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Structural changes in Florida citrus production, 1980-2021 and associated consequences of weather events and diseases.

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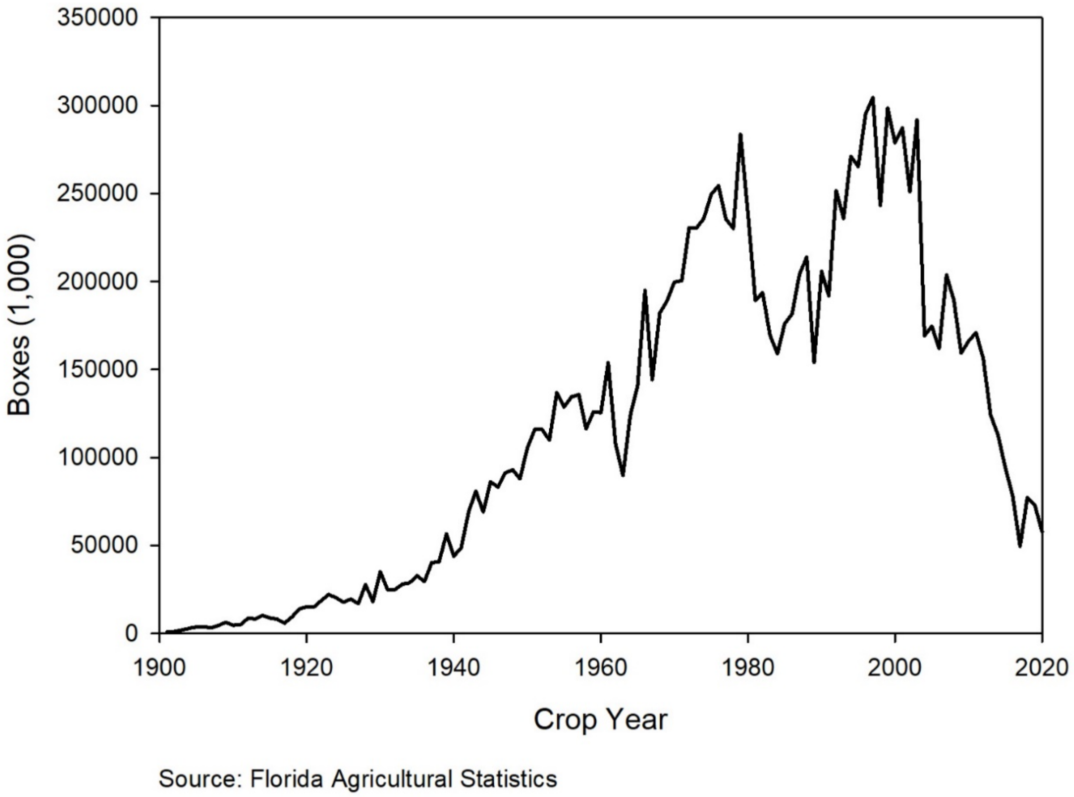
Abstract

Florida citrus production from 1980-2021 was examined and modeled to determine the impacts associated with weather events and disease introductions. Specifically, the study examined the effects of North Atlantic hurricanes, freezes and two disease introductions -- Asiatic citrus canker (ACC), and Huanglongbing (HLB) -- on productions levels and structure of the Florida citrus industry. Citrus production (i.e., yield) was examined to determine if weather and disease have significantly altered production within the Florida citrus industry leading to shifts or changes to the underlying industry structure. The models estimated the quantified effects on production associated with weather events and disease introductions. Three different regression models were utilized to quantify the impacts of weather and disease on the Florida citrus industry. A time series based model outperformed the other model estimates. Using this deterministic model, forecasts were generated to identify future implications of HLB on Florida citrus production. These generated forecasts were compared to actual production levels and the USDA Crop Forecast to test and validate the model. Whereas testing indicated a significant structural change in the Florida citrus industry resulting from adverse weather events and disease introductions, published economic impact studies were examined and reviewed to gauge the resulting reduction in total economic impact that has occurred within the Florida citrus industry since the peak in production during the 1997 crop year.

Keywords: Florida citrus production, freezes, hurricanes, Asiatic citrus canker (ACC), Huanglongbing (HLB), structural change, time-series model

Introduction

Citrus production in Florida has experienced a number of different phases, from rapid and vast expansion of acreage and production to huge losses and reductions in acreage and production due to weather and disease. Of the weather events that have impacted Florida citrus production, none have had a greater and more pronounced effect than prolonged freezing temperatures and hurricanes (USDA-NASS 2020); Tucker et al. 2006). Droughts and flooding have impacted citrus production within Florida, contributing to year to year variation (USDA-NASS 2020; Tucker et al. 2006). Insects, pests, disease, and disease eradication efforts have caused variability in Florida citrus production, and have significantly impacted the structure of the citrus industry (USDA-NASS 2020; Tucker et al. 2006). Figure 1 illustrates the variability and change in total Florida citrus production since 1900 due to these collective impacts (USDA-NASS 2020).



Source: Florida Agricultural Statistics

Fig. 1. Florida total citrus production, 1901-2020.

The period illustrated shows long term expansion and growth of the Florida citrus industry from 1900 to the early 2000s. After this period, significant decreases and consolidation have occurred within the Florida industry. This is the time period of interest and will be the focus of our current examination into the structural shifts and changes impacting the industry.

Since 1981, the Florida citrus industry has experienced multiple events that have significantly impacted production levels. The scope of this study was to identify and quantify those events. The areas of interest include weather and disease.

Freeze events and freezing weather have led to significant reductions in production and long-term impacts on Florida citrus production. The Florida Climate Center at Florida State University (Center) identified 12 significant freeze events in Florida since December 1894 (Table 1), of which six occurred during the time period of interest (FSU-FCC 2021). These freeze events led to significant reductions in citrus production both during the year of the freeze, and beyond when significant tree damage occurred from extended periods of freezing temperatures. In addition to the loss of production during the freeze events, these events have had additional impacts and changes on the structure and scope of the Florida citrus industry. As orchards or plantings were damaged and/or lost due to cold weather, new and replacement plantings were transitioned to regions further south within the state of Florida, thus leading to a southern migration of the citrus industry in an attempt to lessen the impacts of future significant freeze events. This trend and southward shift in citrus acreage is illustrated and documented in county citrus acreage reported by Florida Agricultural Statistics (USDA-NASS 2020).

Table 1. Significant Florida Freezes, 1894-1997

Freeze Event	Tallahassee	Avon Park	Fort Myers
December 1894	15°F	24°F	28°F
February 1899	-2°F	N/A	N/A
December 1934	20°F	21°F	29°F
January 1940	15°F	26°F	29°F
December 1962	20°F	24°F	28°F
January 1977	16°F	21°F	30°F
January 1981	8°F	18°F	28°F
January 1982	14°F	19°F	29°F
December 1983	14°F	23°F	33°F
January 1985	6°F	21°F	30°F
December 1989	13°F	20°F	27°F
January 1997	18°F	24°F	N/A

Source Florida Climate Center

The Atlantic hurricane season encompasses the annual time period from June 1 through December 1 as reported by the national Oceanic and Atmospheric Administration (NOAA-NWS 2020). The hurricane season coincides with key time periods within the yearly Florida citrus production cycle, mainly key growth and development periods for all classes of citrus, and harvest periods for early and mid-season fruit (USDA-NASS 2020). Hurricanes are of particular interest due to the damage that they can inflict to both current and future productive capacity. This damage encompasses loss of current fruit and foliage and/or tree damage collectively reducing future productivity. Potential damage associated with hurricanes includes a range of injuries extending from fruit and foliar vegetation losses to complete destruction and loss of trees and entire orchards (Table 2).

Table 2. Saffir-Simpson hurricane ratings and potential storm damage/losses

Hurricane category, Saffir-Simpson rating	Wind (MPH)	Expected potential damage and losses
1	74–95	Some loss of leaves and fruit, heaviest in exposed areas
2	96–110	Considerable loss of leaves and fruit with some trees blown over
3	111–130	Heavy loss of foliage and fruit, many trees blown over
4	131–155	Trees stripped of all foliage and fruit, many trees blown over and away from property
5	over 155	Damage almost indescribable, orchards completely destroyed

Source: Florida Department of Citrus

In addition to freeze events, hurricanes making landfall in Florida commercial citrus production areas were also examined to quantify the average damage associated with tropical systems making landfall in Florida. NOAA reported 112 hurricanes making landfall in Florida since 1842. These hurricane tracks are shown in Figure 2. During the period of interest, 1980-2021, there were five years that produced Atlantic hurricanes (Category 1 through 5) with storms tracks travelling through citrus production regions in the state of Florida. The storms of interest are listed in Table 3.

