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Evolution of Bacillus thuringiensis Maize Yields in South Africa

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Evolution of *Bacillus thuringiensis* Maize Yields in South Africa

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Abstract

The economic and environmental benefits of genetically modified (GM) maize in South Africa have been well documented in previous literature. However, concerns about the longevity of these benefits, have been raised following reports of *Busseola fusca* developing resistance to *Bacillus thuringiensis* (*Bt*) maize in South Africa in 2006. This study uses empirical data to estimate the potential impact of insect resistance on yields and estimates the economic and food availability impacts of genetic deterioration of *Bt* maize. Using data from South African National Maize Cultivar trials from 1989-2018, yield gains from *Bt* are observed to peak for *Bt* maize in 8 provinces from 2006-2010, causing estimated yield losses of 2,080,122 metric tons between 2008 and 2019, which is an estimated loss of $389.6 million USD.

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Education). However, the contents of the thesis do not necessarily represent the policy of the supporting agencies, and you should not assume endorsement by the supporting agencies.

Dedication

I dedicate this work to my ancestors who gave me the opportunities, resilience, and faith to achieve my dreams, specifically my grandmother, Dorothy Fay Cooper.

Table of Contents

Introduction

Genetically modified (GM) crops have provided economic and social benefits since becoming available for commercial production in the US in 1996 (Klümper & Qaim, 2014; Pray et al., 2002; Xu et al., 2013). The global economic gains from GM adoption is estimated at $224.9 billion USD distributed amongst more than 16 million farmers (ISAAA, 2019) via increased yields (Huang et al., 2008; Shi et al., 2013; Xu et al., 2013) and decreased pesticide and herbicide costs as well as increased household income (Kathage & Qaim, 2012). In addition to economic gains, GM crops have been found to have socioeconomic impacts that can improve producer quality of life such as environmental benefits and labor-saving technology (Brookes & Barfoot, 2010; Lusk et al., 2017). These economic gains are particularly beneficial for producers in low-income countries as economic gains attributed to GM crops are 60% higher per acre in low-income countries than high-income countries (Morse et al., 2004). Because GM crops can potentially provide a more cost-effective solution for producers in low-income countries who usually face fewer options for pest management and higher rates of crop vulnerability, producers in these areas have experienced the largest economic benefits from GM crop adoption.

Good stewardship such as crop and technology rotation are necessary for the continued success of GM crops. Decreased benefits have been experienced in areas where protocols were not followed properly; for example, much of the glyphosate-resistant weed population evolved due to reliance on glyphosate as the sole method of weed control, or when low rates/non-lethal doses, used to save money, were applied for an extended period of time (Nandula*,* 2010*)*. For crops that use *Bascillius thuringensis* genes, or *Bt* crops, strong integrated pest management (IPM) practices are necessary prevent insect resistance from developing, which is a major concern associated with the technology (Bates et al., 2005). Resistance to *Bt* genes is possible in any area that widely adopts *Bt* crops unless proper IPM strategies are in place and has been observed in several countries with high *Bt* adoption including but not limited to the United States, South Africa, China, India, and the Philippines.

The first reports of *Busseola fusca* developing resistance to *Bt* maize in South Africa occurred during the 2006 production year (Van Rensburg 2007). A study by Van den Berg (2013) constructed a timeline of resistance and contributing factors, presenting the theory that the single gene approach to *Bt* genetics as well as limited IPM techniques contributed the quick development of resistance. Van Den Berg asserts that Cry1Ab toxin has lost its efficacy against B. fusca at many localities throughout maize producing regions, and that field tests prior to the commercial release in South Africa showed warning signs for potential resistance development. Between the first plantings of Bt maize during the 1998/1999 growing season and the first report of resistance in 2007, no monitoring or systematic evaluation was done.

Bt maize in South Africa primarily relies on Cry1Ab toxin for pest control against *B. fusca*, and significant levels of survival of the pest were observed even after the first year of commercial release. Van den Berg in 2013 also documented field resistance in South Africa during the 2006-2014 period, indicating the predicted rate of resistance evolution was underestimated (Van den Berg et al 2013). A study by Strydom in 2019 found that resistance varied by region, but overall reported high levels of resistance across the maize growing region of South Africa. The areas with the greatest resistance were areas with large concentrations of *Bt* maize grown commercially, while the least resistant populations came from areas with little to no *Bt* maize grown.

Previous analysis of insect resistance to *Bt* crops has been done on a microlevel, looking from a genetic lens in short-term lab experiments or conducted in limited field-level analyses. No long-term studies at a nationwide view have been done to observe the potential impact of resistance on yields, and no study estimated yield effects in South Africa since resistance was reported.

Another threat to yield gains, or even maintaining yield levels, with GM technology in South Africa is the delay in approval process leading to potentially outdated cultivar genetics being widely used as the basis for GM cultivars. GM cultivars can take years to make it through the regulatory process, meaning the foundational genetics of cultivars can become outdated compared to the genetics of their conventional cultivars. This can result in the benefits of GM technology just counterbalancing the outdated genetics instead of providing additional benefits above the most updated genetics.

This study sets out to define the impact of *Bt* genetic material on maize yields and the economic effects of potential genetic degradation. The results of this study can be used by producers, seed companies, and breeders making cultivar decisions as well as the greater agricultural community to better understand how great potential resistance or genetic degradation can impact producers.

1. Background

2.1 Maize Production and Consumption in South Africa

Maize is the largest locally-produced field crop in South Africa, producing 12.5 million metric tons in 2018 (*FAOSTAT Food Balances*, 2020). South Africa is the main maize producer in the Southern African Development Community (SADC) region, and the 12th largest maize producer in the world. Local consumption of maize amounts to more than 12 million tons per year in 2017 (*FAOSTAT Food Balances*, 2020) and serves for the staple food many low-income households and the majority of the population (Abidoye and Mabaya, 2014; Gouse, 2013).

2.2 Food insecurity in South Africa

Although the World Bank classifies South Africa as an upper-middle-income country, food insecurity is an ongoing concern for much of the country. In 2018, 11% of individuals and 10% of households in South Africa were vulnerable to hunger (STATSA, 2020). Moreover, the prevalence of undernourishment has remained nearly identical from 5% (2.8 million people) in 2014 to 6% (3.5 million people) in 2017 (FAO, 2019). In 2014-2015, 22% of households experienced food insecurity due to a severe drought and subsequent food price shocks (STATSA, 2016). During this time, household food insecurity reached as high as 41% in Northwest province and 32%, 31%, and 26% in Eastern Cape, Northern Cape, and Free State provinces, respectively (STATSA, 2016). In the Gauteng province, 35% of the population is food insecure and has skipped at least one meal due to economic reasons (de Kadt et al., 2021). Continued concerns about food insecurity are amplified as climate change threatens agriculture in sub-Saharan Africa through increased frequency of severe droughts (Conway et al., 2015; Lobell et al., 2011; Rippke et al., 2016). White maize is an important field crop in South Africa as it serves as the staple food for much of the population, particularly for low-income households (Abidoye & Mabaya, 2014; Gouse et al., 2005). Only white maize is used for human consumption, while yellow maize is used for livestock feed.

