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How historical trends in Florida all-citrus production correlate with devastating hurricane and freeze events

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Introduction

The lives and livelihoods of people with agricultural interests in Central Florida are not only shaped by regional climatology, but also by the character of the area's recurring hazardous weather. Each year, season by season, this region endures an onslaught of lightning, severe thunderstorms (with damaging wind and hail), tornadoes, torrential rains and floods, droughts and wildfires, heat stress, cold air outbreaks and hurricanes. Individually, each of these phenomena is capable of causing serious property damage and even loss of life. Moreover, when a high-impact weather event leaves behind a substantial footprint on the landscape, long-term scarring can alter the character of the environment and nearby ecosystems, thereby reshaping local agricultural economies. This becomes especially true when various hazardous weather types co-occur over an area and across the seasons. Such is the case for Central Florida's 'Citrus Belt' over the past 40 years (Figure 1), which historically is

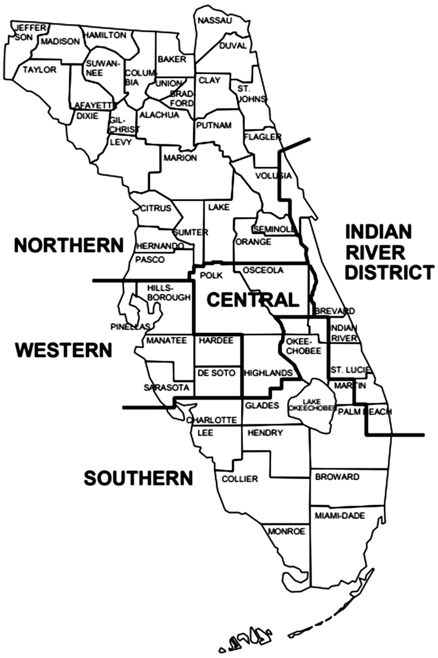

Figure 1. Florida's Commercial Citrus Production Areas (also known as Florida's Citrus Belt), divided by growing area (Source: Florida Citrus Statistics 2016/2017 (March 2018)).

responsible for half of all citrus production in the USA, and is particularly important for orange juice production. This area has been squeezed by the combination of wintertime cold air outbreaks from the north and late summer hurricanes landfalling from all other directions. Historical comparison of total citrus production data by state for the USA (USDA, 2017) has shown that, over the past several decades, the Citrus Belt has been heavily influenced by these two hazards.

The Citrus Belt is uniquely situated at a crossroads for landfalling tropical storms and hurricanes as they track across the North Atlantic Ocean, Caribbean Sea, and Gulf of Mexico, towards the state. Hurricane *Andrew* (1992) is the archetypal example of an extreme wind event that adversely affected the Florida peninsula. Other notable hurricanes such as the Lake Okeechobee Hurricane (1928), Hurricane *David* (1979), Hurricanes *Charley*, *Frances*, and *Jeanne* (2004), Hurricane *Wilma* (2005), Hurricane *Matthew* (2016), and Hurricane *Irma* (2017) have also etched out wind scars. When it comes to flooding from tropical rains, Tropical Storm *Fay* (2008) tops the list – an extraordinary 702mm of rain fell over Melbourne (Indian River District), Florida, leading to floods that swamped much of east central Florida. The rainfall associated with Hurricane *Irma* (2017) also led to in flooding in many areas, especially within the Indian River District (550mm was recorded at Fort Pierce, Florida), and the storm also brought with it an outbreak of tornadoes over the region.

Comprised of coastal counties from Volusia County (north) to Palm Beach County (south), the Indian River District lies almost entirely within that part of the state overseen by the local National Weather Service (NWS) in Melbourne, Florida. The NWS Melbourne (2018) provides weather, water, and climate services to fulfil its purpose of protecting life and property from hazardous weather within east central Florida, with an overlapping commitment to help safeguard the local environment and economy from the same. The NWS Melbourne operates as a federal entity (independent of the citrus industry) to provide weather observations, forecasts, and warnings to county and city emergency management, as well as to local media and the public. Industry stakeholders, citrus growers and agricultural experts rely on the information they provide in order to take protective action, when required, against tropical systems and cold air outbreaks.

From a climatological perspective, the Citrus Belt can be classified as residing in the sub-tropics (i.e. not purely tropical; mostly humid). Periodically, continental air from Canada, or even the Arctic, dives far south towards the lower latitudes, ushering in frigid conditions across the predominantly temperate Florida Peninsula. The link between cold air outbreaks and damage to citrus groves has been well documented throughout Florida's history, most notably after the five devastating freezes of the 1980s (Miller, 1991). Catastrophic damage to citrus trees can occur when temperatures fall below −2.2°C for 4h or more, devastating fruit yield and degrading fruit quality (Johnson, 1958). Local forecasters refer to this as a 'hard freeze', in line with criteria established by the National Weather Service Directive 10-515 (National Weather Service, 2018). A hard freeze is described by the American Meteorological Society (2018) as *a freeze in which seasonal vegetation is destroyed, the ground surface is frozen, and heavy ice is formed on (small) water surfaces*. Negative effects are amplified whenever wintry precipitation and/or strong winds accompany the cold air. Some of the more noteworthy cold air outbreaks that have severely affected the Florida citrus industry occurred in December 1894, February 1895, February 1899, the 1934/1935 winter season, the 1939/1940 winter season, the 1957/1958 winter season, December 1962, January 1977, and the five notorious freezes of the 1980s (which inflicted the most recent bout of damage of this kind on the region).

