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ECONOMIC AND ECOSYSTEM IMPACTS OF GM MAIZE IN SOUTH AFRICA

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Thesis submitted in partial fulfilment of the requirements for the joint academic degree of International Master of Science in Rural Development from Ghent University (Belgium), Agrocampus Ouest (France), Humboldt University of Berlin (Germany), Slovak University of Agriculture in Nitra (Slovakia), University of Pisa (Italy) and University of Córdoba (Spain) in collaboration with Can Tho University (Vietnam), Escuela Superior Politécnica del Litoral (Ecuador), Nanjing Agricultural University (China), University of Agricultural Science Bengaluru (India), University of Pretoria (South-Africa) and University of Arkansas (United States of America)

and the Master of Science in Agricultural Economics issued by the University of Arkansas (USA)

Abstract

White maize in South Africa is the only staple crop produced on a widespread commercial basis for direct human consumption using genetically modified (GM) cultivars. Using a combined economic and environmental approach, we estimate the total welfare benefits attributable to GM white maize in South Africa for 2001-2018 are $694.7 million. Food security benefits attributable to GM white maize in South Africa also manifest through an average of 4.6 million additional white maize rations annually. To achieve these additional annual rations using conventional hybrid maize, the additional land required would range from 1,088 hectares in 2001 to 217,788 hectares in 2014. Results indicate that GM maize reduces environmental damage by $0.34 per hectare or $291,721 annually, compared to conventional hybrid white maize.

Acknowledgments

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Dedication

I dedicate this work to the memory of my father, Vesa Ala-Kokko.

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1. Introduction

Contributing authors: Lawton Lanier Nalley, Aaron M. Shew, Jesse B. Tack, Petronella Chaminuka, Marty D. Matlock, and Marijke D'Haese

White maize is an important field crop in South Africa, serving as the staple food for the majority of its population, particularly for low-income households (Abidoye and Mabaya, 2014; Gouse, 2013). Much of the research evaluating the impacts of transgenic crops (herein subsequently called genetically modified (GM) crops) has focused on the producer benefits (increased yields, reduced costs, or both) of input traits (Shi et al., 2013; Xu et al., 2013). Other findings conclude GM input traits have second-order socioeconomic impacts such as labor-savings and environmental benefits (Ahmed et al., 2020; Brookes and Barfoot, 2018; Gouse et al., 2016; Klümper and Qaim, 2014; Lusk et al., 2017; Qaim and Zilberman, 2003; Smyth et al., 2015; Xu et al., 2013). GM white maize in South Africa, typically produced as food for direct human consumption, provides a testable medium for the impacts of GM on the country's direct food supply. Critics suggest GM crops have not contributed to increases in yields nor led to reductions in pesticide usage (Gurian-Sherman, 2009; Hakim, 2016). Opponents have also highlighted a point in a National Academy of Sciences of the United States report, which stated that there was little evidence the introduction of GM crops in the United States led to increased yield potential beyond those of conventional crops (National Academies of Sciences Engineering and Medicine, 2016).

2. Background

Contributing authors: Lawton Lanier Nalley, Aaron M. Shew, Jesse B. Tack, Petronella Chaminuka, Marty D. Matlock, and Marijke D'Haese

2.1. Food insecurity and climate change in South Africa

Although the World Bank classifies South Africa as an upper-middle-income country, food insecurity is an ongoing concern for a large segment of its population. In 2018, 11% of individuals and 10% of households in South Africa were vulnerable to hunger (STATSA, 2020). Moreover, there has been a marginal increase in the prevalence of undernourishment from five percent (2.8 million people) in 2014 to six percent (3.5 million people) in 2017 (FAO, 2019). In 2014-2015, 22% of households experienced food insecurity due to a severe drought and subsequent staple food price shocks (STATSA, 2016). The price of white maize more than doubled between January and December of 2015 due to the drought (Stoddard, 2016). Household food insecurity, as a consequence of the drought, reached as high as 41% in North West province and 32%, 31%, and 26% in Eastern Cape, Northern Cape, and Free State provinces, respectively (STATSA, 2016).