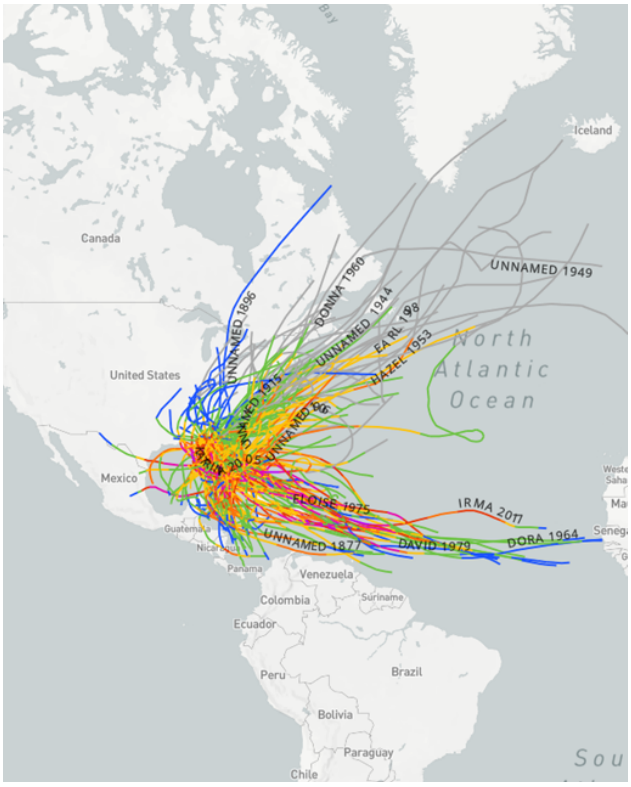


Fig. 2. North Atlantic hurricanes making landfall in Florida, 1842-2020.

Table 3. Florida North Atlantic hurricanes of interest, 1980-2017

Year	Storm Name	Month	Hurricane category, Saffir-Simpson rating at landfall
1995	Erin	August	1
1999	Irene	October	1
2004	Charlie	August	4
	Francis	September	2
	Jeanne	September	3
2005	Wilma	October	3
2017	Irma	September	3

Source: NOAA

In addition to weather events significantly impacting citrus production in Florida, disease outbreaks have also been detrimental to the Florida citrus industry during the time period of interest. Two major disease introductions/outbreaks have occurred since 1980, these being Asiatic citrus canker (ACC) caused by *Xanthomonas citri pv. citri* (Xcc), and Huanglongbing (HLB) presumptively caused by *Candidatus* Liberibacter asiaticus (CLas). Outbreaks of ACC are not uncommon in Florida. The first reported outbreak of ACC in Florida occurred in 1910 and was declared to be eradicated in 1933 the Florida Department of Agriculture and Consumer Services (FDACS 2020). A subsequent outbreak was discovered in 1986 in Manatee County, Florida. This outbreak was deemed to be eradicated in 1994. The last outbreak of note was discovered in 1995 in Miami-Dade County. During this final outbreak, initial and subsequent eradication efforts were primarily targeted in residential citrus in southern counties – Miami-Dade, Broward, Palm Beach, Collier and Lee. The citrus canker eradication program was curtailed due to litigation and a concern that citrus canker was becoming endemic due to vast spread events associated with tropical weather systems (Gottwald et al. 2002; Schubert et al. 2001). This outbreak spread to 24 counties before 2006 when the USDA ceased funding for tree removal when the pathogen was deemed to have become endemic, essentially ending the eradication program for ACC. The focus shifted from eradication to management. The impetus for the shift in program goals was due to the hurricanes in 2004-5 that dispersed the pathogen across large swaths of the Florida commercial citrus production region (FDACS 2020; Gottwald and Irey 2007; Irey et al. 2006).

The initial discovery of HLB in Florida occurred in 2005 in residential citrus in South Florida (Gottwald 2010) just prior to the end of the ACC eradication program. Following confirmation of its presence, extensive pest surveys were conducted in southern Florida to determine the extent of spread of the disease by the Animal and Plant Health Inspection

Service (APHIS). This was imperative as the vector of CLas, the Asiatic citrus psyllid had been discovered in Florida in 1998 (Hall et al. 2013). Given the combined introductions of the disease and its vector combined with highly compatible climate for both, HLB rapidly spread throughout Florida and Florida's major citrus producing regions (Gottwald 2010).

Examining Florida citrus production trends from 1980, illustrates the variability in production that has occurred during the period of interest, as illustrated in Figure 3. A cursory examination of the variability in production appears to indicate areas with distinct and significant regions with short- and long-term trends. The purpose of this study was to examine Florida production, specifically those trends present from 1980 and determine if weather events and disease contributed to structural changes within the industry, and if so, quantitate their associated impacts.

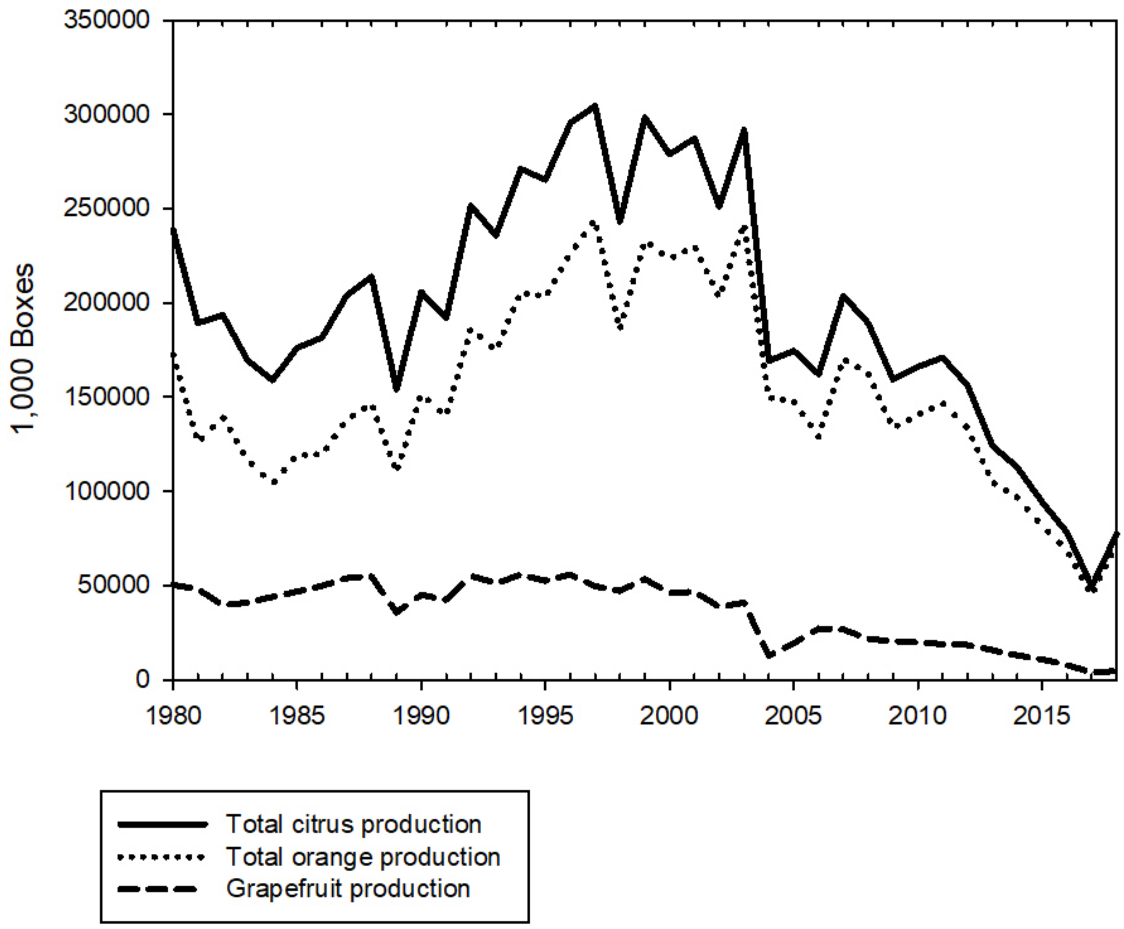


Fig. 3. Florida total citrus, orange and grapefruit production, 1980-2018.

Material and Methods

Three classes of citrus production were examined in this study – total citrus, total oranges, and total grapefruit. The two major classes, oranges and grapefruit, cover the majority (> 90%) of Florida citrus production. These classes were overlaid with weather and disease events of interest as portrayed graphically in Figure 4.