A majority of official weather observing stations (standard; near-surface) in the Citrus Belt measured their all-time coldest temperatures during the aforementioned freezes. The coldest temperature recorded in the state of Florida occurred in February 1899, when the thermometer dropped to −18.9°C in Tallahassee (Northern district). It is worth noting that Tallahassee is located within the northern panhandle, away from the central and south peninsula; even so, on consecutive nights on 13/14 December 1962 temperatures dipped below −3.3°C for 6–12h across much of the Citrus Belt (Johnson, 1963). In January 1977, the Orlando (Central district) area experienced six consecutive nights of temperatures below freezing, and snow fell as far south as Miami (Southern district), dusting many of the state's groves. The worst freezes historically have involved a deadly dose of very low temperatures for many hours on consecutive days. Extreme weather events such as these are usually marked by a sharp decline in temperatures supported by post-frontal windy conditions as cold air initially rushes in (i.e. an advection freeze) and are then followed by successive nights of clear sky and lighter winds in the presence of entrenched cold air (i.e. a radiation freeze). The multi-night Christmas Freeze of 1989 (from 22 to 26 December) is a good example of a scenario in which protective actions for one type of freeze early in the event were different from those later in the event. Importantly, the lingering effects of the major freezes of the 1980s have played a direct role in reshaping the current borders of the citrus industry and have spotlighted the risk for modern-day growers who may otherwise be anxious to reclaim a greater northward reach for their groves.

This article presents an investigation of the combined constraining effects of cold air outbreaks and landfalling hurricanes on citrus production in Florida's Citrus Belt. Meteorological data for known periods of decline in citrus production are examined. We do not consider the other abiotic (loss of farmland, etc.) or biotic (Huanglongbing or greening, canker and other diseases, pests, etc.) factors that are also known to adversely affect all-citrus production. Particular attention is given to the Indian River Growing District, a world-renowned grapefruit growing region (Figure 1).

Research method

The historical weather and climate data used in this study are available from the US National Centers for Environmental Information (NCEI). All-citrus production data is available from the United States Department of Agriculture (USDA) for the state of Florida for each of the five citrus growing districts and for individual counties. The data were analysed for the 40-year period ranging from the 1978/1979 growing season to the 2017/2018 season. For the purpose of this study, 'all-citrus' production is defined as the combined production of oranges, grapefruits and 'specialty fruits'. Included in specialty fruits are: tangelos, tangerines, temples (1978/1979 to 2005/2006, then counted as oranges), K-early (1978/1979 to 2001/2002), limes (1978/1979 to 2001/2002, then discontinued), and lemons (1978–2002, then discontinued).

Estimates of county production were prepared from objective survey data used in forecasting citrus crop production. The sample sizes used in the surveys and the distribution of the sample groves around the state were chosen to minimise error in the estimates of production, and these county-level data should not be considered to be as precise as the state or area level data (USDA, 2017).

Adverse effects of weather on Florida's citrus production

Like other agricultural industries within the state, Florida's citrus industry is vulnerable to tropical systems which can deliver destructive winds and devastating floods. Tropical storms are weaker than hurricanes, with winds of 63–118kmh^{-1}. Hurricanes produce winds of 119kmh^{-1} or more, and as a hurricane strengthens (from category 1 up to category 5), the scope of damage left in its wake increases exponentially. The Saffir–Simpson Hurricane Wind Scale, depicted in Table 1, is used to categorise hurricanes based on their wind speeds and corresponding estimates of potential property damage. Figures 2 and 3 reveal the number of occurrences of tropical storms and hurricanes over the region in which the Citrus Belt is situated, from 1978 to 2017. Figure 2 shows the tracks of a total of 55 tropical storms and hurricanes whose centres came within 240km of the central Citrus Belt (situated approximately at 27°39′00″N, 81°33′36″W), while Figure 3 shows the tracks of the 12 hurricanes whose centres came within 240km of the central Citrus Belt.