Climate change threatens much of sub-Saharan African agriculture, and maize production specifically, through increased frequency and severity of droughts (Conway et al., 2015; Lobell et al., 2011, 2008; Rippke et al., 2016; Serdeczny et al., 2017; Travis, 2016). The degree to which climate change will reduce maize yield is uncertain (Conway et al., 2015; Lobell et al., 2008); however, even conservative estimates signal considerable food security implications in the region, as Botswana, Eswatini, Lesotho, and Namibia depend on importing maize from South Africa (Southern African Development Community, 2020). Producers, researchers, and policymakers alike are considering a wide range of options to reduce food insecurity in the region, including GM crops (Mtui, 2011; Muzhinji and Ntuli, 2021; Zilberman and Lefler, 2021). Although HT and *Bt* traits do not necessarily maximize yield potential, these traits have been associated with narrowing the yield gaps through improved weed control, insect resistance, and more timely planting (Fisher and Edmeades, 2010); each of which constitutes an important adaptation strategy for mitigating the effects of climate change (Ortiz-Bobea and Tack, 2018). Moreover, developments in genome editing and abiotic stress tolerance (e.g., drought tolerance) could help maintain yield or accelerate yield growth (Parisi et al., 2016; Svitashev et al., 2016).

2.2. Impacts of GM crop adoption

Since the United States commercialized GM crops in 1996, the global area of GM crops increased 112-fold, making GM crops the fastest adopted crop technology in recent times (ISAAA, 2019). The predominate traits in GM crops globally are herbicide tolerance (HT) for herbicides such as glyphosate, *Bacillus thuringiensis* (*Bt*) insecticidal traits, or both HT and *Bt* traits (stacked traits). Globally, HT crops account for 47% of the total GM area, *Bt* account for 12%, and stacked account for 12% (ISAAA, 2017).

Systematic reviews of the literature largely confirm the producer and environmental benefits associated with the adoption of GM crops from individual studies. Klümper and Qaim (2014) completed a meta-analysis of 147 studies on the agronomic and economic impacts of GM crop adoption, finding that the profit gains of GM crops are 60% higher in low-income countries than in high-income countries (Klümper and Qaim, 2014). Impoverished farmers in low-income countries have benefited the most from GM technology where there are fewer options for pest management and crop vulnerability tends to be higher (Klümper and Qaim, 2014; Zilberman et al., 2018). Producer benefits associated with the adoption of HT crops can include increases in yield and reductions in costs as a result of improved weed control and reduced labor (Brookes and Barfoot, 2018; Gouse et al., 2016). Producer and environmental benefits associated with the adoption of *Bt* crops have been well documented (Barrows et al., 2014; Bennett et al., 2003; Kouser and Qaim, 2011; Qaim, 2014; Subramanian and Qaim, 2010; Vitale et al., 2014; Yorobe and Smale, 2012). Improved insect control has resulted in increases in yield and less insecticide applications, which in turn has resulted in, cost savings and reductions in pesticide toxicity (Kouser and Qaim, 2011; Qaim, 2014; Subramanian and Qaim, 2010). Another indirect impact of *Bt* maize adoption, has been the reduction of mycotoxin (e.g., fumonisin and aflatoxin) contamination which has resulted in economic benefits and improvements in human health (Wu, 2006; Yu et al., 2020). The improvements to human health as a result of mycotoxin reductions also disproportionately benefit low-income countries where fumonisin and aflatoxin levels are often high, and maize serves as a staple food (Wu, 2006).

GM adoption has created economic and environmental improvements across the agricultural sector (Brookes and Barfoot, 2018; Gouse et al., 2016; Klümper and Qaim, 2014; Lusk et al., 2017; Smyth et al., 2015; Xu et al., 2013). In 2016, the direct global producer income benefit from GM crop adoption was estimated at US$18.2 billion with more than half of these benefits attributable to GM maize varieties (Brookes and Barfoot, 2018). In South Africa, the producer income benefit from GM crops for 1998-2016 was estimated at US$2.3 billion with 97% of these benefits attributable to GM maize varieties (Brookes and Barfoot, 2018). In 1996-2016, the adoption of HT maize and *Bt* maize resulted in eight percent and 56% reductions in herbicide and insecticide usage globally, respectively (Brookes and Barfoot, 2018). Klümper and Qaim (2014) found on average, GM technology has increased crop yields by 21%, while simultaneously reducing the amount of pesticide usage by 37% and pesticide costs by 39%

(Klümper and Qaim, 2014). Despite these benefits and the scientific consensus on the safety of GM technology (European Commission, 2010; National Academies of Sciences Engineering and Medicine, 2016; National Research Council (US) Committee on Identifying and Assessing Unintended Effects of Genetically Engineered Foods on Human Health, 2004; World Health Organization, 2014), adoption of GM technology on the African continent is limited as few governments allow the cultivation of GM crops, citing cautionary concerns about the technology, fear of unforeseen human and environmental risks, and fear of retaliatory trade measures by Europe (Abidoye and Mabaya, 2014; Eicher et al., 2006; Smyth, 2017; Zepeda et al., 2013).