2.3 Impacts of previous GM adoption

While GM crops were primarily designed to address the needs of producers (increased yields, lower costs, etc.), the impacts can reach the demand side of the food security equation. The most common traits in GM crops globally are HT for herbicides such as glyphosate, *Bt* insecticidal traits, or both *Bt* and HT traits (stacked traits) (ISAAA, 2019). *Bt* crops are one method of genetic modification of plant-based pest control. *Bacillus thuringiensis*, or *Bt*, is a strain of soil bacteria with insecticidal properties that can be inserted into the genes of certain crops. The *Cry* protein within *Bt* is toxic to certain insects but other organisms (humans, animals, and non-targeted insects) who lack the receptors effected by the *Cry* protein are unaffected. When inserted into crops, *Bt* crops have a built-in insecticide against certain pests, and can decrease or eliminate the impacts of these pests and the inputs required to mitigate their damage.

Bt accounts for 12% of crops globally and stacked (combining *Bt* traits with HT traits) accounts for another 12%. Previous literature indicates producer and environmental benefits of GM crops, specifically that increased profit due to adoption are 60% higher in low-income countries than high income countries (Klümper & Qaim, 2014). These benefits are especially stark for impoverished farmers in low-income countries where there are fewer options for pest control. *Bt* crops specifically have been well documented to provide decreased pesticide costs, and increased income levels (Klümper & Qaim, 2014; Zilberman et al., 2018).

In a metanalysis of 168 studies comparing yields of GM and non-GM crops, 124 showed positive results (either higher yields, profit, or both) for adopters compared to non-adopters, 32 indicated no difference, and 13 were negative (Carpenter, 2010). Much of this literature comparison focused on yields of adopters and non-adopters in India and the United States, which account for 26% and 23% of the results respectively. Across these studies, average yield increases in developing countries range from 16% for *Bt* maize to 30% for *Bt* cotton, with one single study reporting 85% yield increase observed in HT maize. The first generation of GM crops to be commercialized focused on pest management and therefore reducing or eliminating losses due to pests. While the focus was not on raising yield potential, yields improved overall while the need for conventional control methods was reduced.

Income benefits due to *Bt* crops can be observed across borders and crop types. The first field trials containing Bt cotton in India occurred in 1997 and Bt cotton was approved for commercial release in India in 2002. In a 2001, farm level field studies found that average yields increased over non-Bt cultivars by 80% and over a 4 year period (1997-2001) showed an average advantage of 60% (Qaim & Zilberman, 2003). A follow-up study by Subramanian and Qaim (Subramanian & Qaim, 2010) found that after four years of production, *Bt* cotton yields were 37% higher and pesticide use dropped by 41%. An externality of production was the increased use of paid female labor and increased household incomes as incomes for *Bt* cotton-adopting producers increased by 82%. In the Philippines, a study into the poverty-reduction effects of GM maize found that the mean net income in 2007 for non-GM maize farmers was 16,420 pesos (about US$400) while the mean net income for GM maize farmers was 24,700 pesos (about US$600) – a 50% increase (Yorobe & Smale, 2012).

Bt crops have proven to be beneficial for low-income producers by decreasing the quantity of pesticides needed while also increasing the yields, causing both economic and food security benefits, as well as an environmental benefit from decreased exposure to residue. In a randomized control trial assessing the impacts of *Bt* eggplant (*Bt* Brinjal) in Bangladesh, an overall net increase in profit of 128% resulted from farmers not only selling more eggplants while incurring lower input costs. *Bt* brinjal farmers also decreased the amounts of pesticides used as much as 76%, also leading to fewer instances of pesticide poisoning, an estimated reduction of 11.5% (Ahmed et al, 2020).

The food security benefits of GM crops are primarily indirect, i.e. increase the production and profit of farmers, but there is evidence that GM crops could directly benefit food security efforts through higher production of field-to-plate crops.

2.4 GM crops for direct human consumption

Most GM crops grown today are used as either animal feed (maize and soya) for oil (canola) or for textile production (cotton). Over 70% of harvested GM biomass is used as animal feed, and 75% of cotton grown globally is GM. Even though GM crops grown for direct human consumption could have large positive implications on food security, especially in areas that historically struggle with malnutrition and hunger challenges, hesitation by both the public and by governmental agencies have slowed commercial release of field-to-plate (wheat, rice, and maize for direct human consumption) GM crops. An important GM crop grown for human consumption is Golden Rice, a genetically modified rice developed to biosynthesize bio-carotene to prevent vitamin A deficiency. Major pushback by anti-GM groups in the Philippines caused delays in research on Golden Rice in 2013 after test plots were vandalized (McGrath, 2013). Golden Rice is pending approval for commercial production in the Philippines (Wu, 2013).

Bt crops specifically have seen some release on a commercial scale: in Bangladesh, *Bt* eggplant has been approved and released commercially and producers have seen benefits in terms of increased yield and reduced pesticide cost (Ahmed et al., 2019; Shelton et al., 2018).

2.5 Bt adoption in South Africa

Bt yellow maize (for animal feed) was commercially adopted in South Africa in 1998-1999, with the adoption of *Bt* white maize (for human consumption) following in 2001-2002. The adoption of *Bt* white maize established South Africa as the first GM crop producer for human consumption in the world. The commercial adoption of HT maize and stacked traits followed in 2003-2004 and 2007-2008 respectively, and by 2016, 74% of the country's total maize crop used HT cultivars while 91% of the country's total maize crop used *Bt* cultivars.

While there have been criticisms that GM does not contribute to increased yields resulting in improved food security and increasing producer profitability (Gurian-Sherman, 2009) , the literature is rich in studies which document increased yields along with improvements in welfare benefits, increased white maize rations, and reduced environmental damage. Shew et al. (2021) found that GM maize increased mean yields over conventional hybrid maize by 0.42 Mt/ha, and that specifically, GM white maize increased yields by 0.60 Mt per hectare over conventional maize varieties.

Ala-Kokko et al. (2021) found that the total welfare benefits of GM white maize in South Africa from 2001-2018 were $694.7 million, and the food security benefits attributed to GM white maize were estimated to increase by an average of 4.6 million additional white maize rations annually. The use of GM white maize compared to conventional also was found to reduce environmental damage by $0.34 per hectare, or $291,721 annually (Ala-Kokko et al., 2021).

2.6 Insect Resistance

Insects currently consume between 5-20% of major grain crops globally (Deutsch et al., 2018). These losses will likely increase with climate change; according to Deutsch et al in 2018, for wheat, rice, and maize, yield lost to insects will increase by 10-25% per degree Celsius of warming, with the greatest impacts in the temperate zones, like South Africa. For maize specifically, losses due to insect pests and the costs for mitigating losses represent the largest allocation of resources in worldwide maize production with 31% of potential yield lost to pests (Oerke, 1994; OERKE, 2006). Current methods to control insects in grain crops include plant-based resistance, chemical applications, genetic modification, and hand-removal in small-scale production, among others. In many cases, hand-removal is simply impossible due to the size of the production. Chemical applications can be harmful for both the environment and the producer's health. Pests can also develop resistance to these chemical applications, leading them to be less effective over time. Plant-based resistance and genetic modification also have the potential to develop insect resistance.