Tropical systems are typically large enough to place much (or all) of the Citrus Belt at risk at once. Tropical storm force winds are sufficient to result in increased fruit damage, especially fruit drop, at affected groves. Grapefruits are more susceptible than oranges due to the fact that the peak of the hurricane season (August–October) coincides with the maturing stage of the fruit, which grows to a large size and tends to form 'clumps'. Grapefruit, which is sold for the fresh fruit market, may be blemished or bruised as a result of these adverse weather conditions, considerably reducing the aesthetic value of the fruit and affecting overall profitability. As winds increase to hurricane force, branches and large limbs can be torn off, trunk and root systems severely stressed, and weaker/younger trees seriously damaged. Major hurricane winds in excess of 178kmh^{-1} (category 3) will likely uproot and destroy many trees. This type of damage not only impairs fruit yield and affects the quality of the fruit but also damages the overall health of the groves themselves across several seasons. High winds also spread pests and diseases across the state, both of which represent additional long-term problems for the citrus industry. For example, following Hurricane *Wilma* (2005) there was a rapid spread of citrus canker over affected areas. This promoted a further decrease in seasonal production for southern sections of the region in the wake of the devastating consequences of the historic 2004 hurricane season.

Table 1

The Saffir–Simpson Hurricane Wind Scale is a 1 to 5 rating based on a hurricane's sustained wind speed. The scale estimates potential property damage associated with each wind category.

Category	*Sustained winds*	*Type of damage to community*[a]	*Expected damage to citrus trees*[b]
1	74–95mph 64–82kn 119–153kmh^{-1}	**Very dangerous winds will produce some damage:** Well-constructed framed homes could sustain damage to roof, shingles, vinyl siding and gutters. Large tree branches will snap, and shallowly rooted trees may be toppled. Extensive damage to power lines and poles likely will result in power outages that could last for several days.	Some loss of leaves and fruit, heaviest in exposed areas.
2	96–110mph 83–95kn 154–177kmh^{-1}	**Extremely dangerous winds will cause extensive damage:** Well-constructed framed homes could sustain major roof and siding damage. Many shallowly rooted trees will be snapped or uprooted and block numerous roads. Near-total power loss is expected, with outages that could last from several days to weeks.	Considerable loss of leaves and fruit with some trees blown over.
3	111–129mph 96–112kn 178–208kmh^{-1}	**Devastating damage will occur:** Well-built framed homes may incur major damage or removal of roof decking and gable ends. Many trees will be snapped or uprooted, blocking numerous roads. Electricity and water will be unavailable for several days to weeks after the storm passes.	Heavy loss of foliage and fruit, many trees blown over.
4	130–156mph 113–136kn 209–251kmh^{-1}	**Catastrophic damage will occur:** Well-built framed homes may sustain severe damage, with the loss of most of the roof structure and/or some exterior walls. Most trees will be snapped or uprooted and power poles will be downed. Fallen trees and power poles will isolate residential areas. Power outages will for last weeks, possibly months. Most of the area will be uninhabitable for weeks or months.	Trees stripped of all foliage and fruit, many trees blown over and away from property.
5	157mph or higher 137kn or higher 252kmh^{-1} or higher	**Catastrophic damage will occur:** A high percentage of framed homes will be destroyed, with total roof failure and wall collapse. Fallen trees and power poles will isolate residential areas. Power outages will last for weeks, possibly months. Most of the area will be uninhabitable for weeks or months.	Damage would be almost indescribable – groves and orchards completely destroyed.

[a]Source: National Hurricane Center
[b]Source: Rouse *et al.*, 2006.