2.3. GM crops produced for direct human consumption

Field-to-plate GM crops that could have large implications for global food security have historically struggled to find traction globally. In 2010, India's environmental minister declared a moratorium on the commercial release of the *Bt* eggplant. This "moratorium" overturned the Genetic Engineering Approval Committee's decision—India's biotechnology regulatory panel—which approved the *Bt* eggplant for commercial production (Bagla, 2010; Gupta et al., 2015). Bangladesh approved the *Bt* eggplant for commercial production in 2017 and has been rapidly adopted by producers who have benefited from cost savings associated with reduced pesticide usage (Shelton et al., 2018). In 2013, anti-GM groups in the Philippines received worldwide attention after vandalizing test plots of Golden Rice in the Bicol region (McGrath, 2013). Currently, Golden Rice is pending approval for commercial production in the Philippines (Wu, 2020).

To our knowledge, the only GM crops commercially produced for direct human consumption are the papaya, squash, apple, potato, eggplant, and white maize (ISAAA, 2017).

Notably, white maize is the only staple crop produced on a widespread commercial basis using GM varieties, and in 2017, South Africa commercially produced approximately 1.1 million hectares (85% adoption rate) of GM varieties for direct human consumption.

2.4. GM adoption in South Africa

In 1998-1999, *Bt* yellow maize was commercially adopted in South Africa. In 2001-2002, the adoption of *Bt* white maize established South Africa as the first GM subsistence crop producer in the world (Gouse, 2012). The commercial adoption of HT maize and stacked traits soon followed in 2003-2004 and 2007-2008, respectively (Gouse, 2012). In 2016, 74% of the country's total maize crop used HT cultivars, while 91% of the country's total maize crop used *Bt* cultivars (Brookes and Barfoot, 2018).

Given the criticisms that GM has not contributed to increased yields resulting in improved food security and increased producer profitability, the main objectives of this study are to estimate additional annual rations attributable to GM white maize adoption and to estimate producer profitability (both from a breakeven and relative profitability sense) between GM and conventional white maize in South Africa from 2001-2018. Further, this study compares the environmental impacts per hectare of GM and non-GM white maize production using Life Cycle Assessment (LCA). The study focuses on quantifying the GM impacts for field-to-plate white maize because few GM crops produced commercially are for direct human consumption and the literature is void of this type of analysis. The results of this study are unique in that they address both the large criticisms of GM crops, inability to increase food security and lack of producer profitability, in a medium that few GM studies have analyzed before, a field-to-plate crop. These results are important for policymakers, producers, consumers, NGOs, plant breeders, and other agricultural scientists addressing global food security.

3. Data and Methodology

Contributing authors: Lawton Lanier Nalley, Aaron M. Shew, Jesse B. Tack, Petronella Chaminuka, Marty D. Matlock, and Marijke D'Haese

The Grain Crops Institute of the South African Agricultural Research Council (ARC) 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. Since 1980, the Agricultural Research Council Grain Crops Division (ARC-GC) has conducted multi-season National Maize Cultivar Trials throughout South Africa. ARC-GC, with financial support from the Maize Trust, conducts independent evaluations of maize cultivars from various seed companies with the aim of assisting producers in the decision-making process regarding cultivar selection.

Grain South Africa (Grain SA) was founded in 1999 as a nonprofit organization to provide commodity specific support and services to South African producers. The area devoted to white maize in each of the nine South African provinces was obtained from Grain SA. Table A1 shows the area grown to white maize by province in South Africa from 1999-2018.