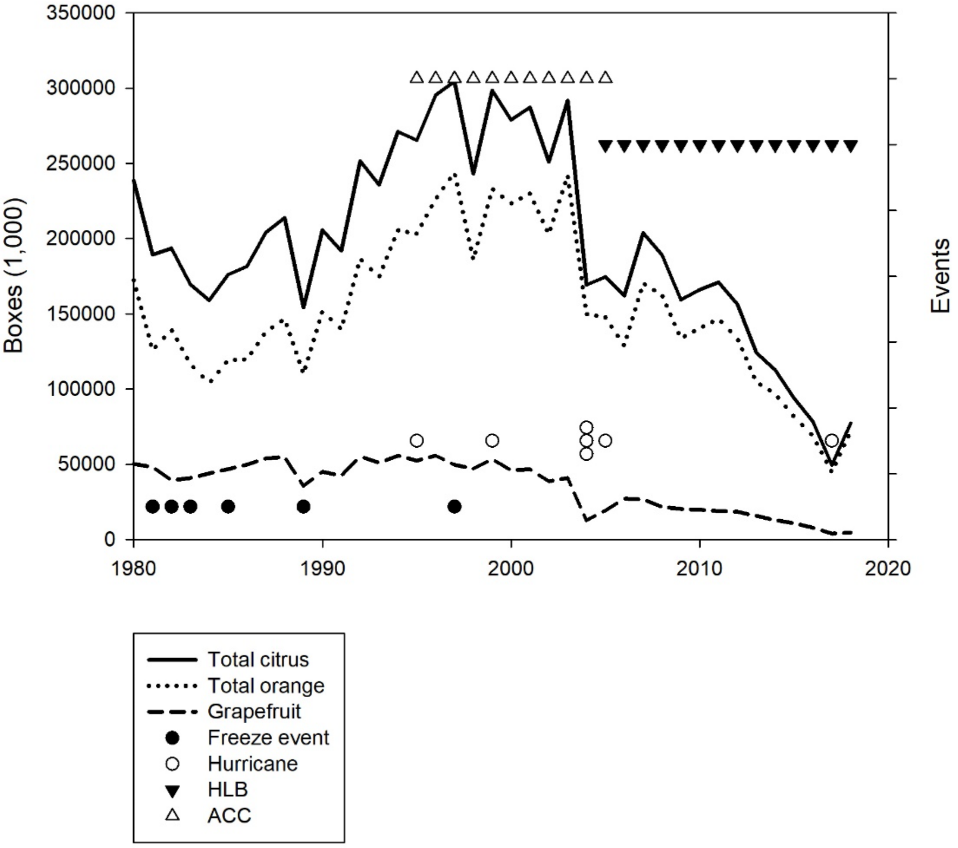


Fig. 4. Florida total citrus, orange, and grapefruit production, weather events and disease introductions, 1980-2018.

Prior to addressing the root causes for structural changes in the Florida citrus industry, first it was determined if any such changes have occurred. Such structural changes within the industry were tested for empirically. Specifically, a regression was performed on the entire data set and results compared to regressions of the subsets of the data (Green 2012; Gujarati 2003). The Chow test was used to examine the differences in the regression output to test the null hypothesis that the regressions for the subsets were the same as the regression for the entire data set. Differences in regressions for the data subsets would indicate that structural changes or differences in the data exist.

$$Yi = \alpha i + \beta i\, Xi + ui;\ For\ i = 1\ to\ N\,, \tag{Eq. 1}$$

Where Yi is the annual production, Xi is the bearing acreage, ui is the error term, and αi and βi are the parameter estimates. Parameter estimates were obtained for each class of citrus -- total citrus production, orange production, and grapefruit production. The equation was estimated for the entire pooled data set, and for each abbreviated data set. The abbreviated data sets were for the time periods where it was believed that structural changes had occurred. In this study, the time period breaks at 2005, the period where HLB was first discovered were used to create two additional data sets D_1 and D_2.

The Chow test was expressed as:

$$F = \frac{RSSpooled-(RSSD1+RSSD2)/K}{(RSSD1+RSSD2)/\ (N1+N2-2K)} - \text{with df=k, N1+N2-2k,} \qquad \text{(Eq. 2)}$$

Where RSS is the regression sum of squares, k is the number of parameters, Ni is the number of observations in the i^{th} group. The F-test was used to test the null hypothesis that the regressions were the same. The alternative being that the regressions were different, thus indicating structural differences, i.e. changes between the two time periods represented by the two data sets.

The Chow test was applied to determine if there had been a shift in the underlying structure of the Florida citrus industry based on examining production trends. Furthermore, three basic models were estimated to test for any changes in the structure of the industry, and to determine the underlying cause(s) and effect(s) if they were shown to exist.

The models estimated examined citrus production as a function of weather events and disease prevalence -- explicitly, $Y = F(Bearing\ Acreage, Freeze\ Events, Hurricanes, ACC, HLB)$. A three step process was applied to examine the structural changes and the underlying cause(s):

1) Identify significance and impact of weather and disease,
2) Incorporate linear time series component examining HLB disease prevalence, and
3) Incorporate a curvilinear time series component to examine HLB disease progress.

These models were estimated for total citrus production, total orange production, and grapefruit production.

This regression analysis was used to identify and quantify the effects of freeze events, hurricanes and disease epidemics on the Florida citrus industry. For the regression analyses, the binary variable was equal to one (1) for years in which either a weather event occurred or disease was prevalent, and zero (0) otherwise. Binary variables were utilized to determine the magnitude and significance of weather and disease. The model estimated was:

$$Yi = a + \beta 1\ Bearing\ Acreage + \beta 2\ Freeze\ Event + \beta 3\ Hurricane + \beta 4\ HLB + \beta 5\ ACC + \varepsilon i\ . \qquad \text{(Eq. 3)}$$

Where *Bearing Acreage* was the yearly total bearing acreage for each class of citrus in the regression analysis. And the remaining variables were binary variables used to denote weather or disease events. The equation was estimated for each of the respective classes of citrus: total citrus, total orange, and total grapefruit.

Examination of Figure 3 revealed both short-term variations and long-term trends in production within the Florida citrus industry. To model these changes, a time series component was added to the model to identify and quantify the long-term trends in production. Our hypothesis was that HLB has significantly altered the structure of the Florida citrus industry and led to long term shifts in production since 2005, the first report of HLB in Florida. The time series component was used to identify and quantify the long-term effects represented in the model both prior to, and subsequent to the introduction and discovery of HLB in Florida.

The model estimated was:

$$Yi = a + \beta 1\ Crop\ Year + \beta 2\ Bearing\ Acreage + \beta 3\ Freeze\ Event + \beta 4\ Hurricane + \beta 5\ HLB + \beta 6\ HLBTS + \beta 7\ ACC + \varepsilon i\ . \qquad \text{(Eq. 4)}$$

The variables included in this model were the same as the previous regression model with two exceptions. *Crop Year* [a time series component denoting duration of the study period (1980-2018)], and *HLBTS* [the binary value of HLB times a time series component indicating the duration of the epidemic in Florida]. This measure accounted for the progression of the epidemic, and the cumulative impact of the pathogen on the industry. These variables also accounted for long term trends in the industry, the first being growth and expansion, the second the long-term effects associated with HLB.

Disease progress within an epidemic, especially a vectored pathogen, is typically curvilinear or geometric in shape and functional form (Madden et al. 2007). The case of HLB is no exception (Gottwald 2010). Equation 2 presents a linear time series component to identify and quantify the disease progress of HLB in the Florida citrus industry. Bassenezi, et al. examined the yield loss in sweet orange production in Sao Paulo, Brazil associated with HLB (Bassanezi et al. 2011). The study concluded that the yield loss parameters followed a negative binomial distribution. To improve model design and performance, the linear time series component provided in Equation 2 was replaced with a negative exponential component to better express the relationship between disease progress and the impact on yield within an epidemic.

The curvilinear model estimated is expressed by:

$$Yi = a + \beta 1\ Crop\ Year + \beta 2\ Bearing\ Acreage + \beta 3\ Freeze\ Event + \beta 4\ Hurricane + \beta 5\ ACC + \beta 6\ HLB * \exp{(-TS)} + \varepsilon i\ . \qquad \text{(Eq. 5)}$$

Where exp($-TS$) is the negative exponential time series component for HLB infection in the Florida citrus industry. The time series component is the arithmetic series of numbers indicating the time period where HLB has been present in Florida. This term, $HLB * exp(-TS)$, imposes a curvilinear time series trend on HLB infection emulating the negative binomial functional form. Inclusion of the time series component in this term serves as a proxy for disease severity in HLB infections.

Models estimated herein identify and quantitate the effects of weather events and disease introductions on Florida citrus production, to address the future implications for the Florida citrus industry. The study period was divided into two shorter time periods. The first encompassed the 1980-2018 crop years, and the second the 2019-2021 crop years. A deterministic model was estimated for the first time period. These results were then utilized to forecast production for the second time period. Insomuch as the time series model presented herein is deterministic and not a forecasting model, it would be remiss to not examine the model in context of illustrating the average effects of weather and disease in an out of sample framework.

