The Devolution of Bt Maize Yields in South Africa: A Case Study of Potential Resistance and its Yield Implications.

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Relevance of Topic

South Africa is one of the largest GM maize producers in the world; in 2016, 74% of the country's total maize crop used HT cultivars, while 91% of the country's entire maize crop used Bt cultivars (Brookes and Barfoot, 2018). Starting in the 2004/2005 season, South African maize producers noted severe maize stalk borer (*Busseola fusca*)-associated damage to Cry1Ab-expressing Bt maize (Bouwer, 2020). The reduced pest control (>10% damaged plants) in the 2004/2005 season was attributed to the development of insect resistance to the Cry1Ab protein in MON810 maize (Kruger et al., 2011). By the 2007/2008 and 2008/2009 maize growing seasons, there was widespread resistance to MON810 in the area around Christiana and Vaalharts in the North West and Northern Cape provinces, respectively, and by 2012 B. fusca populations with resistance to Cry1-Ab expressing maize were found throughout maize production in South Africa (Kruger et al., 2011). While many field-level studies (Strydom et al., 2018) have reported the presence of Bt-resistant insects across South Africa to our knowledge, there has not been a countrywide aggerated study that tried to test for the presence of reduced Bt yields across time due to potential resistance. Given the relative importance of maize in the South African diet and the heavy reliance on Bt for insect control, this study tries to shed light on the yield of Bt over time compared to conventional maize hybrids.

Changes in relative differences between Bt and conventional yield can be attributed to several factors; improved germplasm targeted in varieties with stacked traits (Bt and herbicide tolerance), a shift in breeding funding towards conventional varieties as consumer pressure mounts against GM crops, insect resistance to Bt, a paradigm shift in breeding trait outcomes such as drought tolerance, etc. While most studies provide average yield gains of Bt adoption over time, very few monitor how these yield gains evolve relative to conventional varieties. This literature gap is important because while most studies acknowledge the presence of a yield premium associated with Bt adoption, none have estimated how that premium has evolved across space and time.

A National Academy of Science statement in 2016 suggested that there was little evidence for transgenic crops increasing yields (NASEM, 2016). Thus, the first objective of this study was to assess whether Bt maize has increased yields compared to conventional maize in South Africa since its commercial introduction. A similar study (Shew et al. 2021) compared GM and conventional yields in South Africa but did not disaggregate between herbicide tolerance and insect resistance (Bt), nor did they investigate the evolution of the GM effect across time. The second objective was to assess whether the relative yield difference between Bt and conventional maize has evolved. This study is the first of its kind to estimate if there is a yield premium with Bt adoption and how that premium may have evolved.

Research Methodology

We use a robust dataset that included 85,133 yield observations spanning 36 years (1980-2018 with no data available in 1982, 1991, or 2014), 104 locations, and 702 cultivars. Our statistical model for estimating the yield gains associated with GM cultivars leverages field-trial-location-by-year fixed effects to control for omitted variable bias from unobserved factors that could be correlated with the appearance (or performance) of GM cultivars in the trial. The location component controls for all time-invariant factors at the location level (e.g., climate, soil quality), while the year component effects control for pest pressure, weather shocks, and non-GM technological improvements over time that are common across all cultivars. These include management improvements (e.g. increased fertilizer), widespread droughts or heat waves, "stock" germplasm improvements that are common to both conventional and GM cultivars, and evolutions of pest pressure either through a change in population or resistance to pest management strategies that include GE-specific traits. By crossing these fixed effects, note the use of "by" in the leading sentence above, we are also able to control for any of the above confounders at the location-year level.

Results

The main takeaway from our results is that GM cultivars have exhibited a yield advantage relative to conventional, but this advantage begins eroding around the time that Bt resistance was first reported in South Africa and then seems to improve at least for a subset of stacked (Bt and herbicide tolerant) cultivars. We find an increase in the estimated gains up to approximately 6 years after GM cultivars were introduced, i.e., 2004, which is associated with a yield gain of 0.45 MT/ha (p-value < 0.001), after which they decrease substantially to the 16th year after GM was introduced, i.e., 2014. While still greater than zero at approximately 0.15 MT/ha (p-value < 0.001), the yield effect among cultivars released 16 years after 1999 (in 2014) represents a nearly 70% reduction from its high in 2004.

These results suggest that Bt maize yields have declined, relative to conventional maize cultivars, due to either resistance or a shift in breeding priorities. Importantly, our initial estimated yield decline lines up with the first confirmations of on the ground resistance. Further, our study highlights that once Cry proteins were stacked (meaning another method to combat resistance) yields of Bt cultivars began to increase, relative to conventional, again.

Potential for generating discussion during the meeting.

This study highlights an ongoing challenge threatening the long-term effectiveness of Bt crops is their widespread adoption coupled with high selection pressure on target insects and low producer compliance with non-Bt structured refuge recommendations. While several field studies have confirmed the presence of Bt resistance, there have been none that model its impacts on a national level. This study has the potential to generate discussion at the AAEA meetings in that it highlights the importance of good stewardship in GM crops and the impact that resistance can have on Bt maize yields and ultimate food security implications. Further, this study shows just how fragile embedded seed technology can be and the implications of "losing" a technology that is heavily relied upon for ensuring food security for a direct food-to-plate crop like GM maize in South Africa.

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