This study uses yield (tons/hectare) data for white maize genotypes from the National Maize Cultivar Trials and estimated province level GM white maize yield premiums derived from Shew et al. (2021). Using a multivariate regression model, Shew et al. (2021) regressed yield for each cultivar in a province for a given year on an indicator variable for GM while controlling for location and year fixed effects, resulting in the estimated province level GM white maize yield premiums. The National Maize Cultivar data includes observations for both white and yellow maize, for a total of 58,952 observations across 106 locations (Figure 1) and 491 cultivars across 28 years. Shew et al. (2021) define a "trial" by unique location-year combination of which there are 966 in the dataset. While the National Maize Cultivar Trials test both white and yellow maize, we focus on only white maize, as it is for direct human consumption (Shew et al., 2021). Although a gap between experimental and actual yields exists, Brennan (1984) concluded that the most reliable sources of relative yields are cultivar trials outside actual farm observations (Brennan, 1984). Although yields are often greater in experimental test plots as compared with producers' fields, the relative yield differences between varieties are assumed to be comparable (Shew et al., 2018).

GM maize adoption rates for South Africa were obtained from various sources (Abidoye and Mabaya, 2014; Esterhuizen, 2015; ISAAA, 2018, 2017, 2016). Table A2 provides an overview of GM white maize area in South Africa by province and the adoption rates for GM white maize in South Africa from 2001-2018. Although *Bt* yellow maize was first introduced in South Africa in 1999, this analysis is concerned with GM white maize production, and as such, begins in 2001 when *Bt* white maize was first commercially adopted. Due to limited data availability, for the years 2015-2018 the adoption rates were not disaggregated by maize color and are representative of both GM white and GM yellow maize. Adoption rates for the years 2001-2014 are disaggregated by white and yellow maize, and thus, are reflective of GM white maize adoption. It should be noted that maize production data (e.g., area and yield) and GM maize adoption rates used in this study are not disaggregated by commercial versus subsistence farmers (some estimates suggest that subsistence farmers contribute to approximately two percent of production (Lacambra et al., 2020)). Further research is warranted about the yield, income, and environmental effects of GM adoption between commercial and subsistence white maize producers in South Africa.