Obtaining a forecast with the time series model developed entails estimating bearing acreage for each sector of the citrus industry examined. A parsimonious approach to determining bearing acreage was utilized. The linear trend for bearing acreage from 2005-2018 was examined and regressed to provide parameter estimates for the 2019-2021 crop years. Binary variables for the weather observed during the out of sample time frame – the 2019, 2020, and 2021 crop years – provided the other necessary information. The forecasted production values were compared to actual Florida crop production values for the 2019 and 2020 crop years, and the USDA October Florida forecast for the 2021 crop year.

The regression analysis was conducted utilizing StatTools 7, statistics add-on for Microsoft Excel (Palisades).

Results

The purpose of this study was to examine the impact of weather and disease events and duration on the Florida citrus industry, to quantify the effects of the events, and determine if their influences altered the structure of the citrus industry. Production patterns demonstrated both short and long-term deviations in production consistent with environmental and disease pressures. The introduction and discovery of HLB in Florida brought about a new era for the citrus industry. Historically, HLB has led to significant reductions in production in the areas facing endemic disease pressure. Examination of the Florida citrus industry performed herein was twofold. First to determine if, in fact, the Florida citrus industry has experienced a structural change, and then second to identify and quantify the associated effects brought about by weather and disease events.

Citrus production levels from 1980 through 2018 were examined for total citrus, total oranges, and total grapefruit production. To determine if a statistically significant structural change occurred, the Chow test performed indicated that production levels pre- and post-2005 were significantly different indicating that a structural shift had occurred during this time period, and that the structural change had continued through the end of the study period, 2018. The Chow test results presented in Table 4 indicated that the regressions for the two additional data sets (D_1 : 1980-2004, and D_2 : 2005-2018) were different and indicated structural changes exist and were responsible for the differences between the two subsets of the data series.

Table 4. Chow test for structural change in regression parameters for citrus production in Florida.

	Critical F Value (.05,35)	F Statistic	Ho: Same regression
Total citrus production	3.2674	10.82802079	Reject null hypothesis
Orange production	3.2674	21.15250099	Reject null hypothesis
Grapefruit production	3.2674	18.82852552	Reject null hypothesis

Whereas the Chow test indicated structural differences in the production levels existed during the study time period, a binary regression analysis was utilized to identify and quantify significant weather and disease events affecting Florida citrus production and contributing to or causing changes in the structure of the citrus industry. Equation 2 was estimated for the three respective classes of citrus – total citrus, total oranges, and total grapefruit. The parameter estimates are presented in Table 5.

Table 5. Binary model of weather events and disease epidemics of Florida citrus production, 1980-2018.

Multiple Regression for Total citrus					
Summary	**R-Square**	**Adjusted R-square**	**Std. Err. of Estimate**		
	0.8340	0.8088	28590.12537		
ANOVA Table	**Degrees of Freedom**	**Sum of Squares**	**Mean of Squares**	**F**	**p-Value**
Explained	5	1.3548E+11	27095954313	33.14914503	< 0.0001
Unexplained	33	26974043873	817395268.9		
Regression Table	**Coefficient**	**Standard Error**	**t-Value**	**p-Value**	
Constant	5397.816207	43079.36596	0.125299342	0.9010	
Bearing AC	355.6930109	69.73940054	5.100316437	< 0.0001	
Freeze	33006.73547	13925.61262	-2.37021784	0.0238	
Hurricane	37317.20579	15945.77985	-2.340255926	0.0255	
HLB	26235.96976	14274.87267	-1.837912699	0.0751	
ACC	25214.29608	16310.766	1.545868298	0.1317	
Multiple Regression for Total Oranges					
Summary	**R-Square**	**Adjusted R-square**	**Std. Err. of Estimate**		
	0.8037	0.7740	23978.44361		
ANOVA Table	**Degrees of Freedom**	**Sum of Squares**	**Mean of Squares**	**F**	**p-Value**
Explained	5	77682033070	15536406614	27.02144676	< 0.0001
Unexplained	33	18973870007	574965757.8		
Regression Table	**Coefficient**	**Standard Error**	**t-Value**	**p-Value**	
Constant	11485.04724	35516.45539	0.323372564	0.7485	
Bearing AC	352.6751839	75.71427323	4.657974895	< 0.0001	
Freeze	23996.79888	11624.3823	2.064350454	0.0469	
Hurricane	30994.46072	13454.02313	2.303731785	0.0277	
HLB	-19114.14264	9902.908979	-1.930154329	0.0622	
ACC	28845.7046	15041.96309	1.917682182	0.0638	
Multiple Regression for Grapefruit					
Summary	**R-Square**	**Adjusted R-square**	**Std. Err. of Estimate**		
	0.9221	0.9102	5037.121774		
ANOVA Table	**Degrees of Freedom**	**Sum of Squares**	**Mean of Squares**	**F**	**p-Value**
Explained	5	9904842017	1980968403	78.07511781	< 0.0001
Unexplained	33	837295660.2	25372595.76		
Regression Table	**Coefficient**	**Standard Error**	**t-Value**	**p-Value**	
Constant	-3439.05178	6880.98963	-0.499790287	0.6205	
Bearing AC	472.6931425	61.06335727	7.741027741	< 0.0001	
Freeze	-9107.997028	2493.617759	-3.652523325	0.0009	
Hurricane	-5972.33557	2766.469367	-2.15882946	0.0382	
HLB	-261.8487608	4464.056863	-0.058657129	0.9536	
ACC	-827.9553295	2230.873602	-0.371135025	0.7129	

Regression analysis indicated that bearing acreage combined with weather and disease events significantly impacted Florida citrus production. The adjusted R^2 associated with total citrus, total oranges, and total grapefruit varied from 0.8088, 0.7740, and 0.9102, respectively. The F statistics indicated the regression coefficient estimates were significantly different than zero at $\alpha = 0.01$ when examining all coefficients together, i.e., the null hypothesis was rejected, Ho: $\beta_1 = \beta 2 = \beta 3 = \beta 4 = \beta 5 = 0$, for all three of the citrus classes.

In examining total citrus, bearing acres, freeze and hurricane events were all significantly different from zero (0) at $\alpha = 0.05$, and HLB was significant at $\alpha = 0.10$. ACC was not significant at $\alpha = 0.10$. The magnitude and sign of the significant coefficients were in line with *a priori* expectations.

The event analysis for Florida total orange production followed the Florida total citrus production model with one exception. Examination of the individual events and orange bearing acreage indicate that they were all significantly different than zero – bearing acreage and the weather events at α = 0.05, and the disease events at α = 0.10. As with the total citrus production, all signs were as expected with the exception of ACC, which in this model, the parameter estimate was positive.

Florida total grapefruit production estimates for the event model were strikingly different than for orange and total citrus. Bearing acreage and the weather events were significant at α = 0.05, and both disease events were not significantly different from zero. The signs of the parameter estimates were as expected.

The parameter estimates associated with bearing acres for all three citrus classes were positive and approximately in-line with average yield per acre over the study period. The negative coefficients with the weather events indicated the sharp and drastic changes in production were associated with significant weather events known to have had a bearing on production levels. With regard to ACC, the initial discovery was in residential citrus, and early eradication efforts were primarily centered in residential areas and not major production areas, it would appear that the model parameter estimates were a result of the long-term positive trend in increased citrus production extending from the beginning of the study period through the late 1990s.

One shortcoming of the previous regression model was highlighted by the Chow test and the production levels portrayed in Figure 3. The Chow test indicated structural changes in the production system resulted in two separate regressions to explain production, one for the long-term positive increase in production prior to the introduction of HLB in Florida, and then a totally separate regression for the subsequent years when HLB was present in Florida. The event model previously discussed did not take into account the separation of those two time frames, thus necessitating the inclusion of time series components to address the separate shifts in the regressions through time. Equation 3 incorporated these time series components into the model.

The observed and estimated values for each of these event models are presented in Figure 5. The correlation coefficient between the actual and estimated for total citrus, orange and grapefruit were 0.9132, 0.8965, and 0.9602, respectively. As demonstrated by the figure and the correlation analysis, the binary model identified and quantified the influence of weather events and the two diseases on Florida citrus production levels.

Figure 5 estimates the regression estimates of Equation 5 for total citrus production, total oranges, and grapefruit are presented in Table 6. For the three models estimated, the adjusted R^2 was 0.8584, 0.8366, and 0.9161, for the three classes of citrus, respectively. This indicated improvements in model performance over the previous models presented. The F statistics indicated that all variables, when tested in combination, were significant.

Table 6. Binary and time series for weather events and disease epidemics of Florida citrus production, 1980-2018.

