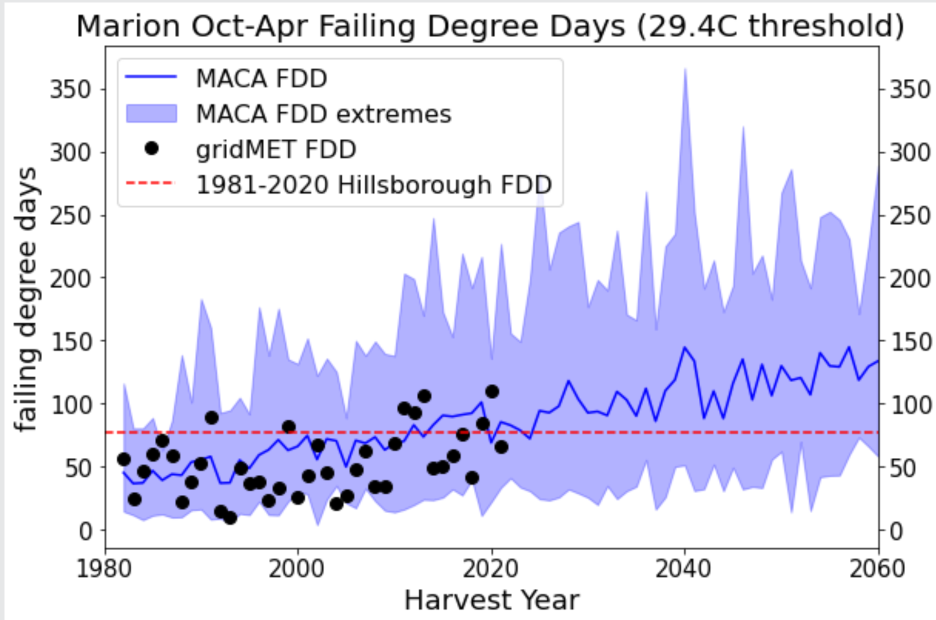

FIGURE 5.

Marion County strawberry growing season killing degree days

Risk of Hurricanes to Florida Speciality Crops

Hurricanes present a considerable risk to Strawberry specialty crop agriculture in Florida as evidenced by a report from CNN on damage caused by Hurricane Ian to 15% of strawberry acreage for Wish Farms in 2022. [4] Unlike the steadily rising temperatures, quantitative modeling of extreme weather events such as hurricanes as a function of climate change is more complex and relatively early in the peer review process.[5] One recently published report from the First Street Foundation[6] projects that hurricane driven losses in the U.S. will increase from $18.5 billion today to $19.9 billion by 2052 with Florida accounting for 70% of these losses.

4 CNN September 30, 2022 Farms in Florida are underwater and without power, pushing back critical planting season | CNN Business
5 Jewson, Stochastic Environmental Research and Risk Assessment, 2022, 36, 3355-3375
6 Worsening Winds, A Report from the First Street Foundation, February 2023

3. FLORIDA STRAWBERRY MARKET DYNAMICS

Strawberries are a high value crop. In 2021, the US produced 1.5 million tons of strawberries, totalling $3.4 billion in value.[7] The US is the second largest producer in the world, commanding 10% of market share.[8] The US is also a large consumer of Strawberries with 86% of its needs being met by production within the US in 2017. Over 99% of strawberry imports in the US are from Mexico, mostly from the Baja California region. Within the US, California produces 90% of Strawberries and Florida ranks second with 9% of the production.

Acreage for Strawberries has increased in both Florida and California at the expense of other states in the last 20 years. Specifically in Florida, the acreage increased significantly from 6,600 acres in 2007 to 10,900 in 2015 and now stabilized around 10,000 acres (Figure 6). Strawberry production in Florida is concentrated in Hillsborough County which commanded an 88% share per USDA 2017 Census of Agriculture.

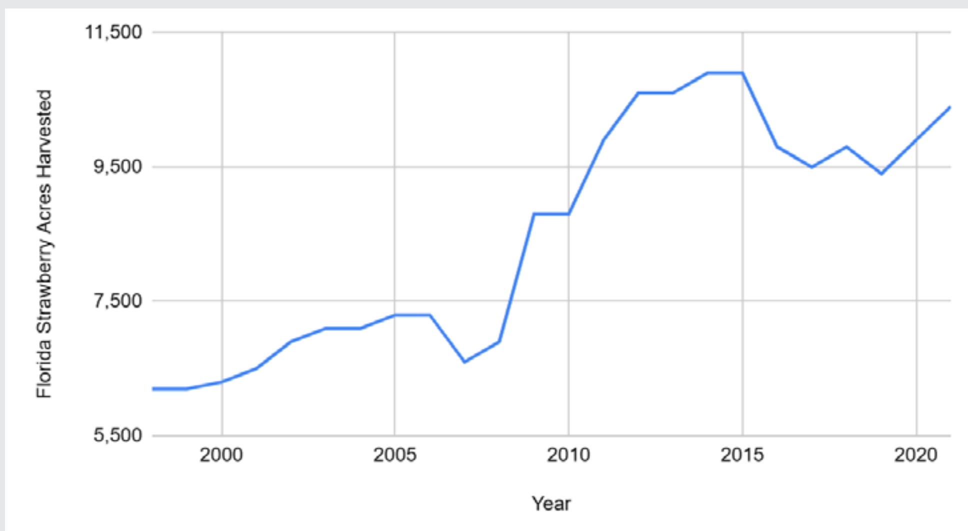

FIGURE 6.

Florida Strawberry Acres Harvested between 1998-2021

However, unlike row crops, strawberry annual yield has stayed pretty steady through this time period (Figure 7). In order to understand that, we must take into consideration the fact that strawberries have multiple harvests in one growing season and that the price varies appreciably from month to month. Figure 8 shows the average price of strawberries in the US for 2000-2022 period by month.

7 USDA Quick Stats
8 UN FAOSTAT

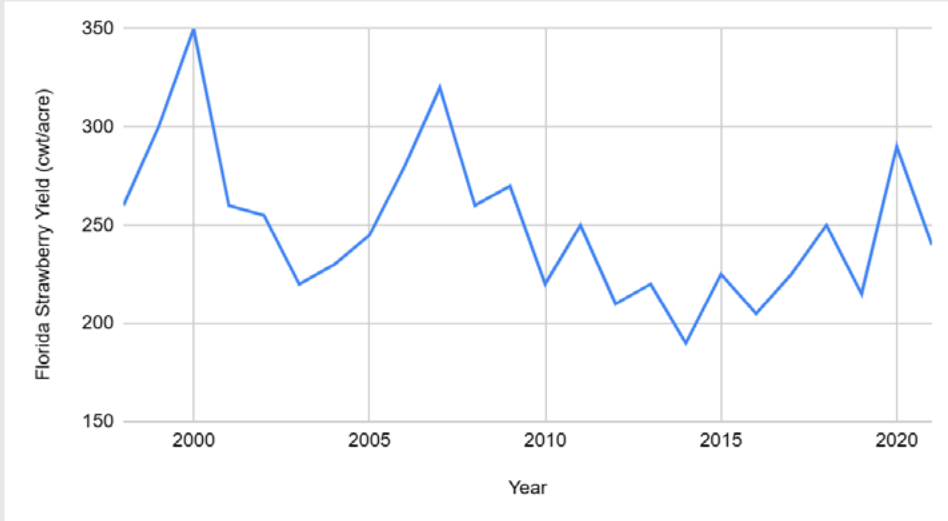

FIGURE 7.

