A major agricultural crop in Florida, sugarcane (Saccharum spp.) production increased between 2010 and 2018 (Fig. 1). In 2017, Florida sugarcane production was 14,730,000 t, accounting for 53.8% of the total production in the United States. The total value of sugarcane at the farm level exceeds US$600 million annually (Schmitz et al., 2017). The interested reader should refer to Polopolus (2002) for an overview of world sugar.

This paper analyzes the dynamics of sugarcane and sugar yields in Florida from 1950 to 2018. During this period, there was a statistically significant increase in both sugarcane and sugar yields. Given these historical changes in Florida sugarcane varieties, we examine four scenarios with different combinations of periods. Scenario 1 is an overall summary for period 1950 to 2018. Scenario 2 uses 1980 as the breakpoint and separates the total data into 1950 to 1980 and 1981 to 2018. In Scenario 3, we use 1980 and 2000 as breakpoints and separate the data into 1950 to 1980, 1981 to 2000, and 2001 to 2018. In Scenario 4, we use 1968 and 2000 as breakpoints and separate the data into 1950 to 1968, 1969 to 2000, and 2001 to 2018. In our analysis, structural breaks are discussed in the context of investments in the development of new sugarcane varieties (Schmitz and Zhu, 2017). A structural break is an unexpected change over time in linear regression models. If structural breaks occur and are not accounted for in modeling, they can lead to large forecast errors, causing a model to become unreliable. Breakpoints are observations connecting two different periods and refer to the data point at which a structural break occurs. Thus, we pick our breakpoints based on the main changes in the adoption of genetics in Florida sugarcane.
Sugarcane is a grass species belonging to the genus *Saccharum* (Brumbley et al., 2009). Six sugarcane species are considered to be the most relevant to the development of modern sugarcane varieties based on their contribution: *S. barberi* Jeswiet, *S. edule*, *S. sinense* Roxb., *S. officinarum* L., *S. spontaneum* L., and *S. robustum* E.W. Brandes & Jeswiet ex Grassl (Brumbley et al., 2009). Before 1911, the Florida sugarcane industry was dominated by the “noble” cultivar (*S. officinarum*); after 1911, the Florida sugarcane industry turned to imported varieties, such as POJ 2725 and Co 290, from Java, Indonesia, and India (James, 1970). With Florida’s muck soil and the susceptibility to disease of some cultivars, it became necessary to develop new sugarcane cultivars adapted to Florida’s environment (Edmé et al., 2005). Genetic diversity and yield maintenance, which are highly desirable in sugarcane varieties, require investments in research and development (Edmé et al., 2005; Sparger et al., 2013; Schmitz and Zhu, 2017). The major participants in Florida sugarcane breeding research include the University of Florida, the USDA Canal Point sugarcane breeding station (the CP cultivars), and the Florida Sugarcane League, a private organization (Edmé et al., 2005). They work collaboratively to cross high-yielding canes with disease-resistant canes (Gilbert, 2013). In 2000, CP cultivars accounted for roughly 90% of all cultivars grown in Florida, based on acreage (Comstock et al., 2004). The first two major sugarcane cultivars developed in Florida, CL 41-0223 and CP 63-0588, were released in 1956 and 1968, respectively. Following Edmé et al. (2005), we use 1968 as the year to evaluate the gains from varietal development. From 1968 to 1980, the Florida sugarcane industry was dominated by cultivars CL 41-0223 and CP 63-0588, where the main focus was on improving sugarcane yield rather than sucrose content (Edmé et al., 2005). During the same period, a series of new diseases wreaked havoc on the Florid sugarcane industry, including smut (*Sporisorium scitaminea* (Syd.) M. Piepenbr., M. Stoll & Oberw.), leaf scald (*Xanthomonas albilineans* (Ashby) Dowson), and rust (*Puccinia melanocephala* Syd. & P. Syd.) (Edmé et al., 2005). Under the disease pressure, Florida sugarcane breeders had to adjust their strategies to acquire both higher yield and higher sucrose content. As a result, cultivars CP 70–1133, CP 72–1210, CP 72–2086, and CP 80–1827 were developed and implemented after 1980. Therefore, we use 1980 as a breakpoint for our study.