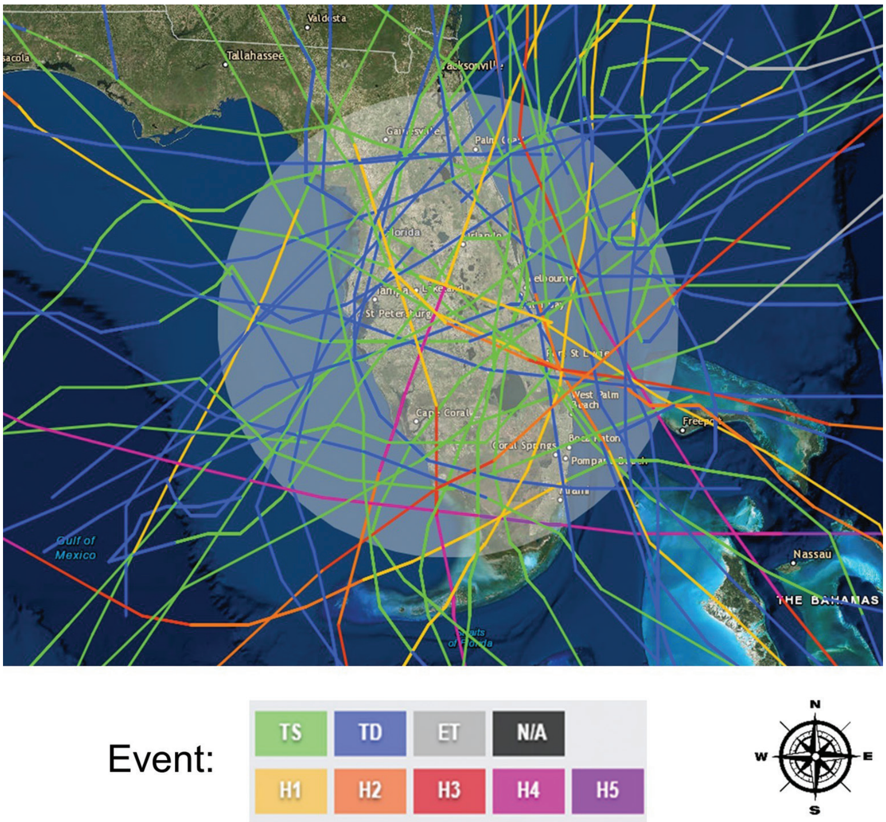

Figure 2. Centre track of all tropical storms and hurricanes (55 total) whose centre has tracked within 240km of the central Florida Citrus Belt (located at approximately 27°39′00″N, 81°33′36″W) for the hurricane seasons from 1978 to 2017. Legend: TS = tropical storm, TD = tropical depression, ET = extratropical, H1–H5 = hurricane (categories 1–5).

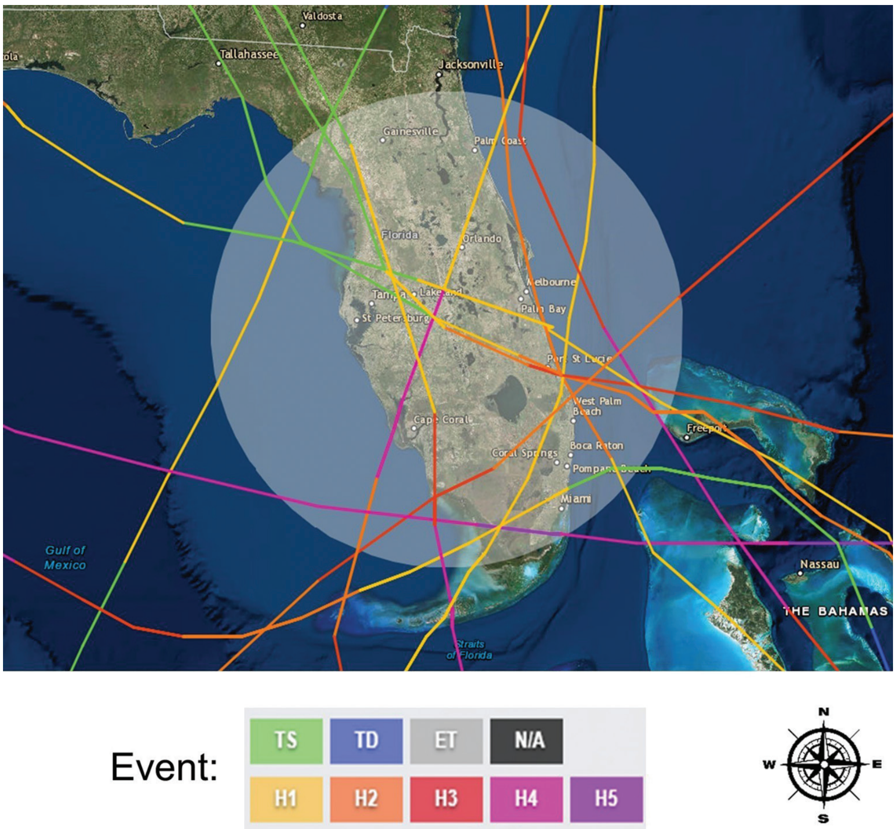

Figure 3. Centre track of all hurricanes (12 total) whose centre has tracked within 240km of the central Florida Citrus Belt (located at approximately 27°39′00″N, 81°33′36″W) for the hurricane seasons from 1978 to 2017. Legend: TS = tropical storm, TD = tropical depression, ET = extratropical, H1–H5 = hurricane (categories 1–5).

Tropical systems also bring excessive rain, which can result in flooding of low-lying groves. If not quickly treated or mitigated against, root rot can slow citrus tree growth and reduce fruit yield over a period of 6 months after the event. The measure and extent of rainfall is not a function of the intensity of a tropical system, but rather of its size and forward speed of motion (i.e. slowness). An erratic, slow-moving, or nearly stationary tropical system offers the greatest risk of excessive rain.

Tropical activity within the North Atlantic Ocean was relatively low during the 1970s and 1980s, but since 1995 it has exhibited an overall increase, and Florida has been subjected to the consequences of this increase. The Indian River District endured record activity in 2004 when Hurricane *Charley* (category 4) crossed the peninsula, moving from southwest Florida at Port Charlotte, travelling inland through Orlando, and then exiting near Daytona Beach (Indian River District) on 13 August. *Charley* was just the first of three hurricanes that would impact Florida's Citrus Belt that season. On 4 September, Hurricane *Frances* made landfall on the south end of Hutchinson Island (near Fort Pierce) as a category 2 hurricane. Frances was big and slow, hammering much of the district for well over a day, and the consequences for growers would prove to be pronounced. Then, adding insult to injury, Hurricane *Jeanne* (category 3) struck at approximately the same location on 25 September – just three weeks later. Evidence of the cumulative effect on citrus yield for the 2004/2005 growing season can be seen in Table 2, where the entire district suffered a decline of more than 33%, with the hardest hit locations experiencing a decline of as much as 75%.