Florida-average strawberry yield (cwt/acre) between 1998-2021

FIGURE 8.

US Average Price of Strawberries ($/12 oz) by month

The increase in price from November to February and the subsequent decrease is well documented by researchers at University of Florida Extension School and ascribed to the drop in California production during the early winter months. Researchers have also constructed an optimal yield profile for Florida strawberries based on these price trends (Figure 9).[9] Therefore most of the research and development efforts for strawberries in Florida has focussed on optimizing the yield profile through the growing season. Researchers at University of Florida such as Dr. Vince Whitaker and others have attempted at developing hybrid varieties of strawberries whose yield profiles through the growing season match the high price months of November, December and January.[10]

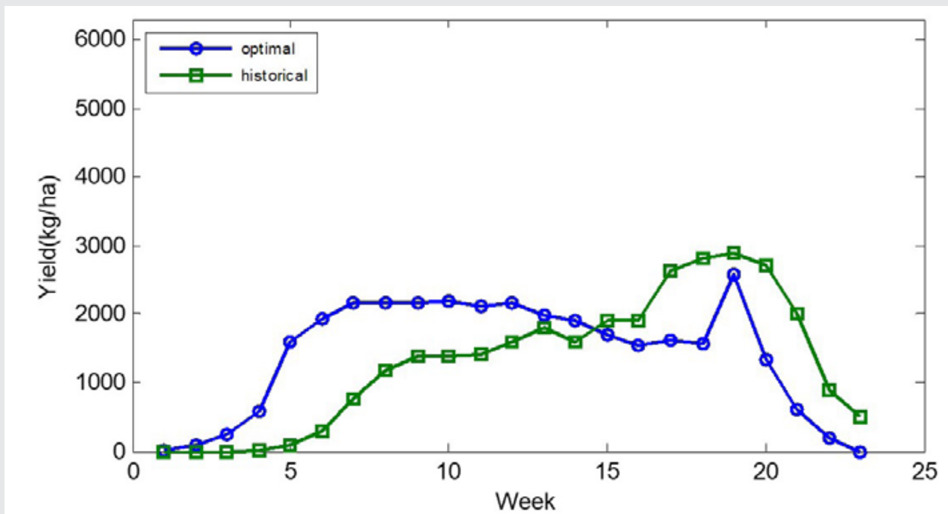

FIGURE 9.

Historical and Optimal Yield for Florida Strawberries reproduced from Wu et al. (2015).[11]

Companies like Wish Farms have commercialized varieties such as Sweet Sensation with early yield in mind. It is possible that climate change may increase the nighttime temperatures critical for strawberry plant flowering and daytime temperatures critical for sugar and acid content in the current growing season, thereby creating a tension with current profitability trends.

9 Wu F, Guan Z, and Whitaker V 2017 Florida Strawberry Growers Need More Early Yield to Improve Profitability, Univ. of Florida IFAS Publication #FE1032
10 Whitaker VM, and Fan Z 2020 What Will Florida Strawberry Varieties Look like in the Future? A Breeder's Perspective International Journal of Fruit Science, 20 992-996
11 Wu F, Guan Z, and Whitaker VM 2015 Optimizing yield distribution under biological and economic constraints: Florida strawberries as a model for perishable commodities Agricultural Systems 141 113-120

One large uncertainty for Florida strawberry growers is how climate change will impact strawberry production in California, given that market's outsized role in setting price. Climate change induced rising temperatures may impact annual yield as well as their distribution through the growing season and the total volume of production. Research from Lobell and Field projects a 10% decrease in strawberry production by mid-century,[12] and research from Deschens and Kolstad projects a 43% decrease by 2070.[13] However other researchers like Davugovish suggest that Southern California may see an increase in winter yield.[14]

We have developed four scenarios for assessing impact of climate change on strawberry agriculture in California:

- Lower production, higher winter yield
- Lower production, current winter yield
- Current production, low winter yield
- Current production, high winter yield

For each of these scenarios, Florida growers need to take different adaptation strategies. Therefore investing in a broad set of adaptation technology development and having these choices deployment ready by mid-century will be a key competitive advantage. These strategies are seen in Figure 10.

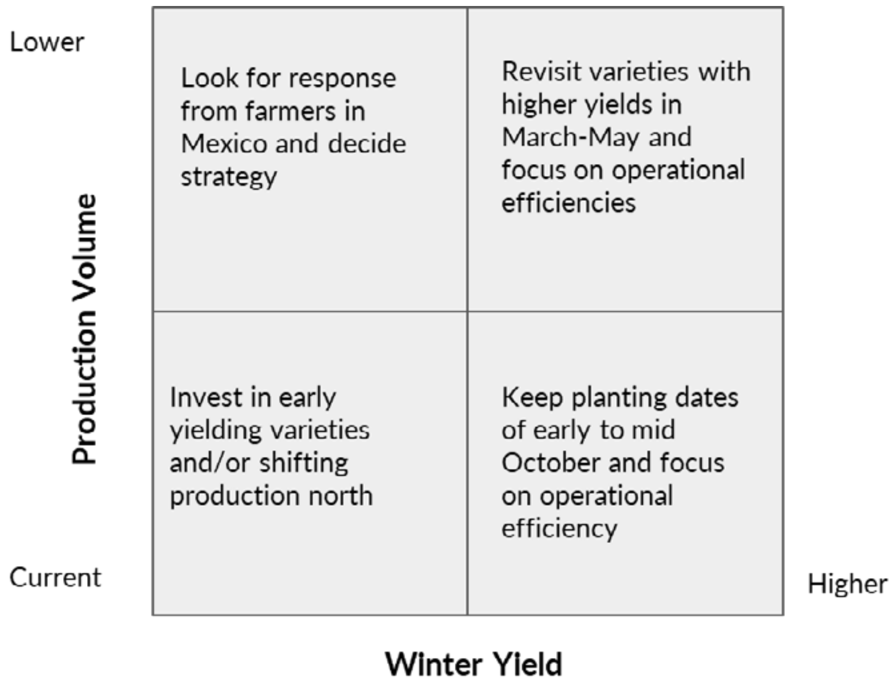

FIGURE 10.

Strategies for Florida Strawberry Growers for Four California Mid-Century Scenarios

12 Lobell DB and Field CB 2011 California Perennial Crops in a Changing Climate Climatic Change 109 317-333

13 Deschenes O and Kolstad C 2011 Economic impacts of climate change on California agriculture. Climatic Change 109, 365–386

14 Elias E, et al. 2015 Southwest Regional Climate Hub and California Subsidiary Hub Assessment of Climate Change Vulnerability and Adaptation and Mitigation Strategies, T. Anderson, Ed., United States Department of Agriculture, 76 pp

4. AGRONOMIC MODELS

It is difficult to develop statistical agronomic models for specialty crops due to the relative lack of production data from USDA and lack of concentrated interest. This is a key difference from agronomic modeling for row crops. Multiple harvests in a single growing season for certain fruits and vegetables also create the need for more data through the growing season.