With advancements in research and development, sugarcane cultivars in Florida continue to change. The percentage change in the adoption of different cultivars varied from 1989 to 2005 (Fig. 2). Sugarcane cultivar CP 72–1210, which accounted for >45% of the total planting acreage in Florida in 1989, dropped to <1% by 2000. Cultivar CP 72–2086 was the most popular variety between 1992 and 1999, before being replaced by cultivar CP 80–1743, which peaked at 33% in percentage of total planting acreage in 2004. The decline in the use of cultivars CP 72–1210 and CP 72–2086, which were widely used during the period of 1980 to 1999, marks one of the breakpoints in our study. Cultivar CP 88–1762, which emerged in 1997, became the most popular sugarcane cultivar in Florida in 2008. Cultivars CP 88–1762 and CP 80–1743 were the most widely grown cultivars in Florida from 2008 to 2011 (Sandhu et al., 2001). Since 2014, cultivar CP 96–1252, which has high cane yield and is orange rust (*Puccinia kuehnii* (Kruger) E. Butler) resistant (Sandhu and Davidson, 2016; VanWeelden et al., 2018), has been the most widely grown variety in Florida, occupying 53,234 ha of land in 2017 (Fig. 3).

![Fig. 1. US sugarcane production in thousand tonnes by state, 2009 to 2018 (USDA-NASS, 2019).](image1)

![Fig. 2. Percentages of selected sugarcane cultivars to total planted acreage, 1989 to 2005 (data for figure taken from Glaz and Gilbert, 2006).](image2)


MATERIALS AND METHODS

To evaluate Florida sugarcane and sugar yields, we follow the piecewise linear model used by Schmitz and Zhu (2017):

\[
y = \sum_{i=1}^{n} \alpha_i d_i + \sum_{i=1}^{n} \beta_i d_i + \mu \quad [1]
\]

where \( y \) is the cane yield, \( t \) is the time variable, \( d_i \) is the dummy variable we use to divide the observations into different periods, and \( n \) is the number of periods. \( \alpha_i \) and \( \beta_i \) denote the constant and the annual sugarcane yield increase rate, respectively, for the \( i \)th period, and \( \mu \) is the error term that follows a normal distribution with \( E(\mu) = 0 \).

Equation [1] is a piecewise linear regression with \((n - 1)\) breakpoints (we choose \( n = 1, 2, \) and \( 3 \) in this paper), and linear regression analysis within each subperiod. Breakpoints are observations that determine the occurrence of structural break within a series of data.

Compared with Edmé et al. (2005) and Schmitz and Zhu (2017), the data used in this study cover a longer period (1950–2018). We used yields based on official Florida sugarcane and sugar statistics covering this period provided by the USDA National Agricultural Statistics Service (USDA-NASS, 2019).

Unlike previous studies, we test whether breakpoints are related to sugarcane genetics. We use the Chow test (Chow, 1960) to find breakpoints by determining whether the parameters are equal in two linear regressions of different but attached subperiods (e.g., \( \beta \) and \( \beta_3 \) in Scenario 2), where we choose the breakpoint to be 1980 and \( N = 2 \). The Chow test is commonly used to test for structural breakpoints in some or all of the parameters of a scenario. Basically, it tests whether one regression line or two separate regression lines best fit a split set of data. The Chow test is an application of the \( F \) test, and it requires the sum of squared errors from three regressions: one for each sample period and one for the pooled data.

