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...
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 over- 
seen by the local National Weather Service (NWS) in Melbourne, Florida. The NWS 
Melbourne (2018) provides weather, water, and climate services to fulfill 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 cit-
rus industry) to provide weather observa-
tions, 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 pro-
vide 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, usher-
ing in frigid conditions across the predomi-
nantly temperate Florida Peninsula. The 
link between cold air outbreaks and dam-
age to citrus groves has been well docu-
mented throughout Florida’s history, most 
notably after the five devastating freezes of 
the 1980s (Miller, 1991). Catastrophic dam-
age to citrus trees can occur when tem-
peratures 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 cri-
teria 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 indus-
try occurred in December 1894, February 
1895, February 1899, the 1934/1935 win-
ter 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 observ-
ing 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 dis-
trict). It is worth noting that Tallahassee is 
located within the northern panhandle, 
away from the central and south pen-
insula; 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 consecu-
tive nights of temperatures below freeze-
ing, and snow fell as far south as Miami 
(Southern district), dusting many of the 
state’s groves. The worst freezes histori-
cally have involved a deadly dose of very 
low temperatures for many hours on con-
secutive 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 succes-
ive 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 bor-
ders of the citrus industry and have spot-
lighted 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 hur-
cricanes 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 coun-
ties. The data were analysed for the 40-year 
period ranging from the 1978/1979 growing 
season to the 2017/2018 season. For

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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)).
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 63–118km$^{-1}$. Hurricanes produce winds of 119km$^{-1}$ 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 178km$^{-1}$ (category 3) will likely uproot and destroy many trees. This type of damage not only impacts 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* | Expected damage to citrus trees* |
|----------|-----------------|-----------------------------|----------------------------------|
| 1        | 74–95mph        | 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. |
|          | 64–82kn         |                             |                                  |
|          | 119–153km$^{-1}$|                             |                                  |
| 2        | 96–110mph       | 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. |
|          | 83–95kn         |                             |                                  |
|          | 154–177km$^{-1}$|                             |                                  |
| 3        | 111–129mph      | 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. |
|          | 96–112kn        |                             |                                  |
|          | 178–208km$^{-1}$|                             |                                  |
| 4        | 130–156mph      | 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. |
|          | 113–136kn       |                             |                                  |
|          | 209–251km$^{-1}$|                             |                                  |
| 5        | 157mph 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. |
|          | 137kn or higher |                             |                                  |
|          | 252km$^{-1}$ or higher |                      |                                  |

*Source: National Hurricane Center
*Source: Rouse et al., 2006.
Extreme weather events and Florida's citrus production

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 | Volusia | Brevard | Indian River | St. Lucie | Martin | Palm Beach |
|-------------------|---------|---------|--------------|-----------|--------|-----------|
| Indian River District (IRD) counties | 1978/1979 | 1979/1980 | 1980/1981 | 1981/1982 | 1982/1983 | 1983/1984 | 1984/1985 | 1985/1986 | 1986/1987 | 1987/1988 | 1988/1989 | 1989/1990 | 1990/1991 | 1991/1992 | 1992/1993 | 1993/1994 | 1994/1995 | 1995/1996 | 1996/1997 | 1997/1998 | 1998/1999 | 1999/2000 | 2000/2001 | 2001/2002 | 2002/2003 | 2003/2004 | 2004/2005 | 2005/2006 | 2006/2007 | 2007/2008 | 2008/2009 | 2009/2010 | 2010/2011 | 2011/2012 | 2012/2013 | 2013/2014 | 2014/2015 | 2015/2016 | 2016/2017 | 2017/2018 | 2018/2019 |
| State of Florida | 1978/1979 | 1979/1980 | 1980/1981 | 1981/1982 | 1982/1983 | 1983/1984 | 1984/1985 | 1985/1986 | 1986/1987 | 1987/1988 | 1988/1989 | 1989/1990 | 1990/1991 | 1991/1992 | 1992/1993 | 1993/1994 | 1994/1995 | 1995/1996 | 1996/1997 | 1997/1998 | 1998/1999 | 1999/2000 | 2000/2001 | 2001/2002 | 2002/2003 | 2003/2004 | 2004/2005 | 2005/2006 | 2006/2007 | 2007/2008 | 2008/2009 | 2009/2010 | 2010/2011 | 2011/2012 | 2012/2013 | 2013/2014 | 2014/2015 | 2015/2016 | 2016/2017 | 2017/2018 | 2018/2019 |
| Northern | -2.24% | 23.18% | -15.86% | -20.69% | 2.32% | -12.43% | -6.28% | 10.77% | 3.13% | 12.43% | 4.78% | -27.90% | 33.39% | -6.73% | 12.14% | -2.08% | 11.28% | 3.09% | -20.13% | 22.73% | -6.58% | 3.03% | -12.62% | 16.25% | -42.00% | 3.16% | -7.19% | 25.76% | -7.16% | -19.53% | 15.78% | -9.05% | 2016/2017 | 2017/2018 |
| Central | -17.27% | 57.97% | -31.78% | -29.79% | 29.58% | -47.20% | 96.58% | 13.33% | 1.39% | 37.18% | 2.58% | -67.90% | -92.49% | -12.13% | -14.64% | -0.56% | -2.46% | 52.39% | -35.87% | 46.86% | -15.34% | 14.66% | -22.71% | -38.87% | -24.27% | -35.88% | 31.90% | -43.09% | 55.03% | -16.78% | -12.38% | 20.52% | -10.08% | -9.93% | -23.98% | -10.18% | -2.46% | -32.15% | 2016/2017 | 2017/2018 |
| Western | -74.51% | 24.74% | -16.82% | -25.22% | 15.03% | -36.97% | 40.46% | 327.84% | 360.39% | 360.39% | 360.39% | 11.50% | 17.37% | -12.13% | -7.60% | 3.42% | 13.56% | -35.87% | -24.75% | -15.34% | 8.78% | -11.59% | 14.02% | -38.88% | 30.00% | -43.09% | 38.38% | -16.78% | -12.38% | 20.52% | -10.08% | -9.93% | -23.98% | -10.18% | -2.46% | -35.87% | 2016/2017 | 2017/2018 |
| Southern | -1.77% | 11.23% | -12.88% | -20.67% | -6.98% | 4.55% | 11.24% | 14.89% | 14.97% | 14.97% | 14.97% | -2.17% | 17.37% | -11.73% | -1.01% | -2.46% | 13.56% | -35.87% | -24.75% | -15.34% | 5.39% | -16.22% | 17.42% | -52.39% | 30.00% | -43.09% | 38.38% | -16.78% | -12.38% | 20.52% | -10.08% | -9.93% | -23.98% | -10.18% | -2.46% | -35.87% | 2016/2017 | 2017/2018 |
| IRD | -17.66% | 17.21% | -2.39% | -26.92% | 30.68% | -14.00% | -3.85% | -11.84% | 12.34% | -14.24% | -17.42% | -19.15% | -27.21% | 4.55% | -11.24% | -1.01% | 13.56% | -35.87% | -24.75% | -15.34% | -10.93% | -2.17% | -16.22% | -52.39% | -14.00% | -14.97% | -13.56% | -16.78% | -12.38% | 20.52% | -10.08% | -9.93% | -23.98% | -10.18% | -2.46% | -35.87% | 2016/2017 | 2017/2018 |

*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.*

*Severe freeze damage to county crop resulted in no reported data for the 1984/1985 and 1985/1986 growing seasons.*
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/night 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 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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