Grain crops like corn, soybeans, and wheat have only one harvest per growing season and a long history of production data on a county basis from the US Department of Agriculture. Lack of production data explains why process-based agronomic models using the Decision Support System for Agrotechnology Transfer (DSSAT) platform seem to be popular among the researchers interviewed. Funding for specific specialty crops comes from regional and state governments or trade associations (e.g. Government of Campania in Italy for Tomatoes and Broccoli Growers Association of Scotland). Experimental data in controlled environments such as chambers with controlled CO2 and temperature levels is critical to develop understanding of growth biology and development of biophysical process based models. Temperature thresholds for failure vary significantly between speciality crops. For example:

- Strawberries: 30°C
- Tomatoes: 32°C
- Peanuts: 39°C

Literature Review & Expert Interviews

In order to understand the current state of agronomic models for specialty crops, we conducted an extensive literature review and interviewed a number of researchers. At a high level, the existence of the DSSAT platform and consortium for the last three decades has enabled a number of these models. See Appendix A for a summary of the literature review.

In addition to the literature review, we interviewed Prof. Gerrit Hoogenboom and graduate student Alwin Hopf. There are a number of studies that measure the impact of climate variables on strawberry yields. Research by Prof. Palencia shows a linear relationship between early yield and temperature up to 30°C,[15] the temperature at which the reproductive function of the plant becomes adversely affected. Past 30°C, yield begins to drop. Solar radiation has a similar impact on yield. Up to 20 MJ/m2 yield increases linearly with increasing solar radiation and then drops past 20 MJ/m2.

There are both statistical and process based agronomic models developed for strawberries. A study from University of Florida reported R-squared values >70% for models that targeted historical yield data with camera imagery and weather variables such as air temperature, humidity, wind speed, and solar radiation as predictors.[16] Alwin Hopf and Gerrit Hoogenboom have developed a process based model using the DSSAT CROPGRO platform using experimental data from multiple growing seasons and multiple Florida cultivars such as Brilliance and Sweet Sensation.[17]

15 Palencia P, Martinez F, Medina JJ, Medina JL 2013 Strawberry yield efficiency and its correlation with temperature and solar radiation. Horticultura Brasileira 31 93-99

16 Abd-Elrahman A, Wu F, Agehara S, and Britt K 2021 Improving Strawberry Yield Prediction by Integrating Ground-Based Canopy Images in Modeling Approaches. ISPRS International Journal of Geo-Information 10 239

17 Hopf A, et al. 2022 Development and improvement of the CROPGRO-Strawberry model Scientia Horticulturae 291 110538

Strawberry Yield Simulations

We explored future climate impacts on Florida strawberry production by running the DSSAT CROPGRO-Strawberry crop model under observed and projected climate conditions for Hillsborough County.[18] We favored the CROPGRO-Strawberry model over statistical approaches because of the paucity of county-level strawberry yield data in Florida. USDA NASS Quick Stats reports historical strawberry yield data for Florida at the state-average and annual-level only. We required monthly yield data for our economic analysis. Statistical methods trained on annual data could only reliably produce annual predictions. In contrast, CROPGRO-Strawberry provides continuous harvest data at daily timescales. This allowed us to develop monthly yield projections under historical and future climate conditions.

Simulated seasonal yields (5-year averages leading up to 2020 and 2050) driven by observed (gridMET) and projected (MACA) climate conditions for Hillsborough County, Florida are compared in Figure 11. The curves are kernel density estimates of yield predictions from CROPGRO-Strawberry driven by gridMET (black) and 20 MACA ensemble members (blue and orange for 2020 and 2050, respectively). They show a ~10% reduction in the ensemble-mean November-March yield between 2020 and 2050. The distribution appears to broaden by 2050 too, indicating that some models produce weather conditions resulting in >10% yield reduction.

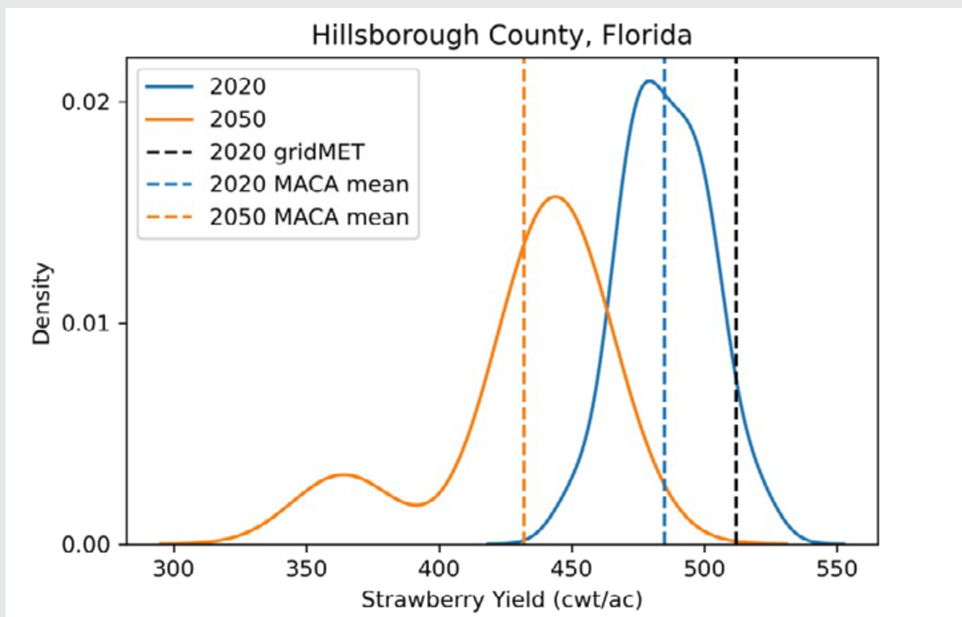

FIGURE 11.

DSSAT CROPGRO-Strawberry November-March yield predictions driven by Hillsborough County climate data from gridMET observations (2020, black dashed line) and MACA downscaled climate projections (2020, blue; 2050, orange). 2020 predictions based on a 5-year average of growing season simulations 2016-2020. 2050 predictions based on a 5-year average of growing season simulations 2046-2050. MACA 20 member ensemble -mean shown in dashed colored lines.