Overall, the data show that most counties experience regular increases and decreases in citrus production on a season-by-season basis, with only a few seasons showing dramatic decreases. The same also applies to the growing area and state levels. A simple statistical box and whisker plot analysis was used to determine what measure of decline in all-citrus production was deemed to be significant, highly significant, and within the bounds of normal season-to-season changes. Using this approach, the study found that 22 of the 40 growing seasons analysed here experienced a decline in all-citrus production, relative to the previous growing season. Each of these years of decline were then used as single data points for the box and whisker plot. The results are displayed in Table 2. The table shows the percentage change (increase or decrease) in all-citrus production relative to the previous growing season. Our study defines a production decline of more

Table 2

Percentage change in all-citrus production for a 40-year period from 1978/1979 to 2017/2018. Years with decline are shaded in green; decline greater than 13% (deemed significant) is shaded in yellow; decline greater than 19% (deemed highly significant) is shaded in red. Data is analysed for state and growing district levels, as well as county level for the Indian River District Growing Area.

		Growing districts					*Indian River District (IRD) counties*					
Season	*State of Florida*	*Northern*	*Central*	*Western*	*Southern*	*IRD*	*Volusia*	*Brevard*	*Indian River*	*St. Lucie*	*Martin*	*Palm Beach*
1978/1979	−2.24%	−17.27%	[–][b]	−74.51%	309.89%	−1.77%	−17.66%	−6.96%	2.39%	−5.49%	3.16%	−0.78%
1979/1980	23.18%	57.97%	[–][b]	24.74%	11.23%	11.96%	58.82%	17.21%	11.40%	13.76%	10.44%	9.93%
1980/1981	−15.86%	−31.78%	[–][b]	−16.82%	−12.88%	1.90%	−29.63%	1.34%	−0.72%	1.59%	6.11%	2.97%
1981/1982	−20.69%	−29.79%	[–][b]	−25.22%	−20.67%	−9.51%	−34.22%	−26.90%	0.31%	−6.56%	−21.07%	−4.97%
1982/1983	2.32%	29.58%	[–][b]	15.03%	−6.98%	−8.74%	30.69%	13.09%	−13.74%	−8.29%	−9.27%	−15.70%
1983/1984	−12.43%	−47.20%	[–][b]	−36.97%	4.55%	9.81%	−49.76%	−34.74%	14.17%	10.96%	25.34%	17.26%
1984/1985	−6.28%	−96.58%	[–][b]	−40.46%	11.24%	23.31%	[–][c]	−3.85%	28.54%	25.89%	18.74%	19.37%
1985/1986	10.77%	13.33%	[–][b]	327.84%	−51.19%	−24.37%	[–][c]	−0.11%	−1.68%	−6.55%	8.62%	15.33%
1986/1987	3.13%	13.39%	360.39%	4.05%	−14.00%	−2.55%	[–][c]	31.66%	10.87%	8.92%	11.34%	1.38%
1987/1988	12.43%	37.18%	14.64%	27.39%	1.11%	8.24%	37.44%	7.32%	6.79%	10.61%	−0.38%	−0.55%
1988/1989	4.78%	54.58%	2.13%	11.50%	−2.17%	2.35%	6.55%	1.60%	1.06%	4.21%	−2.05%	−14.22%
1989/1990	−27.90%	−76.06%	−30.78%	−30.03%	−17.48%	−22.51%	−44.34%	−32.15%	−21.36%	−23.07%	−20.60%	−18.96%
1990/1991	33.39%	−92.49%	−17.37%	65.48%	86.46%	24.13%	18.02%	28.66%	22.79%	26.37%	69.26%	58.75%
1991/1992	−6.73%	965.36%	15.52%	−12.13%	−11.73%	−12.61%	−3.94%	−23.34%	−12.86%	−10.81%	−16.40%	−20.28%