A concern for many critics of GM crops, specifically *Bt* crops, has been the potential for insect resistance. Insects' ability to adapt to not only insecticides but other control methods means that evolution of resistance by pests is the main threat to the success of *Bt* crops (Tabashnik et al., 2013). Repeated exposure of the targeted insect population to a specific cry protein without eliminating the population can lead to evolution of resistance to the toxicity. When some but not all of the population is killed off, the ratio of naturally resistant pests increases in comparison to susceptible pests, which increases the likelihood of genetic resistance within a population. An overview of 77 studies globally that looked at resistance to *Bt* crops and methods to prevent resistance by Tabashnik in 2013 found that field-evolved resistance has been reported in five of 13 major pest species studied, compared to only one in 2005. Some form of resistance has been documented in pest populations in both *Bt* corn and *Bt* cotton in the US, South Africa, India, China, and the Philippines (Tabashnik 2013), with significant resistance (more than 50% of the population comprised of resistant individuals) being reported in South Africa, US, and India.

Good stewardship is key to preventing, delaying, and treating resistance. Innovations such as integrated pest management, diversifying pest management techniques, and host/refuge programs have been used to stay ahead of resistance and prevent a buildup of resistant genes within the targeted population. For example, refuge strategies rely on the concept that naturally resistant pests that survive on *Bt* crops will mate with the abundant susceptible pests from nearby host plants without *Bt* toxins. If resistance is recessive, future generations will die on the *Bt* crops which delays evolution of resistance. Implementing and enforcing these strategies across groups of producers widely using Bt crops will benefit the entire group by maintaining the efficacy of the toxins.

Currently, agrichemicals are the main form of pest control in South Africa, and South Africa is the highest user of pesticides in sub-Saharan Africa with over 500 active ingredients registered for use (Dabrowski, 2014). However, concerns about lack of access to resources and education on safe pesticide use raises concerns that emerging farmers are more likely to suffer from negative health and environmental impacts due to exposure.

The first reports of *Busseola fusca* developing resistance to *Bt* maize in South Africa occurred during the 2006 production year (Van Rensburg 2007). A study by Strydom in 2019 found that resistance varied by region, but overall reported high levels of resistance.

A study by Van den Berg (2013) constructed a timeline of resistance and contributing factors, presenting the theory that the single gene approach to *Bt* genetics as well as limited IPM techniques contributed the quick development of resistance. Van Den Berg asserts that Cry1Ab toxin has lost its efficacy against B. fusca at many localities throughout maize producing regions, and that field tests prior to the commercial release in South Africa showed warning signs for potential resistance development. Between the first plantings of Bt maize during the 1998/1999 growing season and the first report of resistance in 2007, no monitoring or systematic evaluation was done.

Bt maize in South Africa primarily relies on Cry1Ab toxin for pest control against *B. fusca*, and significant levels of survival of the pest were observed even after the first year of commercial release. Severe damage began being reported in the 2004/2005 growing season and was confirmed in a 2007 study that confirmed resistance through larvae gathered from farms.

The greatest resistance was found in areas with large concentrations of *Bt* maize farmed commercially, while the least resistant populations came from areas with little to no *Bt* maize farmed.

Resistance has been largely observed in South Africa on a micro level through regional studies and from the genetics perspective, but a large-scale study to measure the yield and economic impacts has not been done. This study will explore the impact of *Bt* genetic material and potential resistance on the yields of both white and yellow maize on a macro level, through the yields of *Bt* maize and calculate the economic and food security impacts of that potential resistance in South Africa.

3. Data and Methodology

3.1 Data

Data was collected by the Grain Crops Institute of the South African Agricultural Research Council (ARC), which was established in 1981 to conduct research for the public in plant breeding, soil cultivation, pest control, improvement in crop quality, plant nutrition, water utilization, and plant pathology. The ARC-GC has conducted National Maize Cultivar Trials (NMCT) across South Africa annually since 1980, which provides information for producers in the decision-making process of selecting cultivars. This data set includes data collected by the ARC during these trials, ranging from 1981-2019, with data missing from the 2015 growing season due to droughts.

The GM cultivars do not appear in this data set until 2000, but to explore trends in yields prior to the release of GM, yield observations of conventional varieties were included prior to the release of GM. The data includes 125 locations in every province in South Africa, 469 cultivars, for a total of 106,971 yield observations. There were 1190 trials, which we define as a unique year-location combination. We drop any cultivar that does not appear in multiple trials, and any location that does not appear in multiple years. An additional requirement of at least five observations of a technology type (*Bt*, conventional, HT, or stacked) for each year-province combination.

The cleaned dataset resulted in 58% yellow maize 42% white maize. The majority (89%) of the trials included in the NMCT are dryland and rainfed with only 11% being irrigated directly. The trials were completed through a randomized block design with three replications throughout. Trials were randomized annually at each locality, and the genotypes consisted of those entered by the seed companies for that particular season. Trials evaluated the adaptability of commercial genotypes to a wide range of yield potentials. The first half of the data (1980-2010) contained information on fertilizer, pesticides, time and method of application, plant emergence and harvesting dates. The second half of the data (2011-2019) simply contained information on yield, genetics, location, irrigation type, and technology type.

Table 1. Summary Statistics of Yellow Observations by *Bt* and Conventional

Province	Technology	Mean Yield	SD	Min Year	Max Year	# Of Cultivars	# Of Observations	# Of Localities
EC	*Bt*	6.433	3.460	2000	2006	6	14	2
EC	conv	6.612	3.317	1982	2006	193	1792	3
FS	*Bt*	7.148	2.962	2000	2019	49	1875	27
FS	conv	5.621	2.532	1982	2019	272	6447	31
GP	*Bt*	8.402	2.620	2000	2019	42	889	8
GP	conv	7.233	2.770	1986	2019	232	3643	12
KZN	*Bt*	9.361	3.115	2000	2019	44	1158	11
KZN	conv	7.340	2.962	1982	2019	263	5861	14
MP	*Bt*	9.202	2.947	2000	2019	45	1809	18
MP	conv	7.543	2.866	1982	2019	267	6450	22
NC	*Bt*	12.475	3.742	2000	2018	39	608	10
NC	conv	9.117	3.604	1982	2019	241	2343	10
NW	*Bt*	5.736	2.943	2000	2019	45	2358	25
NW	conv	4.729	2.672	1981	2019	251	9044	29
WC	*Bt*	9.088	3.739	2005	2018	38	258	3
WC	conv	7.293	3.402	2000	2018	97	527	3

Table 1 shows the average yield by province and technology type (*Bt* or conventional) for yellow maize, along with the total number of cultivars and observations, and the observed localities. Limpopo province (LP) was left out of this data due to lack of observations. The earliest *Bt* observations were in 2000, in all provinces except Western Cape (WC). The observations from Eastern Cape (EC) are limited to only 2000-2006, and therefore they have the least number of localities and the least number of observations. The second least observations are Western Cape (WC), which are from 2000-2018 but only in 3 localities. The most observations were observed in Free State (FS) and Mpumalanga (MP) provinces. Within each province, average yield is given for *Bt* and conventional (conv) observations.