18 See Appendix C for methods and preliminary results.

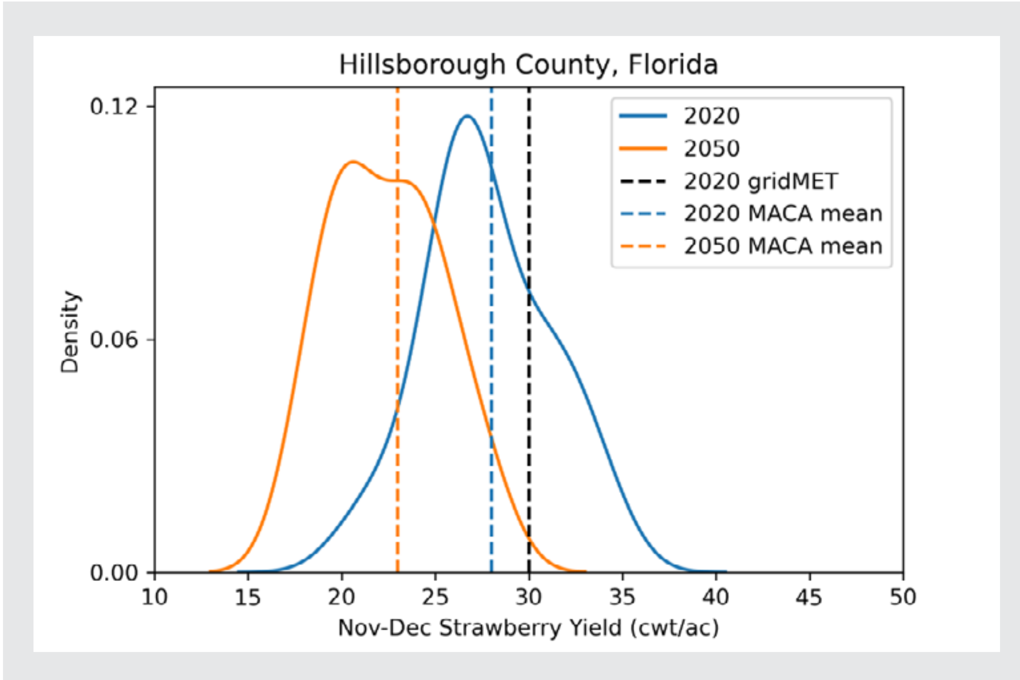

FIGURE 12.

As in Figure 11, but for November-December early yield predictions

Early yield (November-December) also declines between 2020 and 2050 in the CROPGRO-Strawberry simulations (Figure 12). Although the ensemble-mean reduction in terms of percent change is greater than seasonal yield (-17% for early yield versus -10% for seasonal yield), the multi-model distribution does not show the same broadening as total yield. In both cases, the simulations driven by climate observations (gridMET) produce yields that fall within the distributions produced from simulations driven by downscaled climate projections (MACA). Simulated changes in seasonal yield and early yield are summarized in Table 4.

TABLE 4

Ensemble-mean Hillsborough County, FL Brilliance strawberry yields for 2020 and 2050 (cwt/ac), simulated by DSSAT CROPGRO-Strawberry under daily weather from 20 downscaled CMIP5 climate simulations run under RCP4.5

Metric	2020	2050	Change	% Change
Seasonal Yield (Nov-Mar)	485	432	-53	-11%
Early Yield (Nov-Dec)	28	23	-5	-17%

Strawberry Profitability Analysis

We used University of Florida IFAS extension school's survey of production costs for Florida strawberry farmers- the latest version being from 2012-13. An updated version of this survey is slated to be completed by later this year. But in its absence we forward adjusted the production costs for inflation to 2020 and 2050. We used the US average baseline price of 2020 for each month and then adjusted it for inflation to 2050. Details of the production cost and inflation adjustment are in the Appendix.

Revenue is a function of monthly yields and price. We used monthly yield outputs for Brilliance, in Hillsborough County both for 2020 and mid-century that we ourselves came up with using the DSATT process based model. We calculated net income by subtracting costs from revenue. The outputs of the analysis expressed in 2020 USD are shown in Tables 5 and 6.

TABLE 5

Net income analysis for HIllsborough County, Brilliance, 2020

Month	Yield (cwt/ac)	Price ($/cwt)	Production Cost ($/cwt)	Net income ($/cwt)	Net income ($/ac)
November	1	301	161	140	196
December	26	247	161	86	2,262
January	98	245	161	84	8,269
February	167	207	161	46	7,693
March	192	143	161	(18)	(3,457)
Season Total					**$14,963**

TABLE 5

Net income analysis for Hillsborough County, Brilliance, 2050

Month	Yield (cwt/ac)	Price ($/cwt)	Production Cost ($/cwt)	Net income ($/cwt)	Net income ($/ac)
November	1	303	162	141	82
December	22	248	162	86	1,891
January	92	246	162	84	7,715
February	149	208	162	46	6,870
March	169	144	162	(18)	(3,091)
Season Total					**$13,466**

As is evident by comparing Tables 5 and 6, the climate change driven decrease in yield has a significant impact on net income in every month, about 10% totaled over the growing season by mid-century. The transition from a positive net income in February to a negative net income in March in the tables is also independently ascertained in our interviews with farmers and extension school experts who report that Florida farmers typically stop harvesting and terminating the strawberry plants after February 14th.

5. ADAPTATION TECHNOLOGY ANALYSIS

Through our interviews and secondary research, we identified five main technologies that can help Florida Strawberry farmers adapt to the climate change they are likely to experience by mid-century. The adaptation technologies fall into three broad categories (1) enabling heat tolerance (2) operation efficiency and (3) ecosystem interventions.

Enabling Heat Tolerance

New Hybrid Varieties

This set of technologies develops new Strawberry hybrids for better early yield, higher heat tolerance, and resistance to diseases such as Fusarium Wilt. Higher heat tolerance and better early yields may enable farmers to maintain current planting dates in the mid-century climate should the current monthly pricing trends continue.

Example Providers

1. **University of Florida:** Prof. Vince Whitaker has developed and assessed several new varieties, most notably Sweet Sensation that has better early yield performance than conventional varieties such as Brilliance.[19]

2. **University of California Davis:** Michael Hardigan and others have developed strawberry hybrids resistant to Fusarium Wilt. [20]

   Michigan State University: Prof. James Hancock and collaborators have developed a germplasm library of heat tolerant strawberry hybrids using cultivars from California, the Eastern US, and the Pacific Northwest.[23]

Shading technologies

This technology set consists of new materials and fabrics for shading Strawberries from extreme heat. Increased and better shading will reduce the heat exposure for strawberry plants and may help maintain fruit quality, yield, and reduce water needs.

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19 Whitaker VM and Fan Z 2020 What Will Florida Strawberry Varieties Look like in the Future? A Breeder's Perspective International Journal of Fruit Science 20 992-996
20 Dooley EC 2022 Researchers identify genes making strawberries resistant to fusarium wilt UC Davis https://www.ucdavis.edu/food/news/researchers-identify-genes-making-strawberries-resistant-fusarium-wilt
21 He JQ, Harrison RJ, and Li B 2017 A novel 3D imaging system for strawberry phenotyping Plant Methods 13 1-8
22 Barth E, et al. 2020 Selection of experimental hybrids of strawberry using multivariate analysis Agronomy 10, 598
23 Hancock JF, Edger PP, Callow PW, Herlache T, and Finn CE. 2018 Generating a unique germplasm base for the breeding of day-neutral strawberry cultivars HortScience 53 1069-71

Example Providers

1. **Universidade de Passo Fundo:** Prof. Costa and collaborators have studied the efficacy of various shading materials such as textiles, metal screens and polymeric screens on the yield for two Strawberry cultivars. [24]
2. **Universidad Nacional de Colombia:** Prof. Cordoba-Novoa and collaborators have studied the effect of shading on strawberry water needs. [25]

Operational Efficiency

Sustainable Cooling

Rising temperatures would raise the need for cooling the plants and fruits after harvest. These technologies use renewable energy, storage, and energy efficient cooling to reduce cooling costs and GHG emissions.