Multiple Regression for Total citrus					
Summary	**R-Square**	**Adjusted R-square**	**Std. Err. of Estimate**		
	0.8845	0.8584	24607.45946		
ANOVA Table	**Degrees of Freedom**	**Sum of Squares**	**Mean of Squares**	**F**	**p-Value**
Explained	7	1.43682E+11	20526068078	33.89785428	< 0.0001
Unexplained	31	18771338893	605527061.1		
Regression Table	**Coefficient**	**Standard Error**	**t-Value**	**p-Value**	
Constant	-4792191.867	2638158.948	-1.816490955	0.0790	
Crop Year	2424.598946	1322.58518	1.833227064	0.0764	
Bearing AC	301.193932	65.70522224	4.584018161	< 0.0001	
Freeze	-22111.56379	13368.77742	-1.653970524	0.1082	
Hurricane	-31380.63428	14203.4535	-2.209366496	0.0347	
HLB	-24393.72653	22034.30801	-1.107079311	0.2768	
HLBTS	-8639.368348	2400.801898	-3.598534454	0.0011	
ACC	-23.22350099	21559.37769	-0.001077188	0.9991	
Multiple Regression for Total oranges					
Summary	**R-Square**	**Adjusted R-square**	**Std. Err. of Estimate**		
	0.8667	0.8366	20383.78073		
ANOVA Table	**Degrees of Freedom**	**Sum of Squares**	**Mean of Squares**	**F**	**p-Value**
Explained	7	83775449052	11967921293	28.80376416	< 0.0001
Unexplained	31	12880454025	415498516.9		
Regression Table	**Coefficient**	**Standard Error**	**t-Value**	**p-Value**	
Constant	-5094835.948	2145996.952	-2.374111456	0.0240	
Crop Year	2570.080499	1078.218446	2.383636181	0.0235	
Bearing AC	295.2814244	67.83014235	4.353247895	0.0001	
Freeze	-12818.18479	11075.86656	-1.157307622	0.2560	
Hurricane	-25094.16603	11753.20868	-2.135090656	0.0408	
HLB	-22787.96643	18271.64912	-1.247176228	0.2217	
HLBTS	-7649.80726	2006.482792	-3.81254566	0.0006	
ACC	3403.967029	17804.22658	0.191188705	0.8496	
Multiple Regression for Grapefruit					
Summary	**R-Square**	**Adjusted R-square**	**Std. Err. of Estimate**		
	0.9315	0.9161	4871.455382		
ANOVA Table	**Degrees of Freedom**	**Sum of Squares**	**Mean of Squares**	**F**	**p-Value**
Explained	7	10006474273	1429496325	60.23731212	< 0.0001
Unexplained	31	735663403.7	23731077.54		
Regression Table	**Coefficient**	**Standard Error**	**t-Value**	**p-Value**	
Constant	-477559.9578	599932.9575	-0.796022209	0.4321	
Crop Year	239.9202973	299.4137056	0.801300318	0.4291	
Bearing AC	447.4953154	76.8555906	5.822547349	< 0.0001	
Freeze	-7956.914832	2648.688312	-3.004096328	0.0052	
Hurricane	-5192.128576	2790.728265	-1.860492345	0.0723	
HLB	-480.4241677	4720.388255	-0.101776409	0.9196	
HLBTS	-935.7849841	470.0205809	-1.990944699	0.0554	
ACC	-4200.862585	3906.96599	-1.07522374	0.2906	

Adding a time series component to the regression model represented an improvement over the base model reported in Table 5. Of the variables included in the regression analysis, *Crop Year*, *Acreage*, *Hurricane* and *HLBTS* were all significant at α = 0.10 or lower in each of the three classes of citrus. For *Freeze Events*, the coefficient was significantly different from zero at α = 0.10 for grapefruit. Total citrus and total oranges were not significantly different from zero at α = 0.10.

Examination of the sign and magnitude of the estimated coefficients were in line with *a priori* expectations. The crop year and bearing acreage returned significant positive coefficients indicative of a long-term trend and positive relationship between acreage and production. The weather and disease events were negative when significant, indicative of a reduction in production from detrimental events.

Observed and estimated values for Equation 6, the time series model were presented in Figure 6. The correlation coefficients for total citrus, total oranges and total grapefruit were 0.9405, 0.9310, and 0.9652, respectively. As shown by the regression analysis, adjusted R^2 and correlation coefficients, inclusion of the time series component to account for long term trends improved model performance (Figure 6).

The regression results for total citrus, total orange, and total grapefruit production estimates based on the negative exponential model are presented in Table 7. With respect to the regression models' performance, the adjusted R^2 values were 0.7972, 0.7578, and 0.9058 for the total citrus, total orange, and total grapefruit production models, respectfully. The F-value indicated that all variables when considered jointly were significantly different than zero at $\alpha = 0.01$. In terms of significance of variables, the negative exponential time series model performed on par with the other model, exhibiting slightly lower adjusted R^2 values compared to the two other class models estimated. For all three citrus classes, *Bearing Acreage*, *Freeze Event* and *Hurricane* were significant at $\alpha = 0.10$ or less. As for the disease events, ACC, was significant for total citrus and total orange production albeit at a positive value. Likewise, for total citrus and total orange production the *Crop Year* was significant at $\alpha = 0.10$, but with a negative value.

Table 7. Negative Exponential model of weather events and disease epidemics of Florida citrus production, 1980-2018.

Multiple Regression for Total citrus					
Summary	**R-Square**	**Adjusted R-square**	**Std. Err. of Estimate**		
	0.8292	0.7972	29448.30628		
ANOVA Table	**Degrees of Freedom**	**Sum of Squares**	**Mean of Squares**	**F**	**p-Value**
Explained	6	1.34703E+11	22450554612	25.88847279	< 0.0001
Unexplained	32	27750487766	867202742.7		
Regression Table	**Coefficient**	**Standard Error**	**t-Value**	**p-Value**	
Constant	2333535.58	1358667.802	1.717517391	0.0955	
Crop Year	-1170.186412	664.2480483	-1.761670832	0.0877	
Bearing AC	334.2567674	79.52571439	4.203128133	0.0002	
Freeze	-35814.47853	15034.16537	-2.382205972	0.0233	
Hurricane	-40217.64461	18755.83018	-2.1442743	0.0397	
ACC	37475.44749	19660.35998	1.906142488	0.0656	
HLB*exp(-TS)	1834.353707	85774.4579	0.02138578	0.9831	
Multiple Regression for Total oranges					
Summary	**R-Square**	**Adjusted R-square**	**Std. Err. of Estimate**		
	0.7960	0.7578	24821.67186		
ANOVA Table	**Degrees of Freedom**	**Sum of Squares**	**Mean of Squares**	**F**	**p-Value**
Explained	6	76940210467	12823368411	20.81325761	< 0.0001
Unexplained	32	19715692610	616115394		
Regression Table	**Coefficient**	**Standard Error**	**t-Value**	**p-Value**	
Constant	1445572.841	896154.1476	1.613085031	0.1165	
Crop Year	-731.1815392	441.1003301	-1.657630905	0.1072	
Bearing AC	342.994839	81.28074673	4.219878049	0.0002	
Freeze	-25233.82051	12668.66091	-1.99183013	0.0550	
Hurricane	-32403.50546	15758.8666	-2.056207865	0.0480	
ACC	35944.69495	15861.32715	2.266184577	0.0303	
HLB*exp(-TS)	-6039.081736	71720.93784	-0.084202493	0.9334	
Multiple Regression for Grapefruit					
Summary	**R-Square**	**Adjusted R-square**	**Std. Err. of Estimate**		
	0.9207	0.9058	5159.631337		
ANOVA Table	**Degrees of Freedom**	**Sum of Squares**	**Mean of Squares**	**F**	**p-Value**
Explained	6	9890240220	1648373370	61.91818909	< 0.0001
Unexplained	32	851897457.2	26621795.54		
Regression Table	**Coefficient**	**Standard Error**	**t-Value**	**p-Value**	
Constant	216477.4983	501595.3714	0.431577942	0.6689	
Crop Year	-108.8256181	247.6836165	-0.439373502	0.6633	
Bearing AC	440.9166298	83.9099579	5.254640103	< 0.0001	
Freeze	-9166.696981	2649.1538	-3.460235862	0.0016	
Hurricane	-6519.293904	3305.544518	-1.972229951	0.0573	
ACC	-478.4661302	3259.730762	-0.146780874	0.8842	
HLB*exp(-TS)	8666.828481	15918.41499	0.54445298	0.5899	

Figure 7 illustrates the observed and estimated values from Equation 6, the negative exponential model. The correlation coefficients from total citrus, total orange and total grapefruit models were 0.9106, 0.8960, and 0.9595, respectively. The correlation coefficients and adjusted R^2 values associated with this model indicated that its performance is deficient when compared to the two other models estimated (Figure 7).