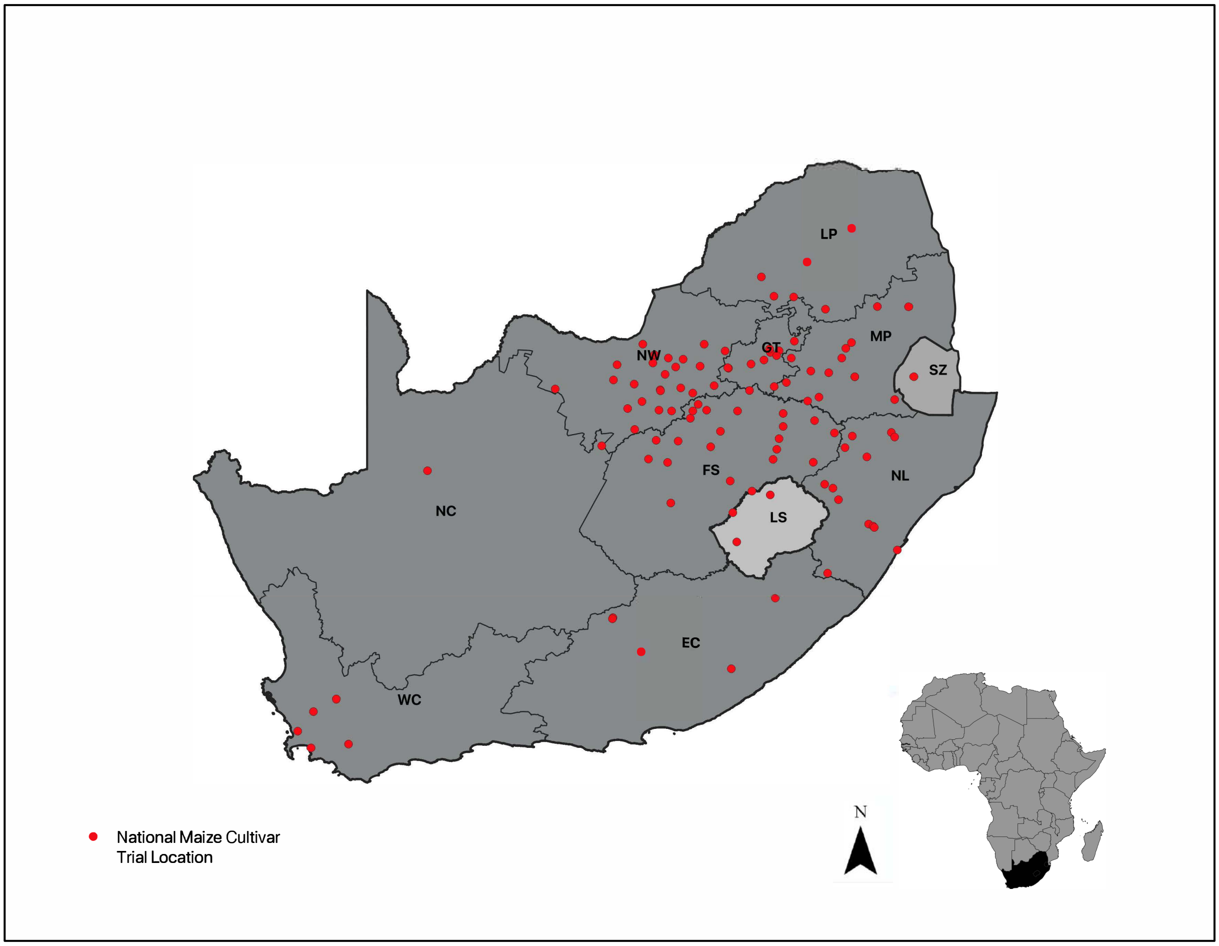

Figure 1. Location of Agricultural Research Council (ARC) National Maize Cultivar Trials used in the study: 1980-2018. LS—Lesotho, SZ—Eswatini, EC—Eastern Cape, FS—Free State, GT—Gauteng, NL—KwaZulu-Natal, LP—Limpopo, MP—Mpumalanga, NC—Northern Cape, NW—North-West, WC—Western Cape.

3.1. Estimation of additional annual rations

For the purposes of this study, annual ration was defined as the average annual consumption of white maize for one individual in South Africa. To estimate the number of additional annual rations attributed to GM white maize adoption in South Africa, the additional tons of white maize produced by province *p* for year *t* attributable to GM adoption ($Q^{A}_{P,t}$) were estimated as:

$$Q^{A}_{pt} = A_{pt}\beta_{pt}y_p \quad (1),$$

Where A_{pt} denotes the area in hectares devoted to white maize production in province *p* for year *t*, β_{pt} denotes the percentage of white maize produced that was GM in province *p* for year *t*, and y_p denotes the estimated yield premium associated with GM white maize adoption for province *p* in tons per hectare from (Shew et al., 2021).

The number of additional annual rations, *R*, attributable to GM maize adoption in year *t* is estimated as (R_t):

$$R_t = \frac{\sum Q^{A}_{pt}}{Q^{R}_{t}} \quad (2),$$

Where $\sum Q^{A}_{pt}$ denotes the summation of additional tons of white maize produced in each of the nine provinces of South Africa, *p*, attributable to GM maize adoption in South Africa for year *t*, and Q^{R}_{t} denotes the maize consumption in kilograms per capita per year in South Africa for year *t*. South Africa's per capita maize consumption between 2001-2017 was retrieved from FAOSTAT (Table 2) (FAO, 2020, 2017).

3.2. Estimation of welfare gains

An equilibrium displacement model (EDM) was developed to quantify changes in producer and consumer surplus attributable to the adoption of GM technology in white maize production in South Africa (Wohlgenant, 2011). The EDM employed for this analysis was specified as:

$$EQ_D = \eta EP - \eta\delta \qquad (3),$$

$$EQ_S = \varepsilon EP - \varepsilon\kappa \qquad (4),$$

$$EQ_D = EQ_S \qquad (5),$$

Where EQ_D and EQ_S are the relative changes in demand and supply, respectively, *EP* denotes the relative change in market equilibrium price, η denotes the own price elasticity of white maize, ε denotes the supply elasticity of white maize, δ denotes the relative change in demand, and κ denotes the relative change in supply.

The relative change in demand, δ, was assumed constant. The relative change in supply, κ, was calculated as the average percent share of additional white maize attributable to GM adoption from the supply of white maize as a sum of domestic production and imports for years 2001-2018. The relative change in supply for the years 2001-2018, κ, was estimated as a 7.05% shift upward.