Example Providers

1. **Hirosaki University:** Prof. Shigeoki has developed a method for cooling strawberry plants using a geothermal heat pump. [26]

Harvesting Automation

Challenged profitability for strawberry farmers due to climate change will create an imperative for other operational efficiencies. Chief among them is managing labor for harvesting. Technologies for automation in harvesting will alleviate the high labor costs and shortage that strawberry farmers are experiencing. These technologies rely on 3D machine vision, artificial intelligence and robotics.

Ecosystem Interventions

Aquifer Recharging

Rising temperatures would increase evapotranspiration for strawberries, thereby water needs. All of the specialty crops in north-central Florida are irrigated due to surface water contamination issues, and have already led to overuse of the northern Florida aquifer leading to the fears of salt water intrusion. Aquifer recharging technologies can help build the groundwater storage over time as well as reduce salt water intrusion in the aquifers. Water for recharging can come from harvesting rainwater and/or recycled/reclaimed water.

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24 Costa RC, Calvete EO, Reginatto FH, Cecchetti D, Loss JT, Rambo A, and Tessaro F 2011 Shading screens in the production of strawberry in greenhouse Horticultura Brasileira 29 98-102
25 Cordoba-Novoa HA, et al. 2022 Shading Reduces Water Deficits in Strawberry (Fragaria X Ananassa) Plants during Vegetative Growth International Journal of Fruit Science 22 725-740
26 Shigeoki M, Hirotada N, Atsushi I 2017 Partial cooling of strawberry plants by water tube utilizing geo-thermal heat pump Journal of Applied Horticulture 19 186-190
27 Burnett C 2021 Solar Cold Rooms Help Struggling Strawberry Farmers through India's Lockdown

6. CONCLUSIONS

Fruits and vegetables dominate Florida agriculture. This sector generates $1.9 billion per year and 9 of the top 10 agricultural commodities in the state are fruits and vegetables. Hence assessing the impact of climate change on Florida agriculture requires us to focus on this sector. However there are significant differences between specialty crops and row crops. Specialty crops have a significantly higher value per acre than row crops, but the importance of individual specialty crops is less than the high volume row crops, making agronomic data gathering and funding difficult. As a result, process-based crop models are more popular among researchers of specialty crops such as Strawberries, Tomatoes, and Peanuts. For some specialty crops such as Melons and Peppers, no known agronomic models exist, although there is a wealth of experimental data on the impact of variables such as temperature, salinity and disease vectors.

Specifically for Strawberries, climate change induced temperature changes at both ends of the spectrum will take Hillsborough county out of the goldilocks zone for Strawberries by mid-century and make counties such as Marion county in the north-central region more attractive. Climate change will result in decreasing yields (11%) and net income per acre (10%) for Strawberry farmers in Hillsborough county. Early yield was simulated to decrease by 17%. However moving production to northern counties may present some barriers for smaller farmers e.g. access to skilled labor, transportation infrastructure, and planting equipment. Besides moving production north, a number of other adaptation options exist including new hybrids, shading, automation, sustainable cooling, and aquifer recharging

One big unknown in these decisions is how strawberry production in California will be impacted by climate change. Although the California analysis is beyond the scope of this study, we can envision scenarios where both overall production and winter yield are impacted. Given that uncertainty and the Florida strawberry sector's price taking position, Florida farmers should invest in piloting a broad swath of adaptation approaches so that they have strategic choices no matter which of the four scenarios for California Strawberry production becomes probable. In a future study, we could quantitatively analyze the impact of climate change on strawberry production in California and Mexico, two competing regions for Florida strawberry growers.

APPENDIX A: LITERATURE REVIEW & EXPERT INTERVIEWS

Tomatoes

We interviewed Prof. David Cammarano at Aarhus University and Prof. Kenneth Boote from University of Florida to understand agronomic modeling for tomatoes. Research on tomatoes is often funded by regional governments. For example, Prof. David Cammarano's research on tomatoes was funded by the Regional Development Council of Campania, a province in Italy. [28]

According to Prof. Boote, the ability to do controlled growth experiments is key. Funding from the state government of Florida in the early 2000s to build chambers that could control temperature and CO_2 levels was critical to the advancement of this research. One of the predominant models for tomatoes is a process-based model developed by Prof. Ken Boote using the DSSAT CROPGRO platform.[29] The major variables affecting yield include temperature, irrigation deficit (defined irrigation as % of evapotranspiration), CO_2 levels, and soil salinity. Temperature has the clearest impact on growth biology as evidenced by the impact on leaf area, plant height, and number of fruits per plant. Yield rises with temperature up to 30°C and then it drops precipitously. The failing degree threshold for Tomatoes is 32°C. The impact of irrigation deficit is more straightforward with yield reducing with the extent of deficit.[30]

Peanuts

We interviewed Prof. Guillermo Baigorria from University of Nebraska, Lincoln and Prof. Kenneth Boote from University of Florida. Research on Peanuts is funded by international multilateral organizations such as International Food Policy Research Institute.

Process based agronomic model development is contingent upon good controlled experiments. Research from Prof. Boote describes the effect of temperature and CO_2 levels on yields for Peanuts and Soybeans.[31] In addition, research from Dr. Ruane, Dr. Cynthia Rosenzweig, and Dr. Baigorria[32] and Prof. Moctar Camara[33] describes the usage of climate simulations to model impact on Peanut yields under RCP4.5 and RCP8.5 emissions scenarios. Not surprisingly, the higher emissions scenario shows lower yields in these

28 Cammarano D, et al. 2020 Impact of climate change on water and nitrogen use efficiencies of processing tomato cultivated in Italy Agricultural Water Management 241 106336
29 Boote KJ, Rybak MR, Scholberg JM, and Jones JW 2012 Improving the CROPGRO-tomato model for predicting growth and yield response to temperature. HortScience 47 1038-1049
30 Sarker M, Choudhury S, Islam N, Zeb T, Zeb B, and Mahmood Q 2020 The effects of climatic change mediated water stress on growth and yield of tomato Cent. Asian J. Environ. Sci. Technol. Innov. 1 85-92
31 Boote KJ, Prasad V, Allen Jr LH, Singh P, and Jones JW 2018 Modeling sensitivity of grain yield to elevated temperature in the DSSAT crop models for peanut, soybean, dry bean, chickpea, sorghum, and millet European Journal of Agronomy 100 99-109
32 Ruane AC, et al. 2014 Carbon–Temperature–Water change analysis for peanut production under climate change: a prototype for the AgMIP Coordinated Climate Crop Modeling Project (C3MIP). Global change biology 20 394-407
33 Sarr AB, and Camara M 2018 Simulation of the impact of climate change on peanut yield in Senegal International Journal of Physical Sciences 13 79-89

simulations. One of the predominant models for Peanuts is a process-based model developed by Prof. Ken Boote using the DSSAT Cropgro platform. The major variables affecting yield include temperature, precipitation, and CO_2 concentration. Temperature has the clearest impact on growth biology. Yield rises with temperature up to 39°C and then drops precipitously. Thus Peanuts are the most heat tolerant of specialty crops being grown in Florida today.