The test statistics can be calculated as

\[
\frac{\sum_{i} (S_i - (S_1 + S_2))/k}{(S_1 + S_2)/(N_1 + N_2 - 2k)} = F(k, N_1 + N_2 - 2k) \quad [2]
\]

where \( S_i \) and \( S_j \) denote the sum of the squared residuals from both subperiods, one before the breakpoint and one after the breakpoint, and \( S_j \) represents the sum of squared residuals of the combined periods. In this Chow test, \( N_1 \) is the number of observations from the first subperiod and \( N_2 \) represents the number of observations from the second one, while \( k \) is the total number of parameters in the regression (\( k = 2 \) in this case).

RESULTS

Regression of the Chow Test

Most of the breakpoints used are significant (Table 1). This result supports our hypothesis that the introduction of genetically improved new sugarcane cultivars has significantly affected both sugarcane yield and sugar yield.

Scenario 1: Overall Linear Regressions (1950–2018)

The percentage increase in Florida sugar yields exceeded sugarcane yield for 1950 to 2018 (Table 2, Fig. 4A and 4B). Sugarcane yield showed an annual increase of 0.143 Mg ha\(^{-1} \) (\( P < 0.01 \)), whereas sugar yield showed an annual increase of 0.056 Mg ha\(^{-1} \) (\( P < 0.01 \)). This result is consistent with results published by Edmé et al. (2005).

Since 1950, sugar yield has increased by roughly 78%, compared with a 30% increase in sugarcane yield. This difference in yield can be explained by research efforts to improve both sugarcane yield and sugar content. Sugarcane has a high water content accounting for \( \sim 75\% \) of total weight of the plant, and normally sugar content of sugarcane ranges from 10 to 15% on a fresh cane basis.

Sugar yield can be represented by sugarcane yield and sugar content in the following equation:

\[
\text{Sugar yield (SY)} = \text{Sugarcane yield (CY) × Sugar content (SC)} \quad [3]
\]

We derive the following equation:

\[
\frac{dSY}{SY} = \frac{dCY}{CY} + \frac{dSC}{SC} \quad [4]
\]

The percentage change in sugar yield equals the sum of the percentage changes in sugarcane yield and sugar content. In Florida, the greater increase in sugar yield compared with sugarcane yield is due largely to the successful sugarcane breeding projects that have combined higher tonnage and sugar content in sugarcane cultivars.

The annual fluctuation of sugar content and growth varied over the period 1950 to 2018 (Fig. 4C). Sugar content has steadily increased over the past 69 yr at a significant rate of 0.50 kg Mg\(^{-1} \) yr\(^{-1} \) (\( P < 0.001 \)). Improving sugar content increases sugar yield. Edmé et al. (2005) argues that it is even more effective than improving cane yield, since improving cane yield intro- duces a greater amount of biomass that would potentially undermine the milling efficiency. In a study on Australian sugar, Jackson (2005) points out that there are difficulties in achieving improvements in sugar content. At least prior to 2005, there had not been significant improvements in sugar content in Australian sugar production. The increase in sugarcane yield contributes the most to the increase in sugar yield.
Scenario 2: Breakpoint (1980)

We further examine the changes in the Florida sugarcane and sugar yields for two separate periods: 1950 to 1980 and 1981 to 2018 (Table 3, Fig. 5A and 5B). For the first period (1950–1980), sugarcane yields and sugar yields showed annual decreases of 0.299 (\(P < 0.05\)) and 0.013 Mg ha\(^{-1}\) (\(P < 0.05\)), respectively. For the second period (1981–2018), increases in both were statistically significant. The annual growth of sugarcane yield was 0.434 Mg ha\(^{-1}\) (\(P < 0.01\)), whereas sugar yield showed a significant increase of 0.088 Mg ha\(^{-1}\) (\(P < 0.01\)).