Table 2. Summary Statistics of White Observations by *Bt* and Conventional

Province	Technology	Mean Yield (Mt/Ha)	SD	Min Year	Max Year	# Of Cultivars	# Of Observations	# Of Localities
EC	conv	6.677	3.439	1982	2006	139	1090	3
FS	*Bt*	6.819	2.491	2005	2019	36	1560	22
FS	conv	5.433	2.394	1982	2019	211	4545	31
GP	*Bt*	8.564	2.284	2005	2018	28	615	8
GP	conv	6.966	2.702	1986	2019	183	2412	12
KZN	*Bt*	8.965	3.134	2004	2017	30	919	10
KZN	conv	7.052	2.838	1982	2019	190	3767	14
MP	*Bt*	9.245	3.040	2004	2018	30	1502	17
MP	conv	7.428	2.961	1982	2019	195	4499	22
NC	*Bt*	8.641	2.959	2005	2014	25	160	4
NC	conv	8.291	3.191	1982	2019	185	1361	10
NW	*Bt*	5.457	2.259	2004	2019	34	2175	20
NW	conv	4.565	2.358	1981	2019	212	7309	29
WC	*Bt*	7.849	2.645	2005	2018	27	177	3
WC	conv	6.772	2.687	2000	2018	87	448	3

Table 2 shows the average yield by province and technology type, along with the total number of cultivars and observations, and the observed localities. Limpopo province (LP) was left out of this data due to lack of observations. The earliest *Bt* observations were in 2004, in all provinces except WC, which was 2005. Eastern Cape (EC) did not have enough white *Bt* observations, and therefore is left out here and in the regressions. The least *Bt* observations are in Northern Cape, with only 160 from 2005-20014. Both NC and Western Cape (WC) had very little localities in addition to limited observations, with 4 and 3 localities respectively. Within each province, average yield is given for *Bt* and conventional (conv) observations.

3.2 Methods

We ran multiple models in this study to understand yield trends over time for *Bt* yellow and white maize, and conventional yellow and white. The first was a linear, multivariate regression model where we regressed yield for a particular cultivar by the year, on an indicator variable for technology and color, while controlling for year, irrigation, and location fixed effects.

$$y_{ijtc} = \alpha_j + \alpha_t + \beta_1 Bt_i + \beta_2 color_c + \varepsilon_{ijtc}$$

The second model was a quadratic regression model that again controlled for year, irrigation, and location fixed effects, with an indicator variable for color, *Bt*, and then for the interaction between *Bt* and year and the interaction of *Bt* and year squared. To estimate the changes in yield gains throughout the years, we created variables called year effect and year squared effect. Those variables included the coefficients in the second model for *Bt*, the coefficients for the interaction between *Bt* and year, and the coefficients for interaction between *Bt* and year squared. These provided us with a calculation of the average yield gain per year of *Bt*.

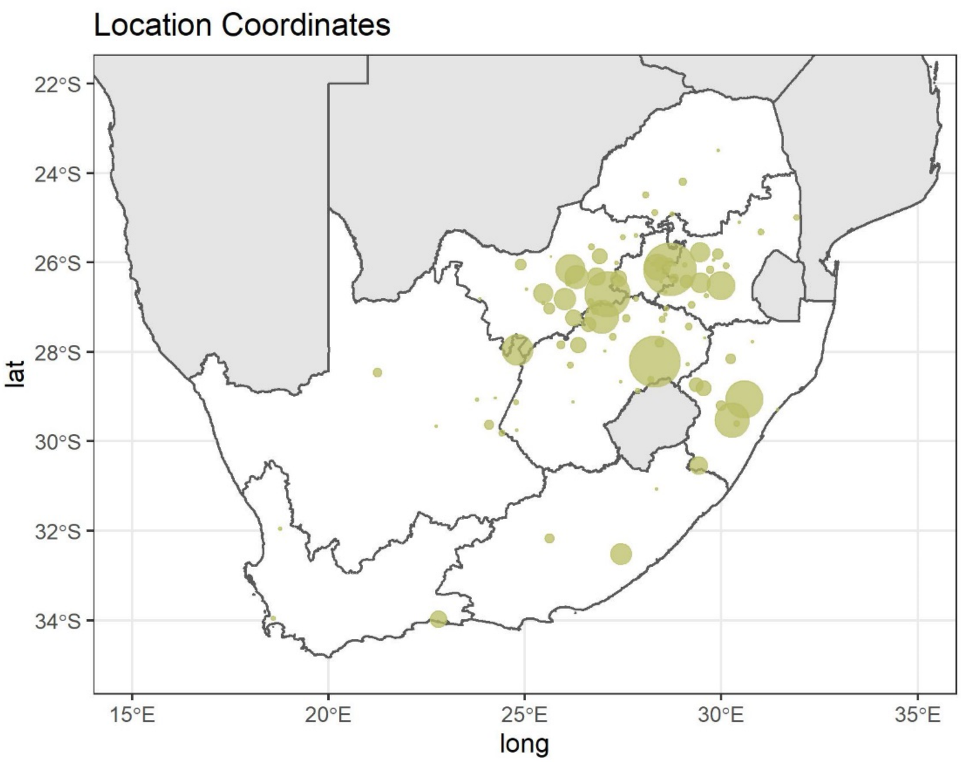
$$y_{ijtc} = \alpha_j + \alpha_t + \beta_1 Bt_{\mathrm{it}} * \beta_2 Bt_{\mathrm{it}}^2 + \beta_3 color_c + \varepsilon_{ijtc}$$

Fixed effects used in the second equation were location, year, and irrigation. Location fixed effects control for factors related to location but are time-invariant (such as soil quality) while year fixed effects control for genetic improvements across both *Bt* and non *Bt* varieties that are common across all locations. Irrigation fixed effects control for any variation in yields attributed to irrigation, leaving the regression to instead capture variation based on color, technology, and the interaction between year and technology.

$$y_{ijtc} = \alpha_j + \alpha_t + \beta_1 Bt_i * \beta_2 Bt_t^2 * \beta_3 province + \beta_4 color_c + \varepsilon_{ijtc}$$

Time invariant factors related to location are controlled for through location fixed effects, while time variant factors such as weather shocks and non-*Bt* technological improvements that are consistent in all locations over time are controlled for through year fixed effects. These include but are not limited to weather extremes such as widespread drought or heat waves, management improvements, and genetic improvements that are common in both conventional and *Bt* cultivars.

The maximum yield gains with respect to time and year were found both overall and at the province level. Overall, this was determined by taking the yield effects for *Bt* by year, finding the maximum within each technology type (*Bt* or conventional) and identifying the year the maximum occurred in. At a province level, the same method was used, but instead the data was broken out into individual provinces prior to finding maximum.



Location Coordinates
Figure 1

Figure 1 shows a map of all localities where data was collected, with the size of circle changing based on number of observations at that locality over all years.

3.3 Revenue Impacts

To estimate the revenue impacts, we used the average yield gain of *Bt*, per year and province based on the coefficients from the quadratic regression (equation 2). This provides a way to compare *Bt* maize to conventional, and *Bt* maize gains and yield to *Bt* maize gains and yield from other years. Revenue impacts were calculated by finding the price (2018 USD) of a metric ton of maize in each year, then any estimated changes in yields could have a common variable to be compared by. Price was taken from the yearly reports from STATA, adjusted for inflation in South Africa and converted into 2018 USD (SAFEX Historic, n.d.).. These numbers were used for revenue impacts of how much revenue was lost overall due to *Bt* genetic degradation, calculated from the reports of overall *Bt* maize yields and projected *Bt* maize yields.

3.4 Food Availability Impacts

To estimate the food availability impacts, we again used the average yield gain of *Bt*, per year and province based on coefficients from the quadratic regression (equation 2). This provides us with a way to compare *Bt* maize to conventional, and the changes in *Bt* and conventional maize gains across time and location. Food availability impacts were calculated in annual rations, based on the average kg of maize eaten in a year by an adult in South Africa. Consumption varies by year, which is shown in table 3 (FAO, 2020, 2017). The maximum annual yield gain was found from the quadratic regression above, and then following years were compared to the maximum year based on number of annual rations lost. This gives the estimated loss in the context of food availability which is key when considering the expected impacts of *Bt* crops is a potential increase in food production.