The actual and estimated values for each of the respective estimated models were compared to judge the relative performance of the deterministic models. In addition to the metrics previously discussed, the mean absolute error (MAE) of the models is shown in Table 8. In this table, the performance of each model was evaluated for the entire time frame of the study, and for the two subsets pre- and post-HLB. The MAE clearly indicated that the time series model outperformed both the event and negative exponential models over the course of the entire data set and for the two subsets. The negative exponential model has mixed results. Over the course of the entire data set, it was outperformed by the event model for both total citrus and total oranges. For the pre-HLB time frame, the model was outperformed in all three citrus class models. Post-HLB, the negative exponential model outperformed the event model in all three citrus classes.

Table 8. Mean Absolute Error (MAE) of the respective deterministic models.

	Event Model		
	Total Citrus	Total Oranges	Total Grapefruit
1980-2018	22923.52	19133.95	3603.31
1980-2004	23367.83	19120.23	4407.30
2005-2018	22130.12	19158.45	2167.61
	Time Series Model		
	Total Citrus	Total Oranges	Total Grapefruit
1980-2018	17435.59	14661.59	3147.67
1980-2004	20511.53	16469.30	4421.29
2005-2018	11942.83	11433.54	873.33
	Negative Exponential Model		
	Total Citrus	Total Oranges	Total Grapefruit
1980-2018	23224.78	19551.27	3594.92
1980-2004	25366.43	20781.84	4521.02
2005-2018	19400.43	17353.81	1941.17

In terms of explaining the short- and long-term deviations and trends in Florida citrus production, the models presented in this study clearly identified the impact of weather and disease on citrus production. Empirical testing indicated significant structural shifts in production levels during the time period from 1980-2018. The analyses presented quantified effects of hurricane and freeze events on the short-term production trends, and the long-term trends associated with disease and disease progress in Florida. Of the three models presented, the time series model (Equation 4) was clearly superior in terms of performance and explained both short- and long-term trends and deviations in production. The HLB and HLB time series interaction time series terms incorporated into the model best illustrated the additive curvilinear reductions in production associated with HLB disease progress in Florida when compared to the negative exponential form tested (Figure 8).

Out of sample forecasting:

Based on the superior performance of the deterministic time series model relative to the other models presented, 'out of sample forecasts' of Florida citrus production were generated for the 2019, 2020, and 2021 crop years to examine the average effects of weather and disease on the Florida industry (Figure 9). Bearing acreage values for the 2019-2021 crop years were based on the trends of bearing acres for total citrus, total oranges and total grapefruit from 2005-2018. The linear regression analysis and the estimated bearing acreage values obtained are presented in Tables 9 and 10, respectively. Forecasts of Florida citrus production were generated for the 2019, 2020 and 2021 crop years (Table 11). Actual Florida citrus production values and the October 2021 USDA estimate of Florida citrus production were obtained from USDA-NASS (Table 12). Florida production history, the forecasted production levels and actual production values are presented in Figures 8 and 9 for comparison. Examination of the forecasted production values for total citrus, total oranges and total grapefruit in comparison to the actual production values yielded a MAE of 7,895.78, 4,878.57, and 2,076.14, respectively. The forecasted values tended to be biased downward, but clearly demonstrated the rapid decline facing Florida citrus producers. The production trends highlighted by both the drastic decreasing trend in bearing acreage and the precipitous reduction in forecasted production demonstrated the serious implications of HLB on Florida citrus production.

Table 9. Linear model of bearing acreage for Florida citrus production, 2005-2018.

Multiple Regression for Total citrus					
Summary	**R-Square**	**Adjusted R-square**	**Std. Err. of Estimate**		
	0.9835	0.9821	7.8608		
ANOVA Table	**Degrees of Freedom**	**Sum of Squares**	**Mean of Squares**	**F**	**p-Value**
Explained	1	44154.26971	44154.26971	714.5678	< 0.0001
Unexplained	12	741.4988571	61.79157143		
Regression Table	**Coefficient**	**Standard Error**	**t-Value**	**p-Value**	
Constant	28507.0971	1048.3223	27.1931	0.0000	
Bearing AC	-13.9314	0.5212	-26.7314	0.0000	
Multiple Regression for Total oranges					
Summary	**R-Square**	**Adjusted R-square**	**Std. Err. of Estimate**		
	0.9803	0.9786	6.3837		
ANOVA Table	**Degrees of Freedom**	**Sum of Squares**	**Mean of Squares**	**F**	**p-Value**
Explained	1	24281.31605	24281.32	595.84241	< 0.0001
Unexplained	12	489.0148617	40.75124		
Regression Table	**Coefficient**	**Standard Error**	**t-Value**	**p-Value**	
Constant	21205.1148	851.3352	24.9081	< 0.0001	
Bearing AC	-10.3311	0.4232	-24.4099	< 0.0001	
Multiple Regression for Grapefruit					
Summary	**R-Square**	**Adjusted R-square**	**Std. Err. of Estimate**		
	0.9692	0.9667	1.8778		
ANOVA Table	**Degrees of Freedom**	**Sum of Squares**	**Mean of Squares**	**F**	**p-Value**
Explained	1	1332.817	1332.8175	377.9815	< 0.0001
Unexplained	12	42.31374	3.5261451		
Regression Table	**Coefficient**	**Standard Error**	**t-Value**	**p-Value**	
Constant	4912.8631	250.4265	19.6180	< 0.0001	
Bearing AC	-2.4204	0.1245	-19.4417	< 0.0001	

Table 10. Florida estimated bearing acreage, 2019-2021 (1,000 AC).

Crop year	Total citrus	Total orange	Total grapefruit
2019	379.5	346.7	26.0
2020	365.6	336.3	23.6
2021	351.7	326.0	21.2

Table 11. Forecasted Florida citrus production (1,000 boxes), 2019-2021 crop years.

	Time Series Model		
Crop year	Total citrus	Total oranges	Total grapefruit
2019	63,392.25	58,995.57	3,952.86
2020	52,990.89	50,844.92	2,173.86
2021	42,589.52	42,723.79	394.86

Table 12. Actual Florida citrus production (1,000 boxes), 2019-2021 crop years.

Crop year	Total citrus	Total oranges	Total grapefruit
2019	73,170	67,400	4,850
2020	57,790	52,800	4,100
2021*	51,700	4,700	3,800

Source: USDA-NASS, Citrus, October Forecast, October 12, 2021

*October 2021 USDA-NASS Forecast

Discussion

The results of this research present significant and profound findings and implications for the Florida citrus industry. The scope and focus of this study were to examine weather and disease events that are threats to the Florida citrus industry, and to identify and quantify the impacts of these threats. The study focused on the time period from 1980 through 2021 and focused on the severe weather and disease introductions facing the citrus industry during that time frame.

Analysis of the disease events yielded mixed results. This can be attributed to the vastly different nature of the two diseases and the responses from the industry. The initial response for citrus canker was an eradication program with removal of diseased and exposed trees. Whereas the initial removals were centered in residential counties leading to limited effects on commercial citrus production. The disease progression and subsequent spread into commercial orchards eventually led to subsequent removal of commercial citrus. The impacts of the removal of commercial citrus at the end of the epidemic were mitigated by the significant weather events that occurred at the same time. Based on CCEP summary data, total commercial citrus losses, both in terms of acreage and number of trees, were approximately 15-percent and losses were halted by the cessation of the eradication program.

The HLB pathosystem created a different scenario for citrus producers. During the early stages of infection, many producers did not even know that their orchards were infected, with significant reductions in yield not manifesting until years after initial infection. Furthermore, initial HLB infections would have posed minimal impacts on production with significant effects not manifested until later in the disease process. This was the impetus for utilizing the time series and negative exponential models to capture the geometric disease progress associated with HLB infections.

Examining the events revealed significant effects and influences on citrus production in Florida. Weather events were significant and detrimental to citrus production. The reduction in yearly production associated with freeze events ranged from 9,107 to 33,006 boxes. Hurricanes led to yearly reduction in production ranging from 5,972 to 37,317 boxes. Disease events associated with HLB identified significance for total citrus and total oranges, with yearly reductions of 26,235 and 19,114 boxes respectively. Reductions for total grapefruit were not significant. This could be due to the relatively small size of the grapefruit industry in Florida in terms of total percent of citrus.