1992/1993	31.14%	187.36%	42.96%	37.24%	22.89%	19.20%	29.74%	13.08%	18.36%	20.38%	16.39%	11.43%
1993/1994	−6.27%	44.47%	−2.17%	−2.31%	−9.62%	−15.40%	−5.53%	−21.71%	−16.24%	−13.02%	−21.89%	−32.07%
1994/1995	14.96%	44.87%	4.79%	10.71%	17.89%	23.27%	42.68%	26.90%	14.81%	28.81%	23.74%	4.68%
1995/1996	−2.08%	−0.56%	15.28%	−7.60%	−1.01%	−14.12%	−11.14%	−24.56%	−14.81%	−12.23%	−11.39%	−4.42%
1996/1997	11.28%	−2.46%	3.42%	14.89%	11.82%	19.52%	12.87%	26.09%	17.82%	20.42%	11.61%	9.10%
1997/1998	3.09%	52.39%	13.56%	7.71%	−9.17%	−6.46%	19.30%	−10.08%	−6.11%	−7.56%	−5.99%	−17.66%
1998/1999	−20.13%	−35.87%	−26.34%	−24.27%	−10.77%	−14.20%	−29.41%	−17.19%	−12.56%	−13.97%	−18.32%	−13.55%
1999/2000	22.73%	46.86%	30.12%	20.52%	19.47%	16.56%	31.94%	22.79%	14.37%	16.30%	21.76%	9.65%
2000/2001	−6.58%	−15.34%	−9.93%	−10.08%	5.82%	−12.44%	−14.74%	−12.36%	−11.73%	−11.87%	−2.20%	−4.17%
2001/2002	3.03%	14.66%	12.70%	8.78%	−10.93%	2.96%	33.02%	−1.08%	6.01%	1.48%	−9.05%	−16.93%
2002/2003	−12.62%	−11.59%	−6.76%	−16.22%	−9.15%	−21.66%	−18.79%	−20.18%	−22.58%	−21.23%	−10.16%	−15.92%
2003/2004	16.25%	14.02%	17.42%	20.51%	12.63%	15.04%	23.43%	−5.25%	16.59%	15.86%	11.37%	−23.32%
2004/2005	−42.00%	−35.88%	−40.88%	−52.39%	−14.00%	−76.22%	−60.88%	−60.96%	−75.79%	−75.58%	−33.91%	−57.00%
2005/2006	3.16%	31.00%	23.04%	47.07%	−47.82%	63.47%	68.64%	−3.40%	79.73%	46.81%	−33.98%	−57.31%
2006/2007	−7.19%	−43.09%	−30.37%	−21.43%	37.07%	48.78%	−19.30%	39.14%	63.49%	43.97%	23.93%	58.88%
2007/2008	25.76%	55.03%	38.38%	28.44%	16.88%	9.88%	36.09%	21.13%	12.51%	6.73%	3.59%	−34.51%
2008/2009	−7.16%	−12.27%	−3.18%	−1.67%	−9.30%	−18.23%	−6.71%	−23.60%	−17.24%	−13.38%	−24.96%	−29.04%
2009/2010	−15.78%	−3.82%	−7.76%	−15.43%	−26.98%	−17.08%	−9.25%	−26.67%	−16.01%	−17.11%	−41.01%	−58.65%
2010/2011	4.20%	−9.91%	6.71%	−2.26%	13.95%	−0.67%	−7.55%	7.78%	6.07%	−3.99%	−23.15%	[–][d]
2011/2012	2.98%	6.14%	3.86%	5.23%	3.82%	−6.39%	−14.29%	0.00%	−8.02%	−4.41%	−23.02%	[–][d]
2012/2013	−8.63%	−16.15%	−20.20%	−2.74%	4.56%	−11.86%	−16.19%	−7.85%	−11.91%	−9.34%	−7.07%	[–][d]
2013/2014	−20.55%	−23.75%	−20.58%	−24.90%	−21.55%	−6.37%	−8.52%	−18.57%	−5.40%	−7.79%	−35.13%	[–][d]
2014/2015	−9.14%	−21.20%	−15.35%	−3.65%	−4.87%	−10.53%	−12.42%	−20.08%	−12.00%	−7.07%	−27.84%	[–][d]
2015/2016	−16.47%	−35.64%	−24.73%	−13.23%	−10.82%	−11.21%	−21.28%	−12.30%	−13.17%	−8.14%	−15.14%	[–][d]
2016/2017	−17.06%	−41.10%	−5.89%	−9.15%	−24.37%	−30.79%	−27.93%	−68.06%	−28.08%	−32.02%	−33.92%	[–][d]
2017/2018[a]	−36.62%	−32.46%	−18.53%	−34.44%	−57.96%	−32.89%	−32.50%	−32.18%	−38.51%	−30.26%	−44.25%	[–][d]

[a]2017/2018 season data is preliminary.
[b]The growing area data for the period 1978/1979 to 1985/1986 are sorted differently from the data for the period 1986/1987 to present.
[c]Severe freeze damage to county crop resulted in no reported data for the 1984/1985 and 1985/1986 growing seasons.
[d]No county data was reported after the 2009/2010 growing season.