Table 3- Annual Price and Consumption for Maize in South Africa

Year	Price/Ton (2018 USD)	Consumption Of Maize (Kg/Capita/Yr)
2001	$307.26	111.96
2002	$154.86	112.64
2003	$161.85	113.48
2004	$107.04	110.71
2005	$182.16	108.03
2006	$236.2	101.17
2007	$224.15	100.05
2008	$180.29	96.67
2009	$132.96	94.15
2010	$200.69	101.19
2011	$240.68	100.43
2012	$217.63	99.4
2013	$200.87	100.1
2014	$248.53	101.31
2015	$350.62	101.95
2016	$159.06	102.46
2017	$154.8	103.4
2018	$163.07	103.4*

Table 3 shows the price per ton of maize in 2018 USD and the consumption of maize in each given year. 2018 data was not provided, and therefore consumption data is carried over from 2017. Price information comes from (SAFEX Historic, n.d.). Data on consumption comes from (FAOSTAT Food Balances, 2020).

3.5 Robustness checks

Northern Cape, Free State, and North West provinces were combined in the model due to lack of *Bt* observations and renamed "Northern Region". For robustness checks several permutations of the preferred model (equation 1) were run. The first alternate model developed required 10 observations per year of each cultivar. The second alternate model required a cultivar present in more than 3 separate years, rather than the current model requirement of just 2 years. The third alternate model required observations in more than 5 years. The fourth model required

10 observations per year in more than 3 years. And the fifth and final model required that the locality data was collected from be present in at least 5 years to be included.

4. Results

4.1 Summary Statistics for the Data

An initial look at the data broken down by technology in Figure 2 shows an increase then subsequent decrease in yield averages from the raw data for *Bt*, *Bt*/RR, and RR observations, with the peak appearing roughly in 2010. Figure 2 illustrates this trend through average yield of all observations by technology starting in 1980 and ending in 2019. The *Bt*/RR average reaches as high as 8.5kg/ha, but then decreases to be comparable to conventional. *Bt* also peaks in 2011 with an average yield of 8.62kg/ha, but by 2020 is below conventional yields.

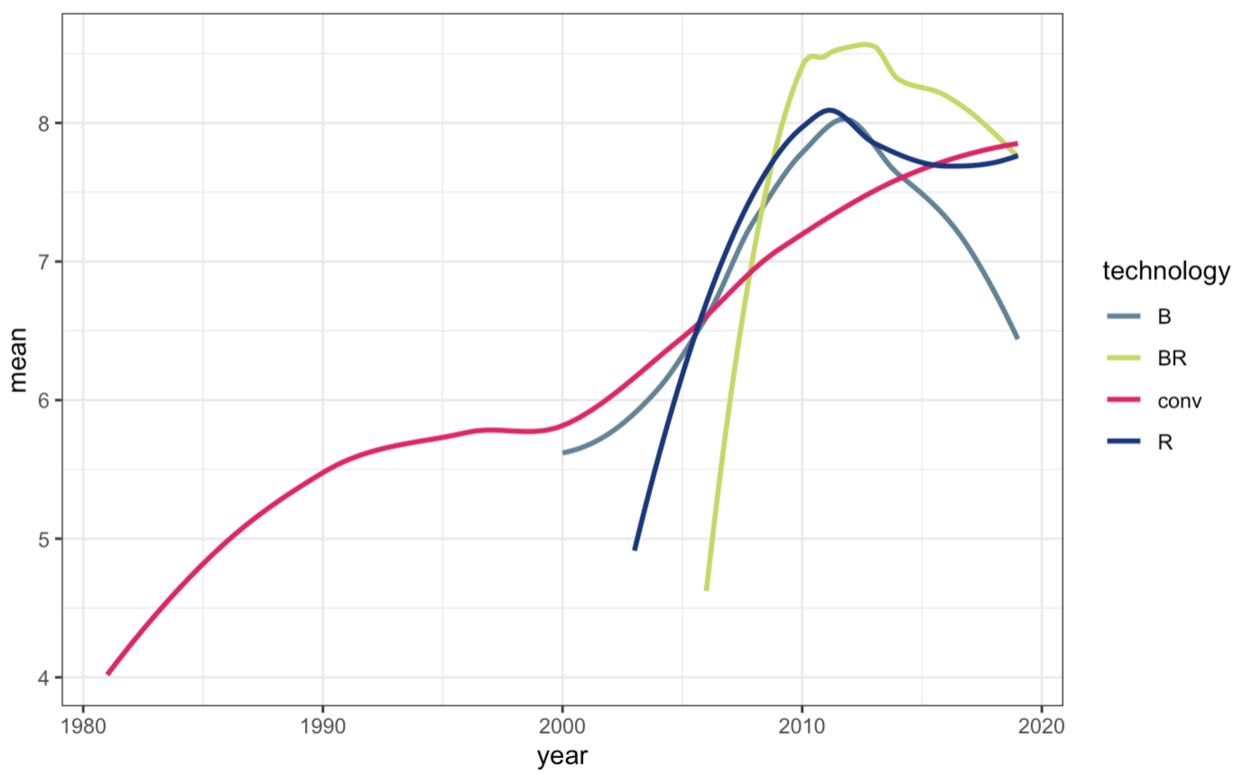


Figure 2

The regression results shown for all equations in figure 3 show a negative coefficient for year and a positive coefficient for year squared, as well as a positive coefficient for *Bt*, which in this regression only contains *Bt* crops. Interactions are included in this regression but omitted from the results table.

Figure 3

Term	Equation 1	Equation 2
(Intercept)	5.911	655,784,862.27
color (yellow)	0.212	0.211
factor(year)1982	-2.089	6,064.45
factor(year)1984	-2.301	17,213.54
factor(year)1985	-1.009	22,297.61
factor(year)1986	-1.874	27,051.59
factor(year)1987	-1.682	31,478.71
factor(year)1988	-0.683	35,578.72
factor(year)1989	0.384	39,350.86
factor(year)1990	0.26	42,793.90
factor(year)1991	0.497	45,909.38
factor(year)1993	-1.446	51,154.15
factor(year)1994	0.185	53,287.25
factor(year)1995	-2.92	55,087.70
factor(year)1996	-0.334	56,565.91
factor(year)1997	-0.381	57,713.57
factor(year)1998	-0.708	58,533.03
factor(year)1999	-0.545	59,025.05
factor(year)2000	-0.262	59,189.28
factor(year)2001	-1	59,024.56
factor(year)2002	0.296	58,533.95
factor(year)2003	-1.094	57,712.73
factor(year)2004	0.006	56,566.09
factor(year)2005	0.548	55,090.94
factor(year)2006	0.543	53,287.34
factor(year)2007	-1.99	51,153.28
factor(year)2008	1.351	48,697.17
factor(year)2009	1.212	45,909.66
factor(year)2010	1.643	42,794.81
factor(year)2011	2.127	39,352.09
factor(year)2012	1.051	35,579.91
factor(year)2013	1.114	31,480.95
factor(year)2014	2.512	27,055.42
factor(year)2016	-0.671	17,214.60
factor(year)2017	1.761	11,806.33
factor(year)2018	1.783	6,067.67
factor(year)2019	0.7	NA
GM	0.175	-19,673.98
GM:year	NA	19.602
GM:yearsq	NA	-0.005
irrigated	4.224	4.214
Province: FS	-0.569	-0.571
Province: GP	0.637	0.635
Province: KZN	1.395	1.392
Province: MP	1.27	1.268
Province: NC	-0.472	-0.47
Province: NW	-1.765	-1.768
Province: WC	0.092	0.089
year	NA	-655,844.07
yearsq	NA	163.961

Figure 4 illustrates the yield averages between *Bt* and conventional over time, with the average yield represented by the box and the confidence intervals shown by the lines. We see both yields moving up gradually, but *Bt* dropping below conventional after 2011. In figure 5, the yield differences between *Bt* and conventional are broken down at the province level. This shows more clearly that while *Bt* did surpass conventional yields, *Bt* yields have since decreased and been surpassed by conventional yields. Figure 5 provides those yield averages by technology and by province level for different comparison.