Melons

We interviewed Prof. Stewart Walters at Southern Illinois University, and Prof. Kevin Athlearn, at University of Florida in addition to the literature review. Professor Walters has studied the impact of heat stress and Fusarium Wilt disease on melons and watermelon varieties in Morocco.[34] Summertime growing conditions were used for the experiments to subject the crops to temperatures as high as 48°C and varieties with least yield sensitivity were identified. Prof. Anthony Keinath at Clemson University has studied the impact of Fusarium wilt disease on watermelon yield.[35] The timing of this disease in a future climate may interfere with the current planting and harvesting times of Florida melon farmers. Prof. Kevin Athlearn at University of Florida has used Monte Carlo simulations to study these future decisions for Florida melon farmers.[36] Although the above papers are illustrative of experimental work in developing the relationship between melon yield, heat stress and disease pressure, no researcher to our knowledge has developed a process based or statistical yield model for watermelons.

Peppers

We interviewed Prof. Bilal Cemek at Akdeniz University (Turkey) and Dr. Sandipan Sammadar at University of California Davis in addition to the literature review. Prof. Cemek has developed relationships between bell pepper yield and salinity through experiments.[37] Bell peppers are sensitive to soil salinity and yield reduces with increasing salinity. To quote from a paper by Dr. Samaddar,[38] "red bell peppers can't regulate the uptake of sodium ions efficiently, paralyzing biological processes thereby reducing biomass." Irrigation is one way to dilute the salinity and higher irrigation can offset salinity. Dr. Rameshwaran at the Center for Ecology and Hydrology in Oxfordshire, U.K. has studied the combined effect of various levels of drip irrigation and salinity on yield for bell peppers.[39]

Although the above two papers are illustrative of experimental work in developing the relationship between bell pepper yield, salinity and irrigation; no researcher to our knowledge has developed a yield model for soil grown bell peppers. However, a DSSAT CropGro model has been developed for hydroponically grown bell peppers by Prof. Joon Woo-Lee at Jeonju University, Korea.[40]

34 Walters SA, Abdelaziz M, and Bouharroud R. 2021 Local melon and watermelon crop populations to moderate yield responses to climate change in North Africa Climate 9 129
35 Keinath AP, et al. 2019 Cucurbit rootstocks resistant to Fusarium oxysporum f. sp. niveum remain resistant when coinfected by Meloidogyne incognita in the field Plant disease 103 1383-1390
36 Athearn K, et al. 2022 Watermelon Planting Decisions with Multiple Risks: A Simulation Analysis. HortTechnology 32 377-381
37 Kurunc A, Unlukara A, and Cemek B 2011 Salinity and drought affect yield response of bell pepper similarly. Acta Agriculturae Scandinavica, Section B-Soil & Plant Science 61 514-522
38 Samaddar S, et al. 2019 Interactions between Pseudomonas spp. and their role in improving the red pepper plant growth under salinity stress. Microbiological research 219 66-73
39 Rameshwaran P, Tepe A, Yazar A, and Ragab R 2016 Effects of drip-irrigation regimes with saline water on pepper productivity and soil salinity under greenhouse conditions Scientia horticulturae 199 114-123
40 Lee JW, Moon T, and Son JE 2021 Development of growth estimation algorithms for hydroponic bell peppers using recurrent neural networks Horticulturae 7 284

APPENDIX B: CLIMATE ANALYSIS

Historical Climate Data

This study uses historical climate data from the gridMET dataset. gridMET is a dataset of daily high-spatial resolution (~4-km, 1/24th degree) surface meteorological data covering the contiguous US from 1979 through present day.[41] To achieve high spatial resolution gridMET superimposes interpolated daily departures of monthly averages from NLDAS-2 (reanalysis) over monthly data from the PRISM dataset.

Future Climate Projections

The Multivariate Adapted Constructed Analogs (MACA) dataset was used for future climate projections.[42] MACA uses daily data from global climate models (GCMs) and historical observations. GCMs produce data at high spatial scales that do not allow a county by county analysis. MACA downscales the data using a statistical method. These statistical methods contrast with so-called dynamical methods, which rely on regional climate models nested in a global climate model. Dynamical downscaling suffers from biases introduced by the driving GCM and computational intensity. Statistical downscaling is comparatively computationally efficient, yet itself has limitations associated with the assumption of stationarity and questionable fidelity to some first principles of meteorology. The MACA data set consists of output from 20 Global Climate Models (GCM) produced by 13 climate research centers.

While a large ensemble increases computation costs it is key for understanding the differences between internal variability (noise) and changes emerging due to anthropogenic global warming (signal). This is particularly important for the climate scenario we chose, RCP4.5, which has lower emissions than the higher warming scenario RCP8.5 and consequently a lower signal to noise. With the deceleration of emissions growth in recent years and advances in non-fossil energy sources RCP8.5 is now viewed as a 'worst case' scenario rather than 'business as usual.'[43] For this reason we find RCP4.5 to be a more useful scenario to study future changes.

41 Abatzoglou JT 2013 Development of gridded surface meteorological data for ecological applications and modelling Int. J. Climatol. 33 121–131 https://doi.org/10.1002/joc.3413
42 Abatzoglou JT, and Brown TJ 2012 A comparison of statistical downscaling methods suited for wildfire applications Int. J. Climatol. 32 772–780 https://doi.org/10.1002/joc.2312
43 Hausfather Z 2019 The high-emissions 'RCP8.5' global warming scenario Carbon Brief https://www.carbonbrief.org/explainer-the-high-emissions-rcp8-5-global-warming-scenario/

Localization

Rather than average climate data over the entire area of each county, we implemented a weighted average using historical crop growing area. In other words, we produced a county-average by up weighting the areas with more intensive crop growing and down weighting the areas with little or no crop growing, like urban areas and inland waters (e.g. lakes, rivers). This is arguably better than averaging all of the gridded data for a county together, particularly for large counties with mixed land-use or a large fraction of inland waters.

The weighting scheme is implemented as follows. First we developed historical strawberry growing baselines for each use case. These were determined from USDA CropScape maps with 30 meter resolution.[44] For each 30 meter grid cell in the state, we determined the strawberry frequency 2012 to 2021. Then we computed the fraction of each 4 kilometer climate data grid cell with any strawberry cultivation 2012 to 2021 (crop frequency>0). Then for each county, grid cell weights were computed by dividing each grid cell's strawberry area fraction by the sum of the strawberry area fractions within the county. Finally, strawberry area-weighted county climate data were formed for each climate variable with the gridded climate data and gridded strawberry area weights.

Climate Variables

gridMET and MACA provide daily 4 km resolution for a variety of climate variables. We downloaded and localized maximum temperature, minimum temperature, precipitation, relative humidity, vapor pressure deficit, downward shortwave radiation, and wind speed.