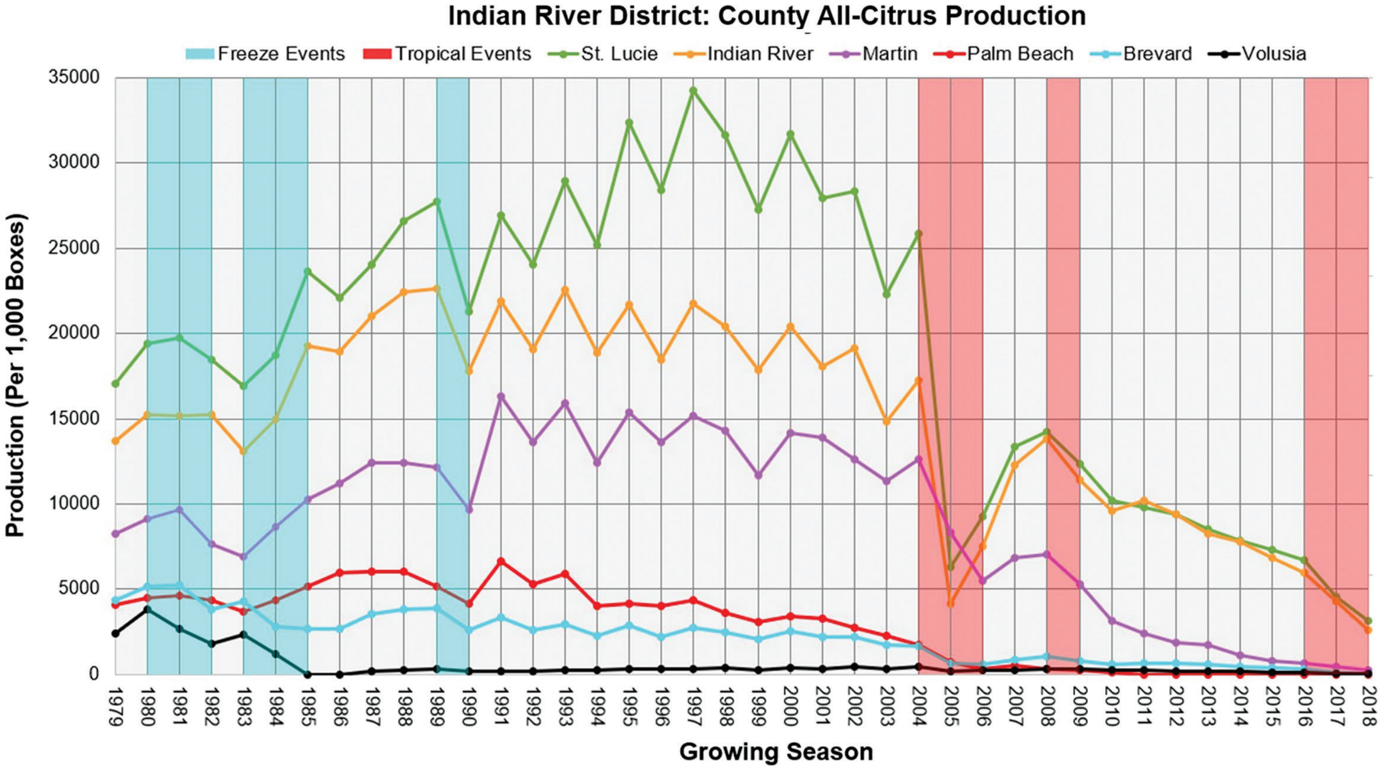

Figure 4. Citrus production in the Indian River Growing District for the growing seasons from 1978/1979 to 2017/2018. The teal bars represent significant freeze events, while the red bars represent significant tropical (hurricane and tropical storm) impacts. The general decline is caused by a mix of abiotic (weather-related, land loss, etc.) and biotic (pests, diseases, etc.) factors. However, the trend lines for each county show a significant drop in production following the 2004 and 2005 Atlantic Hurricane Seasons. The negative effects on fruit yield from the Christmas Freeze of 1989 can also be discerned. The 2017/2018 season data is preliminary (February 2019).

than 13% between two seasons as *significant* (yellow shading in Table 2), a decline of more than 19% as *highly significant* (red shading in Table 2), and a decline of between 0 and 13% as *within the bounds of normal season-to-season changes* (green shading in Table 2).

The 2005 hurricane season was remarkable and record-setting. However, its effects were confined more towards the southern end of the Indian River District and were largely associated with the passage of Hurricane *Wilma*, a category 3 storm that made landfall near Cape Romano (Southern district) and exited near Jupiter, Florida, on the east coast. Figure 4 shows the combined effects of the 2004 and 2005 hurricane seasons on citrus production in the Indian River District. Although several tropical storms impacted the area in the intervening time, it was not until Hurricane *Matthew* in 2016 that hurricane force winds returned to the Citrus Belt.

Citrus production in Florida has also declined drastically since 2005 due to the effects of citrus greening, or Huanglongbing, which is caused by *Candidatus* Liberibacter asiaticus, as well as canker (*Xanthomonas axonopodis*) and urban encroachment. This decline in citrus productivity has resulted in the loss of billions of dollars in citrus growers' revenue, affecting the economy at a regional level. These diseases have been described in multiple literature reviews (Bové, 2006; Dala-Paula *et al.*, 2019) and are currently the focus of dozens of research studies, which aim to find solutions.