Existing literature on the estimates of the elasticity of demand, η, and supply, ε, of white maize in South Africa was sparse. For this analysis, an own price elasticity of -0.149 was used, since it was specific to white maize in South Africa (van Zyl, 1986). A long-run supply elasticity for maize of 0.36 was used since it was specific to maize in South Africa (Shoko et al., 2016) and provides a more conservative estimation of consumer welfare compared to other estimates (Poonyth et al., 2000; Rosegrant et al., 1995). Further sensitivity analysis was performed using all elasticity of demand and supply combinations found in the literature.

The analytical solutions for changes in market price and quantity were specified as:

$$EP = \frac{\varepsilon\kappa}{\varepsilon - \eta} \quad (6),$$

$$EQ = \frac{-\eta\varepsilon\kappa}{\varepsilon - \eta} \quad (7).$$

Given these analytical solutions, the changes in consumer surplus *(ΔCS_t)*, producer surplus *(ΔPS_t)*, and net surplus *(NS_t)* for year *t* were derived:

$$\Delta CS_t = P_t Q_t (EP)(1 + 0.5EQ) \quad (8),$$

$$\Delta PS_t = P_t Q_t (EP - \kappa)(1 + 0.5EQ) \quad (9),$$

$$NS_t = \Delta CS_t + \Delta PS_t \quad (10),$$

Where P_t denotes white maize domestic futures prices in South Africa for year *t* in USD 2018 (SAFEX, n.d.), and Q_t denotes the supply of white maize as a sum of domestic production and imports for year *t* in tons obtained from crop estimates reported by Grain SA (Grain SA, 2020).

3.3. Ecosystem impacts of GM maize adoption

The LCA framework was employed to quantitatively compare cradle-to-farm gate environmental effects associated with conventional and GM maize production in South Africa. Comparisons were made between one hectare of conventional white maize and one hectare of

GM maize using the LCA modeling platform SimaPro 9.0.0.48© (Pre' Sustainability, Amsersfoort, The Netherlands) and the ecoinvent database (Wernet et al., 2016). An evaluation was conducted for the counterfactual scenario of no GM white maize adoption to estimate the subsequent environmental cost savings of GM white maize adoption. That is, how much greater would the environmental damage (in dollars) have been if GM white maize was not adopted in South Africa?

The mean yield for conventional dryland white maize for 2001-2018 was estimated at 3.998 tons per hectare (Grain SA, 2020). The yield for GM dryland white maize was estimated as 4.421 tons per hectare and was calculated as the sum of the mean yield for conventional dryland white maize (3.998 tons per hectare) (Grain SA, 2020) and the estimated yield premium for GM dryland maize (0.423 tons per hectare) (Shew et al., 2021). Table 3 shows the recommended pesticides and herbicides used in one hectare of conventional and GM (stacked technology) maize production during one growing season (Grain SA, 2019a). Other inputs (e.g., fuel, fertilizer, land preparation, etc.) were assumed constant across maize seed technology due to a lack of data, however, the main differences in both production systems manifest from the differences in yield and pesticide requirements.

The Stepwise Life Cycle Impact Assessment (LCIA) method was utilized to provide a combined score for both human and environmental effects, in dollar terms (Weidema, 2009). Table 4A details the impact categories used in this LCA. The Stepwise LCIA method has midpoint and endpoint characterization factors (Weidema, 2009). This LCIA method uses normalization and weighting factors based on 1995 European Union cumulative per-capita emissions. The Stepwise LCIA defines impact categories in terms of Quality Adjusted Life Years (QALYs) for impacts on human well-being, Biodiversity Adjusted Hectare Years

(BAHYs) for impacts on ecosystems, and monetary units for impacts on resource productivity (Weidema, 2009). Based on the budget constraint, it is estimated the potential annual economic production per capita is 88,737 (2018 USD) (Weidema, 2005). The Stepwise method assigns a cost of 1/14 QALY per BAHY (Weidema, 2015). This allows impacts associated with resources and ecosystems to be expressed in the same units as impacts associated with human well-being.