Scenario 3: Breakpoints (1980 and 2000)

In Scenario 3, we consider three periods (1950–1980, 1981–2000, and 2001–2018) to determine Florida sugarcane and sugar yield changes over time (Table 4, Fig. 6A and 6B). For 1950 to 1980, there was a nonsignificant (\(P > 0.05\)) decrease in sugar yield, whereas sugarcane yield showed a significant decrease (0.299 Mg ha\(^{-1}\) annual decrease, \(P < 0.05\)). For 1981 to 2000, there was a significant annual increase in both types of yields (0.664 Mg ha\(^{-1}\) for sugarcane yield and 0.156 Mg ha\(^{-1}\) for sugar yield, \(P < 0.01\)). For 2001 to 2018, sugarcane yield remained at a high rate of annual growth, whereas sugar yield annual growth decelerated, though still statistically significant (\(P < 0.10\)).

Scenario 4: Breakpoints (1968 and 2000)

Previously, Edmé et al. (2005) used linear trend analysis to find that for the period 1969 to 2000, there were significant increases in yields of both sugarcane and sugar (Table 5, Fig. 7A and 7B). We present results for the three first period (1950–1980), sugarcane yields and sugar yields showed annual decreases of 0.299 (\(P < 0.05\)) and 0.013 Mg ha\(^{-1}\) (\(P < 0.05\)), respectively. For the second period (1981–2018), increases in both were statistically significant. The annual growth of sugarcane yield was 0.434 Mg ha\(^{-1}\) (\(P < 0.01\)), whereas sugar yield showed a significant increase of 0.088 Mg ha\(^{-1}\) (\(P < 0.01\)).

**Table 1. Sugar and sugarcane yields: Chow test for chosen breakpoints, 1968, 1980, and 2000.†**

<table>
<thead>
<tr>
<th>Breakpoint</th>
<th>Sugar yield</th>
<th>Sugarcane yield</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>(t) statistics</td>
<td>(df^2)</td>
</tr>
<tr>
<td>1980 (Scenario 2)</td>
<td>11.09</td>
<td>65</td>
</tr>
<tr>
<td>1980 (Scenario 3)</td>
<td>14.06</td>
<td>47</td>
</tr>
<tr>
<td>2000 (Scenario 3)</td>
<td>2.97</td>
<td>34</td>
</tr>
<tr>
<td>1968 (Scenario 4)</td>
<td>7.79</td>
<td>47</td>
</tr>
<tr>
<td>2000 (Scenario 4)</td>
<td>0.54</td>
<td>46</td>
</tr>
</tbody>
</table>

† \(t\) statistics calculated in the \(F\) test always follows distribution \(F(k, N_1 + N_2 - 2k)\), and \(k\) is the number of parameters in a single regression (two in this case). We therefore only present the second \(df\) in the table \((N_1 + N_2 - 2k)\).

**Table 2. Means (and SEs) of regression: Florida sugarcane and sugar yields and sugar content, 1950 to 2018.†**

<table>
<thead>
<tr>
<th>Estimated parameters</th>
<th>Sugarcane yield</th>
<th>Sugar yield</th>
<th>Sugar content</th>
</tr>
</thead>
<tbody>
<tr>
<td>(\alpha_1)</td>
<td>-206.62 ± 83.99*</td>
<td>-102.78 ± 11.71***</td>
<td>-882.63 ± 137.05***</td>
</tr>
<tr>
<td>(\beta_1)</td>
<td>0.14 ± 0.04**</td>
<td>0.06 ± 0.01***</td>
<td>0.50 ± 0.07***</td>
</tr>
</tbody>
</table>

* ** *** Significant at the 0.05, 0.01, and 0.001 probability levels, respectively.

† Results from Table 2 are based on Scenario 1.

**Scenario 2: Breakpoint (1980)**

We further examine the changes in the Florida sugarcane and sugar yields for two separate periods: 1950 to 1980 and 1981 to 2018 (Table 3, Fig. 5A and 5B). For the first period (1950–1980), sugarcane yields and sugar yields showed annual decreases of 0.299 (\(P < 0.05\)) and 0.013 Mg ha\(^{-1}\) (\(P < 0.05\)), respectively. For the second period (1981–2018), increases in both were statistically significant. The annual growth of sugarcane yield was 0.434 Mg ha\(^{-1}\) (\(P < 0.01\)), whereas sugar yield showed a significant increase of 0.088 Mg ha\(^{-1}\) (\(P < 0.01\)).