For the climate statistics we chose a historic period of 1981-2020, a span that captures a generation of farmer experience with the modern climate. For the future mid-century period we chose 2041-2060, a standard IPCC definition for studying medium-term climate change.[45]

44 USDA 2023 CropScape https://nassgeodata.gmu.edu/CropScape/

45 IPCC 2021 Summary for Policymakers. In: Climate Change 2021: The Physical Science Basis. [Masson-Delmotte, V et al. (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp. 3−32

Manatee County Analysis

Manatee County climate and climate changes are detailed below in Table A1.

TABLE A1

Manatee County historical (gridMET) and mid-century change (MACA)

Strawberry Growing Season (October - April)	Historical average gridMET	Mid-century change MACA	Mid-century % change MACA
Total precipitation	**45.2cm**	**+2.59cm**	**+5.6%**
Daily maximum temperature	26.0°C	+1.0°C	+4.0%
Daily minimum temperature	13.4°C	+1.1°C	+8.0%
Daily average specific humidity	0.0104 kg/kg	+0.00067 kg/kg	+6.4%
Daily average vapor pressure deficit	0.837 kPa	+0.0647 kPa	+7.3%
Daily average wind speed	4.11 m/s	-0.03 m/s	-0.62%
Daily average downwelling solar radiation at the surface	193 W/m2	+2.3W/m2	+1.2%

APPENDIX C: AGRONOMIC MODELING

This study performed agronomic modeling to inform an economic analysis of climate change impacts on Florida strawberry production. Due to the seasonal variation in strawberry prices, the study team determined that the economic analysis would be more robust if monthly yield predictions were available. Previous studies investigated climate impacts on US strawberry production using statistical models that targeted early yield or total growing season yield.[46, 47] Lobell and Field had the benefit of county-level California strawberry annual yield data. In the case of Florida, however, historical strawberry annual yield data is only available at the state-level. This necessitated a different approach. Fortunately, a process-based crop model tailored to strawberries recently became available from the Decision Support System for Agrotechnology Transfer (DSSAT) software application.

The study team collaborated with the DSSAT CROPGRO-Strawberry model developers, including Alwin Hopf and Gerrit Hoogenboom from the University of Florida.[48] The model was made available to the study team in DSSAT version 4.7.6. Like other DSSAT mechanistic crop models, CROPGRO-Strawberry features a daily time step driven by weather, soil, plant, irrigation, and fertilizer parameters. We followed Hopf et al. (2022), running the model one season at a time using weather parameters from Hillsborough County strawberry growing areas, a standard soil profile from the Candler series, planting 4.3 strawberry transplants per square meter on October 10, harvesting every 3-4 days from November through March, irrigating as needed to provide 80% available soil water, and no fertilization-related modules to simulate optimal fertilizer.

Figures A1 and A2 compare two years of strawberry harvests from the DSSAT CROPGRO-Strawberry model: 2000-01 and 2014-15. Figure A1 highlights differences in the amount of daily yield over the course of the growing season, and Figure A2 highlights how those differences result in different cumulative yield profiles. Florida strawberry harvests begin 45 to 75 days after planting, ramp up slowly in December and January before peaking in February.

Hopf et al. (2022) undertook model development, improvement, and validation using field trial data conducted at the Gulf Coast Research and Education Center in west-central Florida. Experimental data for three cultivars were used: Florida Radiance,[49] Florida Sensation,[50] and Florida Brilliance.[51] This enabled the researchers to include all 3 in DSSAT CROPGRO-Strawberry.

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46 Palencia P, Martínez F, Medina JJ, Vázquez E, Flores F, and López-Medina J 2008 Effects of climate change on Strawberry Production Workshop on Berry Production in Changing Climate Conditions and Cultivation Systems. COST-Action 863: Euroberry Research: from 838

47 Lobell DB, and Field CB 2009 California Perennial Crops in a Changing Climate Climatic Change 109

48 Hopf A, et al. 2022 Development and Improvement of the CROPGRO-Strawberry Model Scientia Horticulturae 291

49 Chandler CK, Santos BM, Peres NA, Jouquand C, Plotto A, and Sims CA. 2009 'Florida radiance' strawberry HortScience 44, 1769-70

50 Whitaker VM, Chandler CK, Peres N, do Nascimento Nunes MC, Plotto A, and Sims CA 2015 Sensation™ 'Florida127' strawberry HortScience 50 1088-91

51 Whitaker VM, Peres NA, Osorio LF, Fan Z, do Nascimento Nunes MC, Plotto A, Sims CA. 'Florida Brilliance' Strawberry 2019 HortScience 54 2073-2077

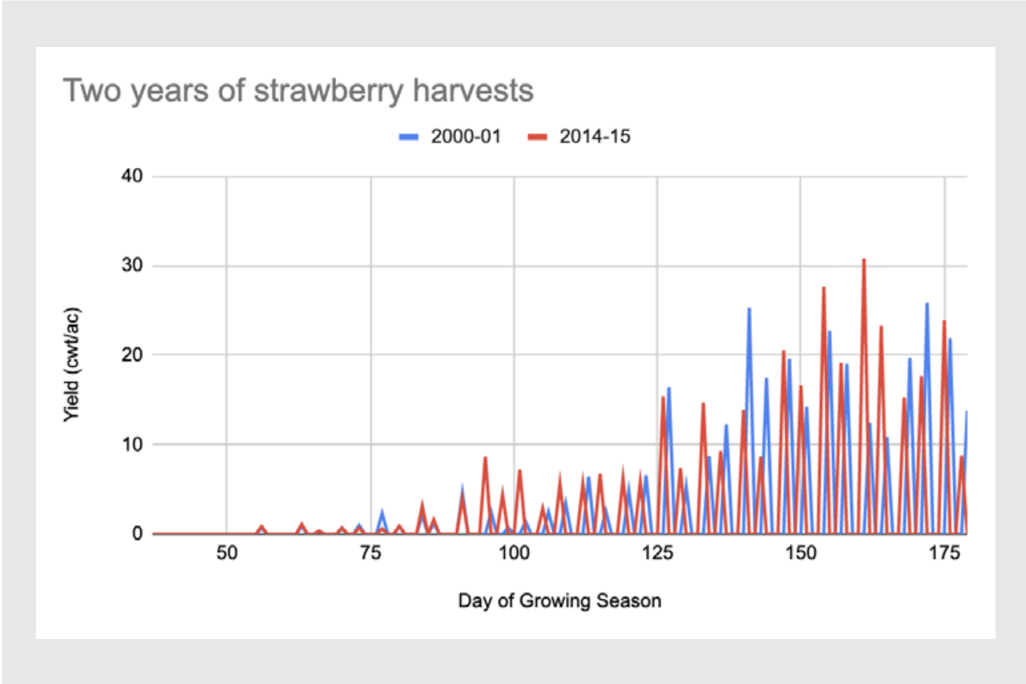

FIGURE A1.