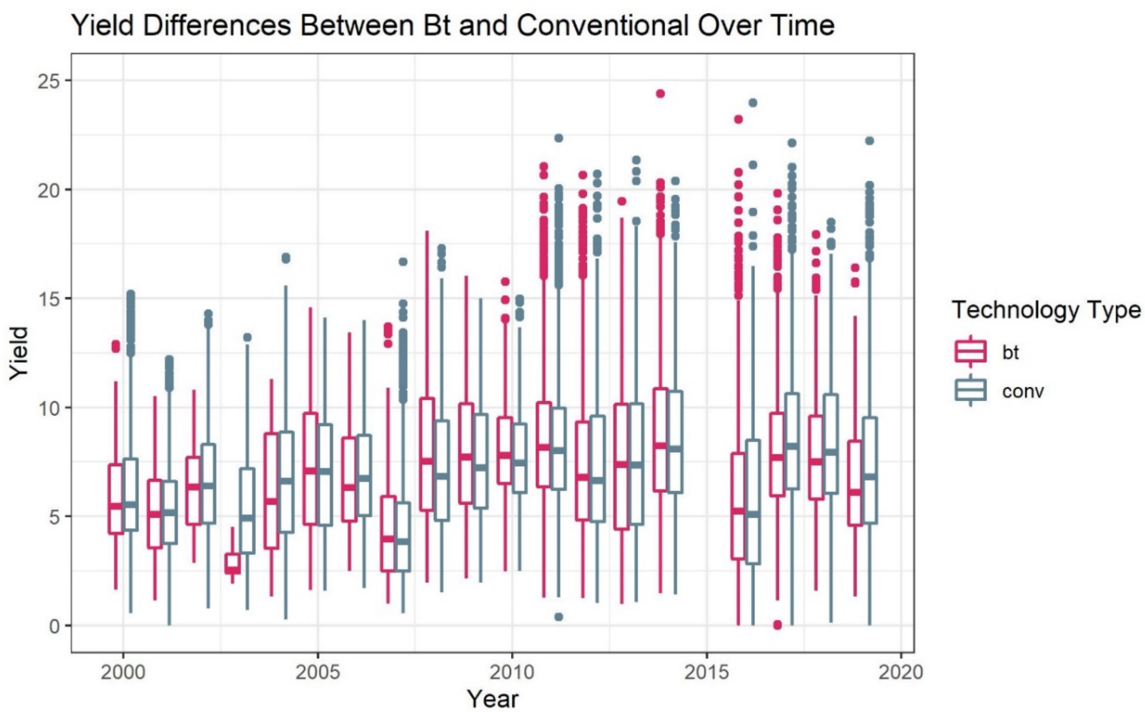


Figure 4- Yield Differences between Bt anc Conventional

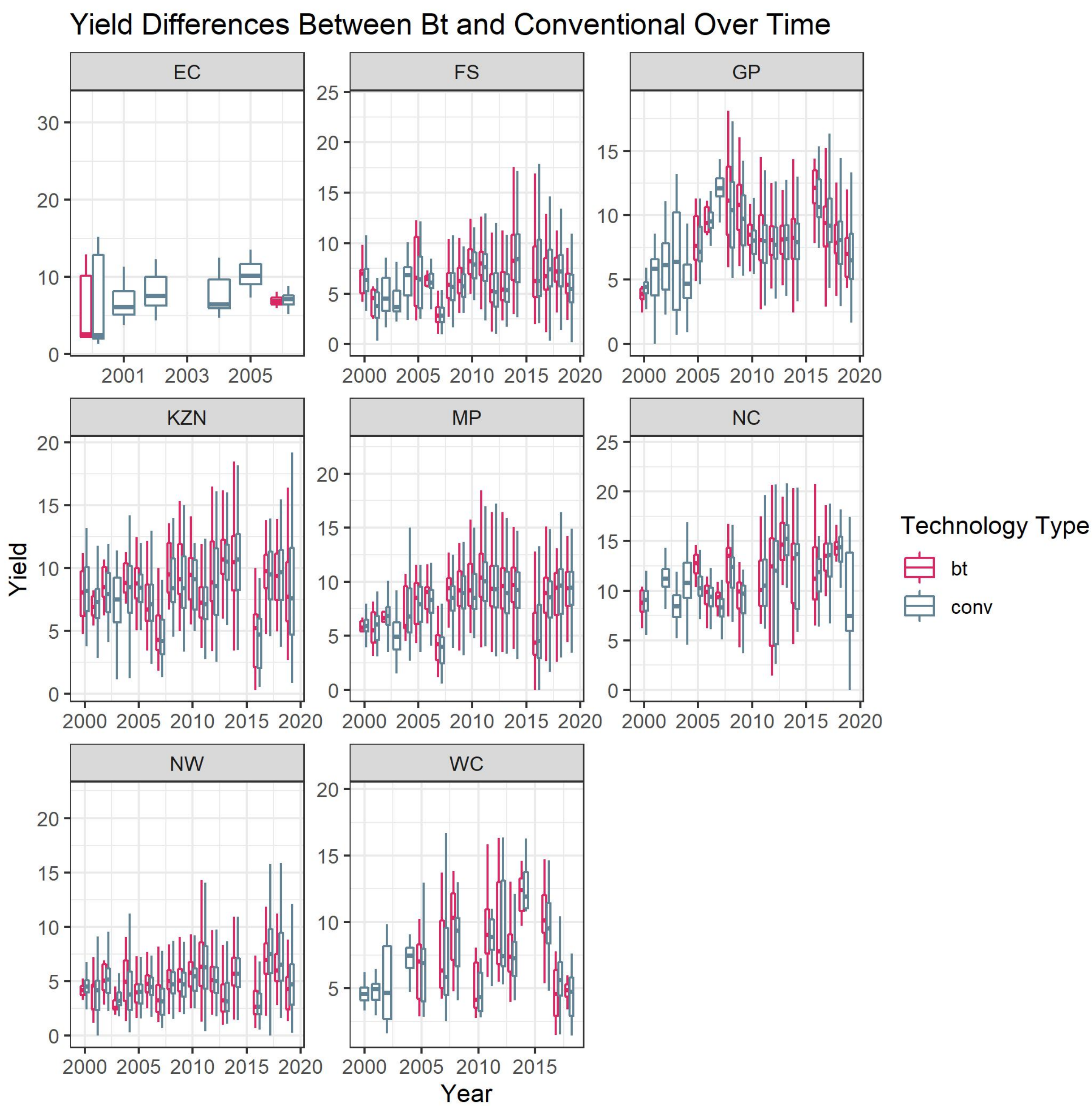


Figure 5

4.2 Estimates of Bt versus conventional yield gains

Estimates of *Bt* vs conventional yield gains were calculated using the second equation separately by color, in addition to combined. For white maize, the yield gains for *Bt* peaked in 2009 for GP and KZN and 2008 for the combined Northern Region, composed of Northern

Cape, Free State, and North West provinces. There was no decrease in yield gains for WC for white maize. Table 3 shows these yield gains broken down by color and province and includes the number of observations for the peak year for a given province. The peak annual yield gains listed are the maximum annual yield gain, and the mean yield for that year is provided as well as the number of observations in the peak year. This matches with when resistance was found in previous studies; Strydom (2013) found that the hotspots of resistance occurred in Free State (Northern Region) and MP, and in 2010 which matches the results found here.