Subsequent calculations were performed to derive the environmental externalities (*E Externalities*) differences from GM white maize adoption for year *t* and the net impacts of GM white maize adoption (*Net Impacts*) for year *t*:

$$E\ Externalities_t = \sum A_{pt}\beta_{pt}\,(Total\ Cost_{Conv} - Total\ Cost_{GM}) \qquad (11),$$

$$Net\ Impacts_t = E\ Externalities_t + NS_t \qquad (12),$$

Where ∑Ap,t denotes the hectares of white maize produced in province p for year t, βpt denotes the percentage of white maize hectares that were GM in province p for year t, Total CostConv and Total CostGM denotes the endpoint impact score, in USD 2018 per hectare, from the Stepwise LCIA for one hectare of conventional white maize production and one hectare of GM white maize production, respectively, and NSt denotes the change in net surplus for year t in USD 2018 (Equation 10). By using the stacked GM technology (instead of HT or Bt) this study likely overestimates total LCA benefits when aggregated up to South Africa in its entirety, as approximately 66% of the total GM maize production was under stacked technology in 2018 followed by HT (23%) and Bt (11%) (ISAAA, 2018). However, using the LCA metric of comparing one hectare of conventional maize to one hectare of GM (thus no aggregation needed) the difference would represent the largest potential benefit of GM adoption.

3.4. Profitability and profit margin differentials between GM and non-GM white maize

Given that GM crop production is typically associated with greater up-front costs to producers (mainly in seed expense), yield should not be the sole metric considered when evaluating GM white maize producer benefits. Conventional and *Bt* cultivars were compared in a head-to-head profitability comparison using cost of production, mean yield from the National Maize Cultivar Trials in 18 locations in Free State and North West provinces, and estimated yield variance derived from Shew et al. (2021) (Table A5). Free State and North West are two of the three the largest maize producing provinces in South Africa, and only locations in Free State and North West were used in this analysis due to the availability of their production budgets. Unlike the LCA, where stacked GM technology was used in which there were no cost of production but detailed input amounts (Grain SA, 2019a), in the profitability analyses we use Grain SA (2020) *Bt* maize production budget which provides the costs associated with *Bt* maize but not the input amounts (Grain SA, 2019b, 2019c). Given the National Maize Cultivar Trials test many cultivars (i.e., some are older cultivars used as checks with low yield and no current producer adoption) only the top ten highest yielding conventional and *Bt* cultivars were compared. Table A6 shows cost of production for conventional and *Bt* maize for both provinces, which were provided by Grain SA (Grain SA, 2019c, 2019b).

Profitability was simulated using @Risk© (Palisade Corp., Ithaca, NY) for conventional and *Bt* white maize across 18 locations in Free State and 18 locations in North West. From the 1,000 simulation iterations, a two-tailed t-test was used to test for statistical differences between the profitability of conventional and *Bt* white maize. Two levels of profitability were considered. First, an estimation of the breakeven percentage producing conventional and *Bt* white maize was conducted. Second, the relative return on investment for conventional and *Bt* white maize by location was investigated. Given that *Bt* production is associated with greater up-front costs to producers, another measure of profitability is the return on investment, which is defined as the cost of production in this study. The profit margin in this sense is defined as profit per unit of cost. Profit margin estimates were obtained by the simulations described above. Thus, this study explores the percentage of times a producer would breakeven or earn a profit as well as the profit margin comparison between conventional and *Bt* maize for 36 locations across two provinces in South Africa.

4. Results

Contributing authors: Lawton Lanier Nalley, Aaron M. Shew, Jesse B. Tack, Petronella Chaminuka, Marty D. Matlock, and Marijke D'Haese

4.1. Estimation of additional annual rations

Table 1 illustrates the differences in the GM white maize yield premiums across provinces. Estimated yield gains range from a low of 0.370 t/ha in North West to a high of 0.986 t/ha in Gauteng ($P < 0.01$). The estimated yield gain in the top maize producing province, Free State, is 0.591 ($P < 0.01$) (Shew et al., 2021). Table 1 also presents the results associated with the additional tons of white maize attributed to the adoption of GM maize by province for 2001-2018. In 2018, it is estimated that the adoption of GM white maize in South Africa resulted in 610,744 additional tons of white maize. The average additional production among the top two white maize producing provinces, Free State and North West, is 219,678 and 111,738, respectively. Additional production ranges from a low of 3,271 tons in 2001 to a high of 763,949 tons in 2017. To put these gains in perspective, they range from 0.05% in 2001 to 11.96% in 2013 of the total white maize output in South Africa. Moreover, in order to achieve comparable quantities of white maize produced using non-GM cultivars (i.e., without the estimated yield premiums associated with GM white maize production) the additional land required would range from 1,088 hectares in 2001 to 217,788 hectares in 2014, or 0.07% and 14.04% additional production area, respectively.