Long-term trends indicated both substantial growth in the industry prior to 2005, and substantial reductions since. These trends supported and highlight the results from the Chow test and indicated two separate regressions for citrus production, related to shifts in the structure of the industry. The long-term trend identified in the model varied from 2,424 to 2,570 boxes. Per acre increases ranged from 295 to 447 boxes. Within this time series framework, freeze events reduced production from 7,956 to 22,111 boxes, and hurricanes further reduced production ranging from 5,192 to 31,380 boxes. The impact of disease on the industry was due to the interaction of HLB and the duration of time that the pathogen had been in the state. The mere presence of the pathogen in the industry did not indicate a significant reduction in production, but the time series interaction was significant and indicated a geometric progression and reduction in crop yields. This interaction term ranged from 935 to 8,639 boxes.

Using the negative exponential within the construct of this framework did not prove beneficial, and based on the sign and magnitude of the coefficients, actually led to erosion of model performance. Whereas, disease progress is exponential in nature, the slope and interaction terms for HLB utilized in Equation 2 outperformed the implied negative exponential model.

Previous studies have examined the effect of HLB on citrus production by looking at yield loss (Bassanezi et al. 2011; Neupane et al. 2016), whereas others have utilized economic impact as a measure and determinant of the total effect of HLB infection (Costa et al. 2021; Court et al. 2020; Farnsworth et al. 2014; Hodges et al. 2018; Hodges and Spreen 2012; Rahmani and Hodges 2009). These studies all indicated the various and significant effects associated with HLB on the underlying economic impact.

With respect to Florida, the changing structure of the citrus industry was illustrated by the economic conditions reported in the literature. Court, Ferreira and Cruz highlighted the changes to the Florida citrus industry since 2000. They noted the 48% decline in bearing acreage since 2000, and the associated 74% decrease in citrus fruit production for fresh and processed markets. The changes within the economic impact of the Florida citrus industry are summarized in Table 13. The Florida citrus industry experienced growth through the mid 2000's. Following the introduction of HLB and the subsequent disease progress throughout the industry, the total economic impact of the Florida citrus industry has been reduced by 30%, and total employment has decreased by 51% during the same period. These values indicated and illustrated the significant structural shifts occurring within the Florida citrus industry resulting from HLB.

Table 13. Total economic impact and employment, Florida citrus industry 1999-2019.

	1999[A]	2003[B]	2007[C]	2018[d]
Total Economic Impact	9.13 billion	9.29 billion	8.91 billion	6.53 billion
Total Jobs	89,778	76,336	75,828	37,431

Sources: [A] Hodges et al. 2001. [B] Hodges et al. 2006. [C] Rahmani and Hodges 2009. [D] Court et al. 2020.

The effects of HLB on the Florida citrus industry present implications and warnings for other citrus producing regions, states and countries. As shown within Florida, the rapid onset and spread of HLB throughout the entire production region was dramatic. The rapid spread had significant impacts on not only production, but the entire industry. Currently, Florida is at the terminal end of the infection curve, with disease incidence at greater than 95% in plantings 2 years old or older (Taylor and Gottwald 2019). In addition to increases in disease incidence, disease severity continues to increase in infected plantings. As shown empirically, yield is decreasing at an accelerated rate. The dramatic reductions on yield and bearing acreage have led to significant closings and consolidation across the industry. This trend has continued as production and bearing acreage continue to decrease. Other citrus production areas should examine the case of Florida and take steps to mitigate potential infection and demise of their industries at the hands of HLB. Within the US, HLB has been confirmed in six states – Florida, Georgia, South Carolina, Louisiana, Texas, California, with the Asian Citrus Psyllid reported in ten states (APHIS).

The major threat associated with HLB is the rapid dispersal and spread of the disease. HLB was first reported in Texas and California in 2012. Since that time, there has been extensive spread in Texas with disease incidence exceeding 50%. HLB infections in

California have been limited to residential areas in the LA basin and southern California (Gottwald et al. 2019; McRoberts et al. 2019). The number of HLB infected trees continues to grow with over 2500 confirmed positive trees as of October 2021 (DATOC 2020) . This indicates HLB infection and detection are expressing exponential growth. The number of infections can be misleading in terms of the true threat of the disease. Do to the latency period between infection and detection, the true numbers of infections are greatly understated, often by orders of magnitude (Gottwald 2017). Key implications for the California citrus industry are containing the spread of HLB within the current quarantine area and preventing it from reaching the major production areas of the California Central Valley. To effectively and efficiently slow and or prohibit the entry of ACP and HLB into major production areas, all disease management and mitigation factors should be examined and employed. Key among this is the fully and widespread implementation of early detection technologies. Whereas PCR is the gold standard for disease detection and regulatory action, the latency period associated with HLB highlights the need for additional measures and technologies. New technologies and techniques being utilized and introduced have shown significant ability to detect and slow the spread of HLB. These key advancements include the use of area-wide management to provide coordinated management for the control of ACP and control/prevention of HLB (Bassanezi et al. 2013; Bergamin et al. 2016; Sétamou 2020; Singerman et al. 2017), and the use of canines as an early detection technology (Gottwald et al. 2020; Gottwald et al. 2017a; Gottwald et al. 2017b; Graham et al. 2020). As shown by the rapid disease progress and resulting decrease in production in the Florida citrus industry, HLB infection and spread into major production areas is deleterious and has severe and lasting effects and implications for those production areas.

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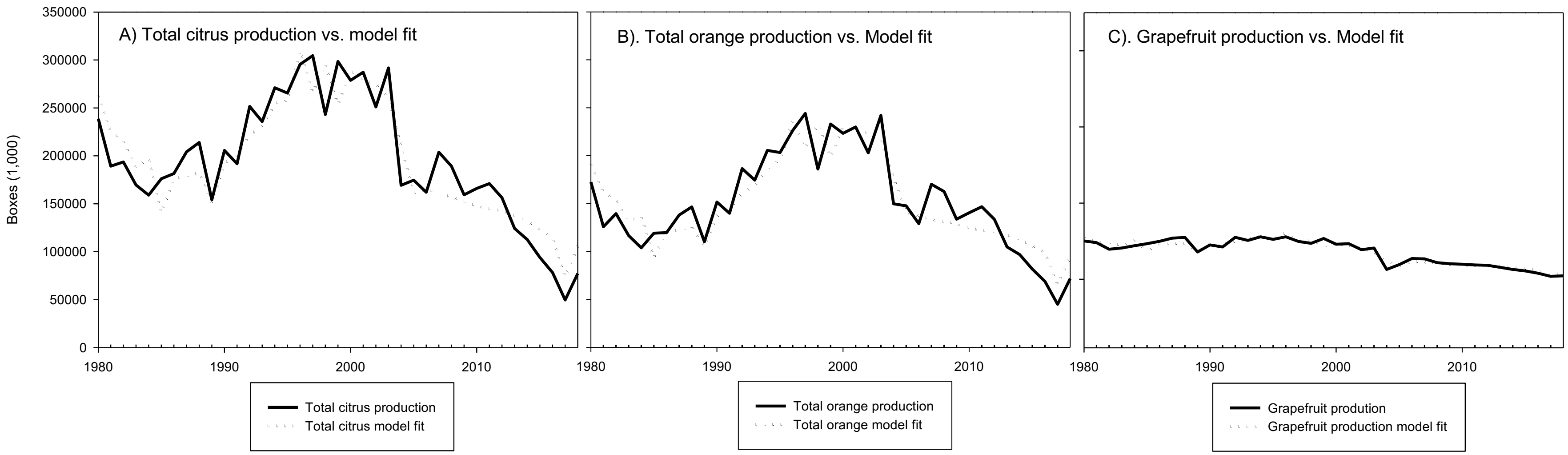

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627 **Figure 5**. Florida citrus production actual values and regression fit from event study model, 1980-2018**.**

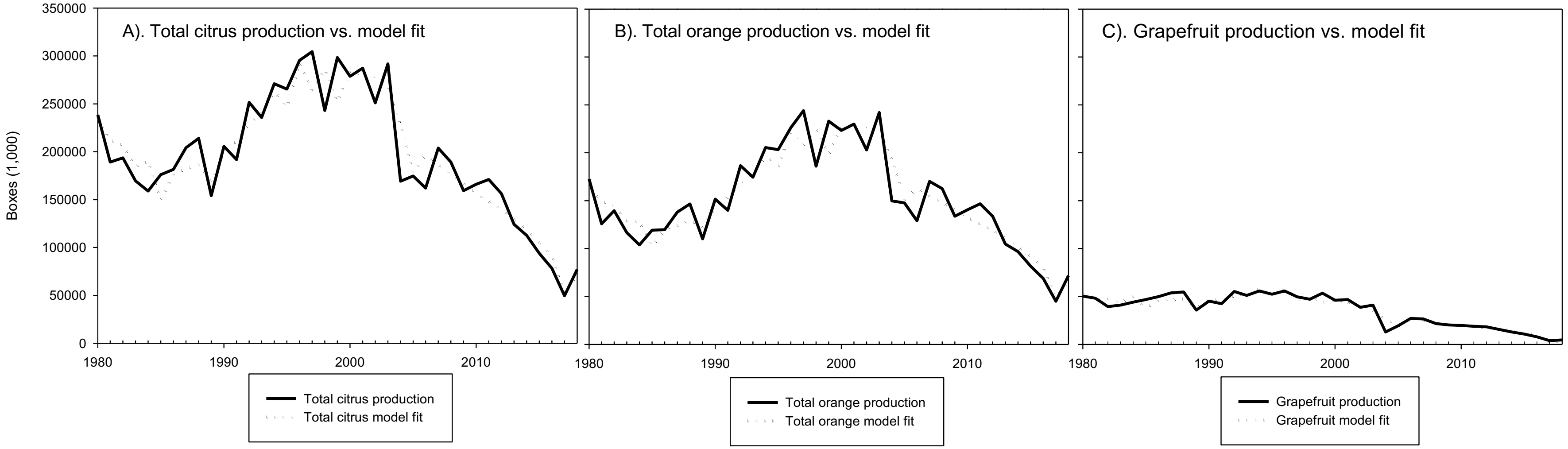

Figure 6. Florida citrus production actual values and regression fit from time series model, 1980-2018.