Year	Province	Color	Peak Annual Yield Gains for *Bt* (mt/ha)	Mean Yield	SD	Number of observations in peak year
2006	GP	yellow	0.489539	9.65125	1.11361	8
2009	KZN	white	0.451282	9.974071	2.460064	56
2009	KZN	yellow	0.451282	9.61869	2.338679	42
2010	MP	white	0.459697	9.753238	2.194115	80
2010	MP	yellow	0.459697	9.34575	2.501564	60
2007	Northern Region	white	0.279896	4.072284	2.527282	95
2007	Northern Region	yellow	0.279896	4.158915	2.359936	94

Table 1

Figure 6 shows the annual yield gains contributed by *Bt* technology by province in a given year. All provinces peak sometime between 2005-2010.

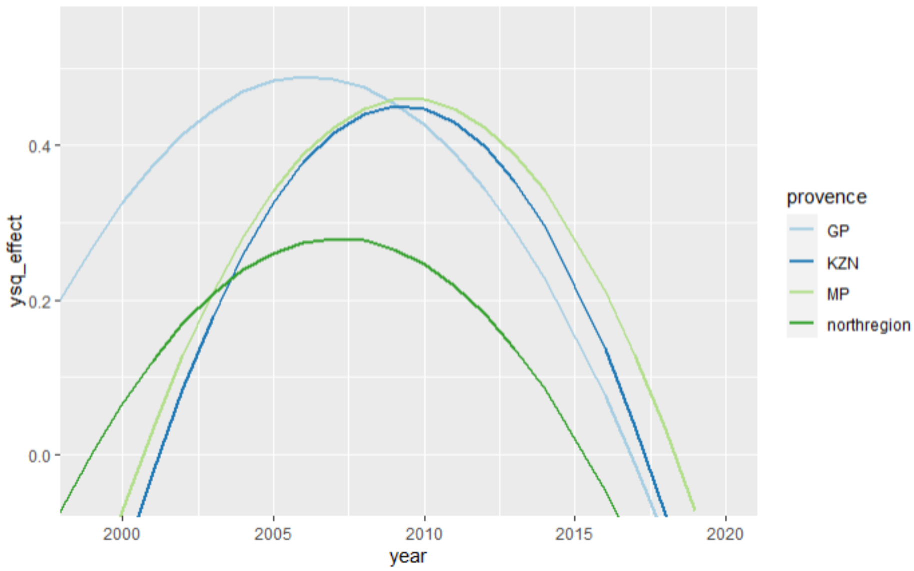


Figure 6- Yield Gains Due to Bt vs Conventional

4.3 Revenue Impacts

Due to insect resistance, devolution of *Bt* yields, or both, it is estimated that a total of 2,080,122 metric tons were lost between 2008 and 2019, which is an estimated total loss of $389.6 million, calculated by taking the price of 1 metric ton of maize in each year multiplied by the metric tons lost in each year, summarized through all years of loss. Also calculated was the dollar loss per hectare due to insect resistance, which varied per year but was as high as $110.27 lost per hectare in 2016. This economic loss not only impacts the larger economy of South Africa and sub-Saharan Africa, but also individual producers. When understanding the economic impacts of the losses, it must be acknowledged that *Bt* crops are often more expensive to produce due to higher seed prices than their conventional counterparts, and farmers spending more money on these varieties are seeing the same if not lower yields than the less expensive conventional varieties. Normally they could buy these varieties as a way to increase yields and potentially decrease their pest management expenses, but instead they are spending the same amount on pest management with decreased yields, causing their individual losses to be even greater than those enumerated here.

Table 4 shows how the decrease in yield gains by *Bt* technology over conventional technology decreased starting in 2008 overall. The table shows both the yield gains attributed to *Bt* technology in each year and compares those to the maximum yield gain from 2007. The difference between the annual yield gains and maximum are listed in the yield gain loss column, which increase year over year. The calculated yield gains lost were multiplied by the *Bt* acreage in South Africa on each respective year, and then applied to the following columns, specifically the economic loss per year and the rations lost per year. Economic loss per year was found by taking the price in USD per metric ton of maize in a given year times the metric tons lost, and then converting the USD for that year to 2020 USD for better comparison. Rations lost per year was calculated by taking the metric tons lost and dividing by the average annual consumption (in Mt) in each year in South Africa.

Year	Yield Gains due to Bt	Peak Yield Gains	Lost Yield Gains	Mt Loss	Annual Loss	Consumption	Rations Lost	Dollar Lost/Ha	Total Value of Maize Lost
2007	0.3630	0.3630	-	-	-	-	-	-	-
2008	0.3624	0.3630	-0.001	851	$191,784	96.67	8,806	0.15	$2,965,667,536
2009	0.3519	0.3630	-0.011	13,487	$2,357,060	94.15	143,253	1.94	$2,196,234,054
2010	0.3318	0.3630	-0.031	48,991	$6,635,225	101.19	484,152	4.24	$1,817,697,292
2011	0.3018	0.3630	-0.061	52,521	$10,568,855	100.43	522,964	12.32	$2,198,236,520
2012	0.2621	0.3630	-0.101	110,985	$26,705,607	99.4	1,116,547	24.29	$3,070,121,616
2013	0.2126	0.3630	-0.150	141,266	$30,444,642	100.1	1,411,244	32.42	$2,690,902,809
2014	0.1533	0.3630	-0.210	188,266	$37,903,226	101.31	1,858,320	42.22	$3,004,814,430
2016	0.0056	0.3630	-0.357	229,419	$70,767,506	102.46	2,239,112	110.27	$2,533,718,367
2017	-0.0830	0.3630	-0.446	387,392	$62,292,396	103.4	3,746,537	71.72	$2,822,190,269
2018	-0.1813	0.3630	-0.544	415,791	$65,007,022	103.4	4,021,185	85.10	$2,048,752,742
2019	-0.2894	0.3630	-0.652	491,152	$76,789,508	103.4	4,750,023	102.00	$1,848,630,374

Table 2- Total Revenue Impacts

Table 4 shows how the decrease in yield gains by *Bt* technology over conventional technology decreased starting in 2008 overall, which resulted in an average yearly loss of 173,343 metric tons and $32.4 million. The largest single year for loss was 2019, with 491,152 metric tons lost, at a value of $76.7 million. The total rations lost during this time was 20.3 million, and an average yearly loss of 1.69 million rations. Average revenue loss per hectare was $40.56, with the highest year being 2016 at $110.27.