Two years of strawberry harvests (2000-01, 2014-15) compared in terms of daily yield with havests every 3-4 days after planting on October 10

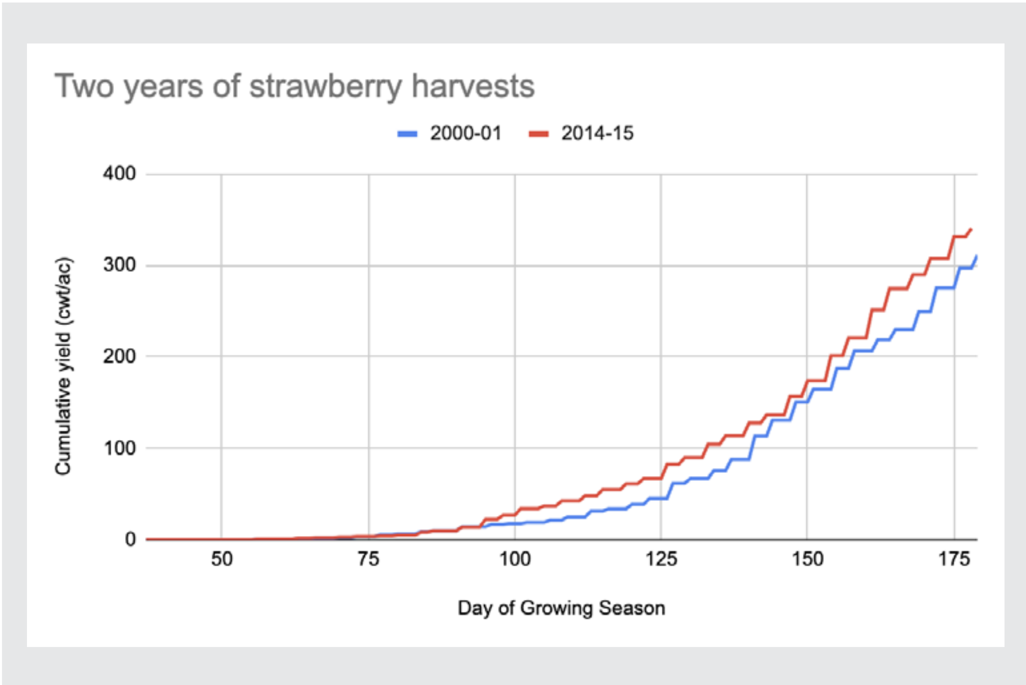

FIGURE A2.

As in Figure A1, but for cumulative yield over the course of the growing season

Monthly and growing-season total strawberry cultivar yields from DSSAT simulations driven by gridMET daily weather data are shown in Table A2. The results show higher yields for the more recently developed cultivars, particularly the improvement in early yield for Brilliance. Although Hopf et al. (2022) discuss a number of further improvements that could be made to the model, the preliminary results shown in Table A2 are supportive of the broader set of simulations we summarize in the main text. Additional research is warranted as the DSSAT CROPGRO-Strawberry model undergoes further improvement.

TABLE 5

Net Income analysis for Hillsborough County, Brilliance, 2050

Cultivar	November	December	January	February	March	Total
Brilliance	1	29	111	180	191	512
Sensation	1	15	74	160	180	430
Radiance	1	18	72	154	158	403

APPENDIX D: ECONOMIC ANALYSIS

We used University of Florida IFAS extension school's survey of production costs for Florida strawberry farmers released in 2008/09, 2010/11, and 2012/13. An example of the cost breakdown per acre can be seen in Figure A3. Although the survey reports only annualized costs and doesn't report month-to-month variations, it does differentiate between the types of production costs that scale with yield e.g. fertilizer costs and types of production costs that don't scale with yield e.g. land and planting equipment costs. An updated version of this survey is slated to be completed by later this year. But in order to project these costs from 2012/13 to 2021/22 and to mid-century, we used an interest rate of 3% per year for all non-cooling costs; to be in line with the % increases in that 2008/09 to 2021/22. We adjusted cooling costs upwards at a rate of 4% CAGR.

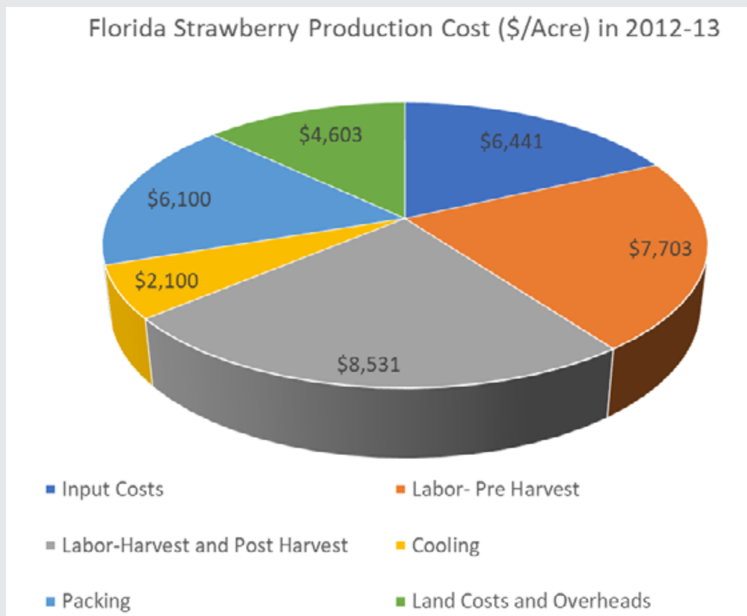

FIGURE A3.

Florida Strawberry Production Cost in 2012-2013, reproduced from Guan et al.[52]

Revenue is a function of monthly yields and price. We used the US average baseline price of 2020 for each month and then adjusted it for inflation at 3% CAGR to mid-century. We used monthly yield outputs for Brilliance, both for 2020 and mid-century that we ourselves came up with using the DSSAT process based model. We calculated net income in $/cwt by subtracting costs from revenue. Then using yield in cwt/acre we calculated Net Income in $/acre.

52 Guan Z, Wu F, and Whidden A 2020 Florida Production Costs and Trends, Univ. of Florida IFAS Publication #FE1013

List of Interviews

We interviewed the following individuals to inform our methodology and compliment our quantitative analysis.

TABLE 5

Net Income analysis for Hillsborough County, Brilliance, 2050

Name	Organization	Relevant Crop
Mr. Nick Wishnatzki	Wish Farms	Strawberries
Mr. Kenneth Parker	Florida Strawberry Growers Association	Strawberries
Dr. Wael Elwakil	University of Florida IFAS Extension	Strawberries
Dr. Gerritt Hoogenboom	University of Florida	Strawberries, Tomatoes
Mr. Alwin Hopf	University of Florida	Strawberries
Dr. Kenneth Boote	University of Florida	Tomatoes, Peanuts, Soybeans
Dr. Davide Cammarano	Aarhus University (Denmark)	Tomatoes, Broccoli
Dr. Bilal Cemek	Akdeniz University (Turkey)	Bell Peppers
Dr. Sandipan Samaddar	University of California	Bell Peppers
Dr. Stewart Walters	Southern Illinois University	Melons
Dr. Kevin Athlearn	University of Florida	Melons