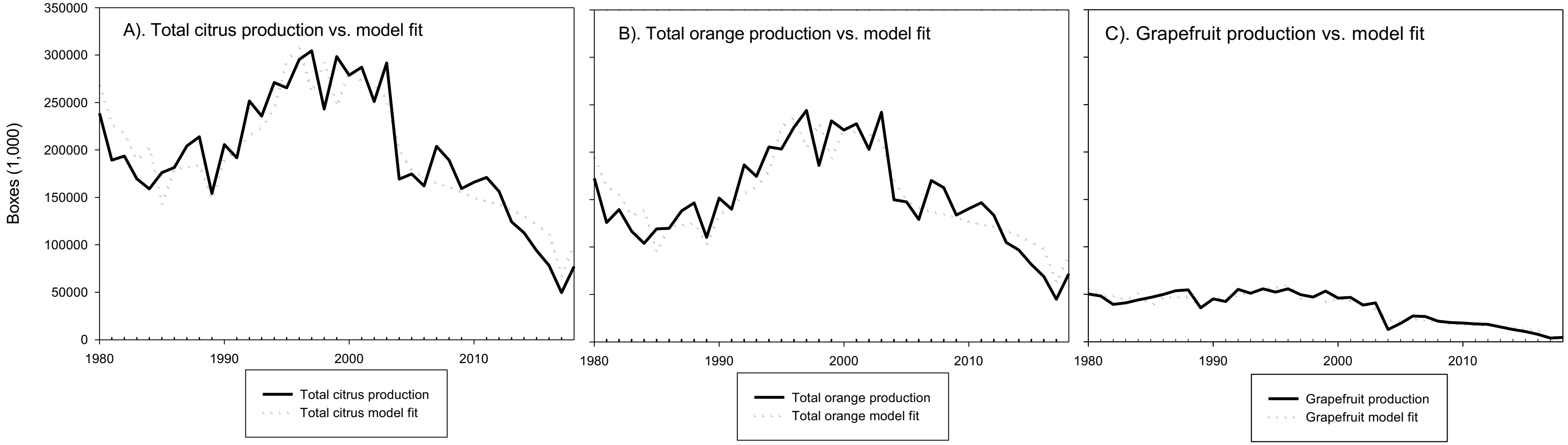

Figure 7. Florida citrus production actual values and regression fit from negative exponential model, 1980-2018.

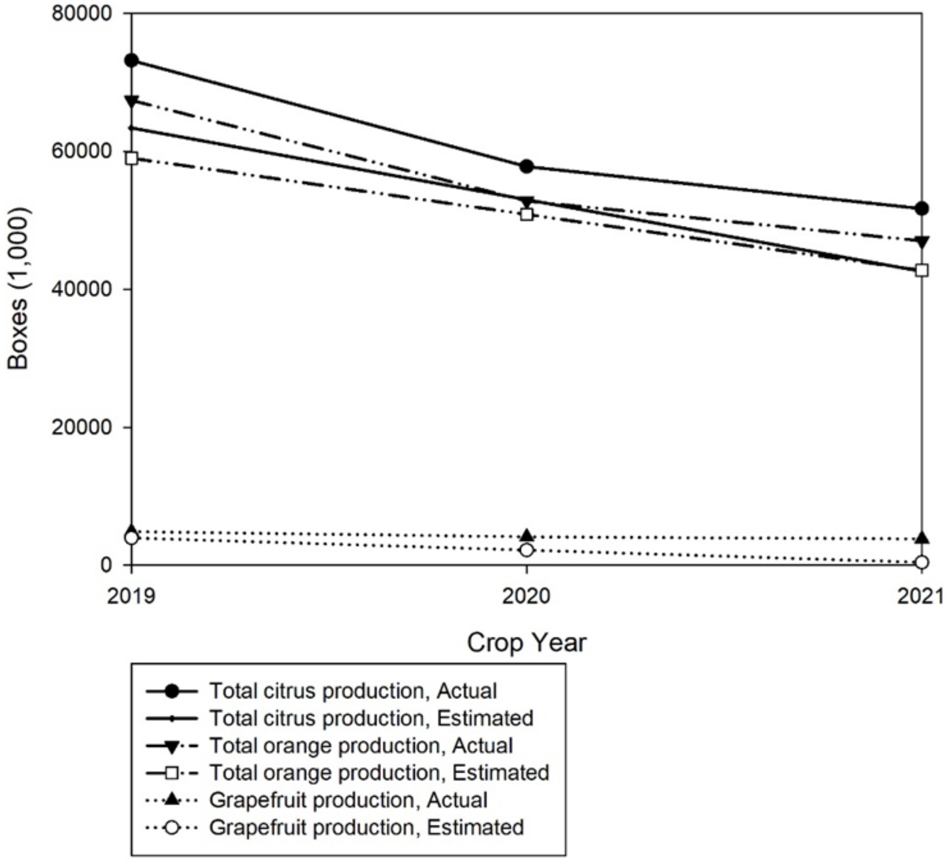

Figure 8. Florida citrus production and time series model estimates, 2019-21 crop years.

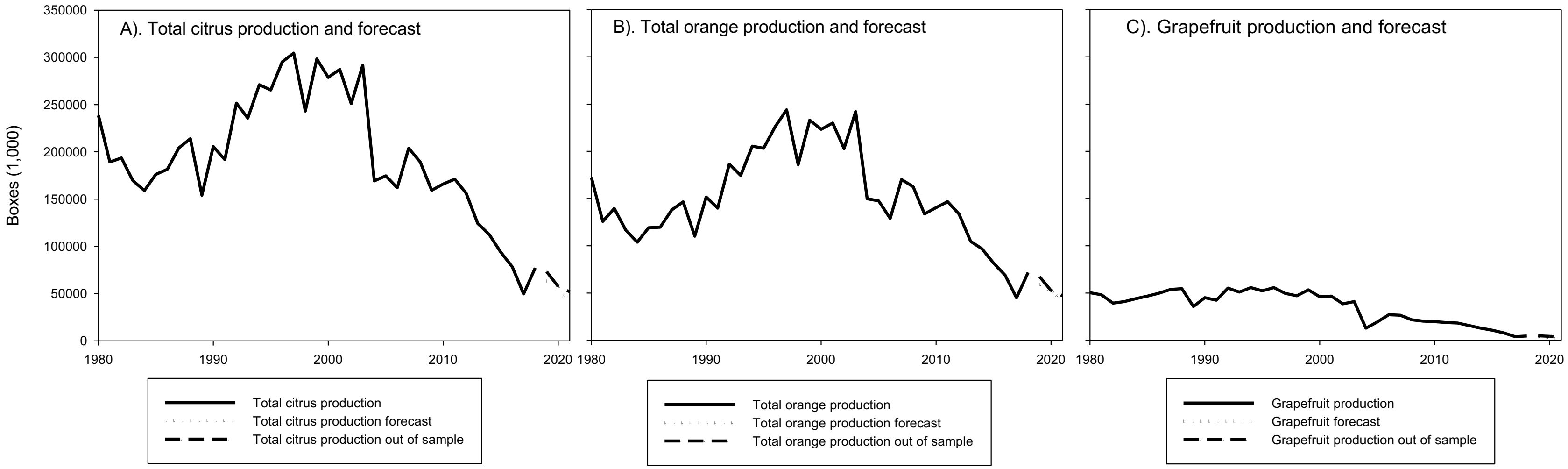

Figure 9. Florida citrus production and out of sample production forecast, 1980-2021.