In Scenario 3, we consider three periods (1950–1980, 1981–2000, and 2001–2018) to determine Florida sugarcane and sugar yield changes over time (Table 4, Fig. 6A and 6B). For 1950 to 1980, there was a nonsignificant (\(P > 0.05\)) decrease in sugar yield, whereas sugarcane yield showed a significant decrease (0.299 Mg ha\(^{-1}\) annual decrease, \(P < 0.05\)). For 1981 to 2000, there was a significant annual increase in both types of yields (0.664 Mg ha\(^{-1}\) for sugarcane yield and 0.156 Mg ha\(^{-1}\) for sugar yield, \(P < 0.01\)). For 2001 to 2018, sugarcane yield remained at a high rate of annual growth, whereas sugar yield annual growth decelerated, though still statistically significant (\(P < 0.10\)).

**Scenario 4: Breakpoints (1968 and 2000)**

Previously, Edmé et al. (2005) used linear trend analysis to find that for the period 1969 to 2000, there were significant increases in yields of both sugarcane and sugar (Table 5, Fig. 7A and 7B). We present results for the three...
We emphasize the importance of genetics in bringing about yield increases for both sugarcane and sugar, as did Edmé et al. (2005) and Schmitz and Zhu (2017), by reviewing and highlighting the major genetic developments in sugarcane production in Florida. Our results show impressive increases in sugarcane and sugar yields after 1980 based on the development of new sugar-cane varieties and mechanization. This was not the case for 1950 to 1980. Although sugarcane and sugar yields showed a statistically significant decrease for 1950 to 1968, they displayed statistically significant increases for 1969 to 2000 and 2001 to 2018. These findings are consistent with the study by Edmé et al. (2005) that showed an increase in sugarcane and sugar yields for a shorter period, 1969 to 2000 (approximately 47% for sugarcane yield and 53% for sugar yield), due largely to improvements in genetics.

The first period (1950–1968) did not show a significant decrease in either sugarcane or sugar yields. For the second (1969–2000) and third (2001–2018) periods, both were statistically significant. Sugarcane yield increased by 0.292 Mg ha⁻¹ (P < 0.01) for the second period and 0.691 Mg ha⁻¹ (P < 0.05) for the third period, whereas sugar yield increased by 0.094 Mg ha⁻¹ (P < 0.01) for the second period and 0.096 Mg ha⁻¹ (P < 0.05) for the third period.

**Table 4. Piecewise regression of Florida sugarcane and sugar yield, 1950 to 2018.†**

<table>
<thead>
<tr>
<th>Estimated parameter</th>
<th>Sugarcane yield</th>
<th>Sugar yield</th>
</tr>
</thead>
<tbody>
<tr>
<td>α₁</td>
<td>663.02 ± 274.23*</td>
<td>32.32 ± 34.04ns‡</td>
</tr>
<tr>
<td>β₁</td>
<td>−0.3 ± 0.14*</td>
<td>−0.01 ± 0.02ns</td>
</tr>
<tr>
<td>α₂</td>
<td>−1245.53 ± 326.11**</td>
<td>−301.44 ± 46.25***</td>
</tr>
<tr>
<td>β₂</td>
<td>0.66 ± 0.16***</td>
<td>0.16 ± 0.02***</td>
</tr>
<tr>
<td>α₃</td>
<td>−1304.95 ± 559.21*</td>
<td>−183.51 ± 90.52ns</td>
</tr>
<tr>
<td>β₃</td>
<td>0.69 ± 0.28*</td>
<td>0.10 ± 0.05*</td>
</tr>
</tbody>
</table>

*, **, *** Significant at the 0.05, 0.01, and 0.001 probability levels, respectively.