From 2006 to 2015, the tropical hazards associated with the extreme weather events described here shifted from those caused by high winds (hurricane impacts) to those caused by flooding rain and tornadoes (cyclone hazards). Tropical Storm *Fay* in 2008 was perhaps the most notable, the passage of which resulted in rainfall in excess of 635mm at several locations. This extreme flooding is likely responsible, in part, for the appreciable declines in citrus production observed during the 2008/2009 growing season. The combined effects of multiple tropical hazards, such as Hurricanes *Matthew* (category 3) in 2016 and *Irma* (category 4) in 2017, likely contributed to the decreased citrus production seen in the 2016/2017 and 2017/2018 growing seasons.

Prior to 1995 (but within the period of study), tropical activity was more subdued. However, extreme cold events constituted an infrequent but recurring hazard. These events had notable adverse effects for the citrus industry. For example, in the 1980s five harsh winters with lengthy periods of hard freezes decimated citrus production in northern sections of the Citrus Belt. Again, the most prolific freeze was associated with a multi-day outbreak of cold air remembered by many as the Christmas Freeze of 1989.

Much of the region experienced temperatures that plummeted into the −4°C to −8°C range. As previously described, this historical and record-breaking freeze event lasted for five successive days/nights in December, during which windy conditions, along with a mix of wintry precipitation, knocked out power when the cold air arrived. It resulted in massive crop losses, with 30% of Florida's entire citrus industry taking an immense hit. Generational farms were put out of business and many workers were left unemployed (Miller, 1991). Within the Indian River District, an overall decline of 20–40% in production occurred, though a lot of fruit was quickly sent to juice factories.

Additionally, extreme droughts and wildfires, though rare in Florida, can lead to serious problems for citrus production if proper irrigation and field management techniques are not used. Prominent, extensive periods of dry conditions were observed in the Citrus Belt in 1998, 2000/2001, 2010/2011, and more recently in 2017. These drought conditions likely played a role in the decline in production experienced in those growing seasons. Most notably, the extreme 1998 heatwave and drought, from May to July, resulted in numerous destructive wildfires across Florida, along with record-setting temperatures that climbed to values in excess of 37.8°C, and the wet season, which typically starts in mid-to-late May, did not begin until July, as documented by NWS Melbourne (2018).

Conclusion

Hazardous weather is just one of many factors that has contributed to the overall decline in citrus production in Florida, but it is one of the most influential. The constraining effects of both cold air outbreaks and tropical systems are worthy of investigation by the industry. Historical data show that even single occurrences of these phenomena can have highly significant effects across the region in question, and in combination and across seasons, their occurrences have reshaped the borders of Florida's Citrus Belt and the Indian River District. These ideas are supported by analyses of the declines in citrus production, which have been examined relative to the values derived for the 50th and 75th percentiles. Here, a decline is considered significant when it reaches 13% and highly significant at 19%, relative to the previous growing season. Past hurricane and freeze events were then scrutinised to assess whether such events might have made significant contributions to such notable declines in the all-citrus yield.

It was found that the hyper-activity in hurricanes since 1995 has played a role in the decline in citrus production, and major tropical events in Florida were shown to be well-aligned with several of the growing seasons during which a significant decline in production was observed. The consequences of the 2004 hurricane season were probably most notable over the Indian River District, which endured three hurricane impacts, with two direct landfalls. It has also been shown that major cold air outbreaks were well-aligned with certain down seasons. The most notable example is the Christmas Freeze of 1989, which devastated the industry, but other freezes of the 1980s probably had significant effects on citrus production too, especially over northern sections of the state.

The Citrus Belt is situated at a unique location on the Florida Peninsula. To the north, there is a greater frequency of freezing temperatures and destructive hard freeze events. To the south, there is a higher frequency of hurricanes and greater exposure to destructive winds. Combined, they put the squeeze on Florida's citrus production. Specifics regarding the longer-term effects of climate change on Florida's weather are difficult to predict (Florida Climate Center – Office of the State Climatologist, 2018). However, seasonal variability in the coming decades will likely be marked by increases in the frequency of extreme weather events. Accounting for future periods of excessive rainfall and drought, pronounced heat and cold, and hyper-active (or hyper-dormant) tropical activity will be essential in order to bolster industry resilience. Additional constraining effects will probably be observed, alongside the continuation of known constraints related to factors such as urban encroachment, land use and water management.

As a final thought, the authors are reminded of the lessons learned over the past 125 years. After each deep freeze or hurricane landfall, hard-learned lessons have allowed for the continued success of Florida's citrus industry. After the Great Freeze of 1894/1895, USDA's Herbert J. Webber made mention that *the jolt of a future freeze should remind all growers to be more cautious of where, when, and what we plant…*; Webber noted that particular emphasis should be given to *where* (Webber, 1895). Over a century later the saying holds true, as many people forget the destructive nature of the hurricanes and cold air outbreaks of the past. The tolerance for risk increases further if the weather becomes tranquil during several successive growing seasons. Although local meteorologists are unsure as to whether such significant events will occur in any given season, they are certain that extreme weather events will continue to occur. Growers must be ready to withstand their destructive influence. Planning and preparation remain as crucial as ever.

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