4.4 Food Security Impacts

Due to losses in yield gains, it is estimated that a total of 29.95 million rations of white maize were lost between 2008-2019, with the highest individual annual loss occurring in 2019 with 7.2 million rations. Losses in 2019 would feed 12.4% of the total population of South Africa in 2019. The full table of results is provided in table 5. In previous research on food security impacts of GM maize in South Africa, it was found that GM technology (*Bt* and HT) for white maize provided an average of 4.6 million additional annual rations. While the average lost per year is significantly lower, the losses are concerning because they are not just losses in potential gains, but decreased yields, in some places decreased yields below conventional yields.

Table 3: Food Availability Impacts

Year	Yield Gains due to Bt	Peak Yield Gains	Lost Yield Gains	Mt Loss	Annual Loss	Dollar Lost/Ha	Consumption	Rations Lost
2008	0.5397	0.5397	-	-	-	-	-	-
2009	0.5290	0.5397	-0.0107	12,980	$2,268,327	$1.86	94.15	137,860
2010	0.5024	0.5397	-0.0373	58,459	$7,917,542	$5.06	101.19	577,718
2011	0.4597	0.5397	-0.0800	68,582	$13,800,769	$16.09	100.43	682,884
2012	0.4011	0.5397	-0.1386	152,346	$36,658,192	$33.35	99.4	1,532,660
2013	0.3265	0.5397	-0.2132	200,179	$43,141,386	$45.94	100.1	1,999,794
2014	0.2359	0.5397	-0.3038	272,730	$54,907,992	$61.16	101.31	2,692,030
2016	0.0068	0.5397	-0.5329	341,983	$105,489,210	$164.37	102.46	3,337,721
2017	-0.1317	0.5397	-0.6714	583,148	$93,769,894	$107.96	103.4	5,639,732
2018	-0.2862	0.5397	-0.8259	630,885	$98,636,035	$129.13	103.4	6,101,399
2019	-0.4567	0.5397	-0.9964	750,138	$117,280,793	$155.78	103.4	7,254,721

5. Discussion

While the yield decreases in the *Bt* crops observed in South Africa could be explained by several things, the clear theme seen here is some form genetic degradation over time. We see that the *Bt* cultivars originally showed significant yield gains over conventional cultivars, but after several years the yield gains were reduced, leading to yields of *Bt* cultivars holding even with conventional cultivars. This leads to clear economic and food security impacts due to losses in yields, compared to if yields of *Bt* maize had maintained their yields. Under those conditions, the economic impact is estimated to be a total of 860,608 metric tons were lost between 2012 and 2019, which is an estimated total loss of $153.5 million. This can also be understood on a yearly level, which varied by year but was as high as $59.51 lost per hectare in 2019. Unfortunately, the data is also limited and does not shed light on what if any factors could influence the economic impact and potentially make it even higher per hectare for some producers or lower for others.

Multiple factors could be responsible for the significant decreases in yields seen for *Bt* and not for conventional varieties post 2007, but most can be described as genetic degradation.

One key to understanding genetic degradation lies in the process of releasing new GM cultivars. The process for releasing new GM cultivars can often take several years, meaning that by the time the GM cultivar is approved and released for general production, the base genetics used in the variety are now considered more outdated than conventional cultivars with significant breeding improvements. This prevents the true potential of GM yields from being realized and means that while the GM crops can still provide some insect resistance, any benefits they provide to increase yields only help keep the GM cultivar competitive with the conventional cultivars.

Another potential explanation for the decrease in yield gains and subsequent converging of yields between *Bt* maize and convention maize is the potential for insect resistance. As seen in several studies since the commercial approval of Bt maize in South Africa, insect damage is still occurring in *Bt* maize cultivars, and survival rates of these insects have raised concerns. Insect resistance is always a possibility for Bt crops, particularly in areas where IPM strategies may not be followed or enforced.

We also see that the yield gain peaks and subsequent decrease in *Bt* yields happens in different years at a province level. While this could capture the differing speed of resistance of different insect communities, it isn't as clear as possible due to the geographic size of some provinces. The original insect resistance was found at the intersection of several provinces, meaning that while the insect population was increasing resistance, the ability to study the impact of the resistance through yield gains/losses on a province level is not as accurate (Strydom et al., 2019). However, the occurrence of yield decreases at different rates in different provinces does increase the likelihood that resistance is a factor instead of just outdated genetics, as outdated genetics would have a yield decrease occurring at roughly the same time across all locations.

Definitively determining the cause of these converging yields is unlikely but understanding the possible contributing factors can provide context for producers moving forward. This study was limited by not having the information on the release years for the underlying genetics on *Bt* cultivars, which would provide clarity on the impact of outdated genetics. The data set used here also lacked any details on observed insect damage, which could have been used to add more context to the potential for insect resistance.

While the data in this study shows significant loss in yield, future studies need to be undertaken to further understand these trends and the drivers behind these trends. The data used here was limited to just the yield data, the location, and the cultivars. Because the information on what if any pesticides were applied is missing, we cannot know what the exact inputs were. This could impact the yields. More research into the effect of specific inputs on *Bt* cultivar yields would clarify the exact impact of *Bt* genetics vs inputs, and how those are impacted by potential insect resistance. This study is also limited by number of observations in a few different locations, with several locations and provinces having a smaller number of observations compared to others in the same year.

6. Conclusion

The most common criticisms of GM crops overall are that GM crops do not increase the food supply, do not benefit producers financially, and do not reduce the environmental impact of agriculture. Several studies have documented increases in yield and economic benefits of GM crops, both globally and in South Africa. Specifically, the study from Shew et al. (2020) a similar dataset showed those benefits in South Africa. This study looked to take those results and update them with newer data in the face of reported insect resistance and long approval times for GM crops. With those updates, this study sees benefits of *Bt* maize decreasing, because the yield gains compared to conventional yields across both white and yellow maize have decreased. This loss of benefits, either due to insect resistance that has been warned of by researchers (Bates et al., 2005), or through genetic degradation, creates serious concerns for the commercial producers of South Africa that have wholeheartedly embraced GM and specifically *Bt* crops. While the impacts observed and quantified here were limited to economic and food security impacts, environmental impacts could also be quantified in further research. Proponents of *Bt* technology provide the increases in yield as well as decreased need for pesticides as environmental benefits due to the decreased chemical impact on the environment, but decreased need for land to produce the same yields.

The loss of benefits seen in this study are concerning due to the immediate economic and food availability impacts estimated here, but also concerning when extrapolating the possibilities for the impacts for other countries. Researchers have previously warned that benefits from *Bt* crops could decrease if proper insect management techniques were not observed, and that through climate change impacts on weather patterns, pest impacts will increase. This study provides estimates on the economic and food security impacts of the loss of those benefits, which can be expanded on in other countries with other *Bt* crops.

Unlike previous studies on insect resistance to *Bt* crops, this study observes the resistance through the impacts rather than the genetics of the pests, which provides an example of how other *Bt* crops could fare if resistance were to develop. This is the only large-scale study on insect resistance of *Bt* crops in the field, particularly in *Bt* crops for direct human consumption.

As scientists look at ways to increase food production and decrease hunger on a global scale, *Bt* crops have been promoted as a potential way to increase yields by decreasing impacts of pests. However, scientists have warned that *Bt* crops can only be successful in the long term if the network of producers using them commit to IRM practices, and that in the absence of those, resistance would develop. This study provides information on what the loss in yield gains could look like, and what the economic and food security implications of that loss would look like.

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