† Based on Scenario 3, we chose the breakpoints to be 1980 and 2000.

‡ ns, not significant.

**Table 5. Piecewise regression of Florida sugarcane and sugar yield: 1950 to 1968, 1969 to 2000, and 2001 to 2018.†**

<table>
<thead>
<tr>
<th>Estimated parameter</th>
<th>Sugarcane yield</th>
<th>Sugar yield</th>
</tr>
</thead>
<tbody>
<tr>
<td>α₁</td>
<td>788.12 ± 642.33ns‡</td>
<td>68.62 ± 82.23ns</td>
</tr>
<tr>
<td>β₁</td>
<td>−0.3632 ± 0.33ns</td>
<td>−0.03 ± 0.04ns</td>
</tr>
<tr>
<td>α₂</td>
<td>504.52 ± 206.14*</td>
<td>177.80 ± 28.26***</td>
</tr>
<tr>
<td>β₂</td>
<td>0.29 ± 0.10**</td>
<td>0.09 ± 0.01***</td>
</tr>
<tr>
<td>α₃</td>
<td>−1304.95 ± 559.21*</td>
<td>−183.51 ± 90.52ns</td>
</tr>
<tr>
<td>β₃</td>
<td>0.69 ± 0.28*</td>
<td>0.10 ± 0.05*</td>
</tr>
</tbody>
</table>

*, **, *** Significant at the 0.05, 0.01, and 0.001 probability levels, respectively.

† Based on Scenario 4, we chose the breakpoints to be 1968 and 2000.

‡ ns, not significant.
The study by Schmitz and Zhu (2017) showed that the significant increases for sugarcane and sugar yields for 2001 to 2006 were directly related to investments in new sugarcane varieties. Edmé et al. (2005) emphasized the importance of genetic improvement on yields over the period of 1969 to 2000. Our findings based on a longer period, 1950 to 2018, strengthen these earlier results and improve on the model used by Schmitz and Zhu (2017). Unlike previous studies, we test whether breakpoints are related to sugarcane genetics. We further confirm the validity of our model by incorporating a Chow test to determine the statistical relationship between sugarcane genetics and the breakpoints we use in the model.

There has been an increased interest in the economics of new varietal development for agricultural crops since the pioneering work of Griliches (1960). He estimated that the rate of return from hybrid corn (*Zea mays* L.) research in the United States was roughly 90%. Since then, other researchers have reported that the return on investment in varietal development in other selected crops is in the neighborhood of 35% (Fuglie and Heisey, 2007; Schmitz et al., 2010). However, little work has been done on the economics of the introduction of new sugarcane varieties.

Future work could build on our findings to formally estimate the rates of return in the development of new sugar varieties. In the framework outlined by Schmitz et al. (2010) and Schmitz and Zhu (2017), it is necessary to calculate the gains and costs from research and development, which would be easy to do since the research and development is limited to the USDA, University of Florida, and the Florida Sugar Cane League. It appears likely that the rate of return could exceed 30%.

When calculating rates of return to research, other factors should also be taken into account. First, mechanization has had a positive impact on yield, with essentially all sugarcane in the United States being mechanically harvested. Edmé et al. (2005) and Schmitz and Moss (2015) suggest that mechanization contributes 30 to 35% of the yield increases due to significant improvements in mechanized technology. For example, the new mechanical harvesters are equipped with vertical pickup augers that are capable of harvesting flat sugarcane stalks (Schmitz and Moss, 2015). Mechanization has also reduced labor costs for both planting and harvesting (Baucum and Rice, 2006). Second, research and development has greatly improved yield maintenance (Schmitz and Zhu, 2017). Third, sugar production in Florida has contributed to the deterioration of the Florida Everglades due to phosphorus runoff (Schmitz et al., 2012, 2013). Research and development efforts could help alleviate this problem.

**Conflict of Interest**
The authors declare that there is no conflict of interest.

**Acknowledgments**
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**References**