Using the results from Table 1, the additional annual rations of maize attributed to GM white maize adoption, based on yearly per capita maize consumption, was estimated (Equation 2). South Africa's per capita maize consumption ranges from 94.15 kg in 2009 to 113.48 kg in 2003 (Table 2). The adoption of GM white maize has contributed an average of 4.6 million additional annual rations with a high of 7.4 million in 2017 and a low of 29,215 in 2001. To put the 2017 results in perspective, GM white maize adoption provided additional annual maize rations for 12.6% of the total 58.6 million people estimated to live in South Africa in 2017. In total, GM white maize adoption has contributed 83.5 million additional rations of maize for 2001-2018 (Table 2). These results are important as they refute, at least in the South African context, an often-cited criticism of GM crops have ambiguous effects on food insecurity (Gurian-Sherman, 2009; Hakim, 2016; Heinemann, 2009; Nature, 2010; UNCTAD, 2013; WHO, 2005).

Table 1. Additional tons of white maize attributed to the adoption of GM maize by province: 2001-2018.

Year	% White Maize that is GM	Eastern Cape[a]	Free State[a]	Gauteng[a]	Kwazulu-Natal[a]	Limpopo[a]	Mpumalanga[a]	North West[a]	Northern Cape[a]	Western Cape[a]	South Africa[b]
2001	0.4%	0.0	1,442.0[e]	220.9	72.2	89.6	470.2	962.0	122.3	0.3	**3,271**
2002	3.0%	0.0	12,198.2	1,789.6	690.3	756.0	4,544.9	8,735.7	1,041.9	1.7	**28,834**
2003	8.0%	0.0	38,060.4	5,955.4	2,548.8	2,884.0	14,627.2	28,416.0	8,204.6	2.9	**93,426**
2004	8.0%	0.0	31,204.8	6,310.4	2,022.0	1,848.0	13,686.9	22,496.0	4,381.6	5.8	**78,059**
2005	29.0%	0.0	113,117.4	17,156.4	7,186.2	6,902.0	42,418.9	72,964.0	7,876.1	0.0	**260,596**
2006	44.0%	0.0	89,713.8	21,692.0	9,968.6	3,696.0	44,821.9	68,376.0	63,801.5	0.0	**244,723**
2007	62.0%	0.0	234,508.8	36,679.2	16,680.5	17,360.0	89,069.2	142,228.0	22,848.3	13.5	**538,825**
2008	56.0%	0.0	228,362.4	44,172.8	16,255.7	16,072.0	98,002.2	126,392.0	16,996.4	407.1	**531,307**
2009	79.0%	0.0	263,792.9	53,746.9	22,372.8	18,249.0	110,912.1	163,688.0	20,515.7	861.5	**635,555**
2010	75.0%	0.0	305,842.5	62,857.5	24,426.0	13,650.0	113,622.0	176,212.5	14,497.5	272.6	**698,350**
2011	72.0%	0.0	253,149.2	52,526.8	19,877.9	12,598.3	84,617.0	133,181.5	14,021.0	157.0	**557,516**
2012	81.0%	0.0	339,884.1	59,100.8	25,233.1	18,144.0	84,628.8	182,817.0	17,533.2	294.4	**711,845**
2013	84.0%	0.0	359,919.0	61,289.8	27,951.8	17,640.0	93,248.4	175,602.0	18,055.4	183.2	**737,642**
2014	84.0%	0.0	362,401.2	53,835.6	25,573.0	17,640.0	92,151.4	158,508.0	17,839.7	305.3	**712,222**
2015	90.0%	0.0	377,649.0	39,045.6	25,488.0	17,955.0	90,505.8	154,845.0	30,217.8	294.4	**708,864**
2016	90.0%	0.0	207,441.0	43,482.6	24,213.6	19,845.0	94,032.0	113,220.0	32,215.0	327.2	**505,862**
2017	85.0%	0.0	404,391.8	50,286.0	30,090.0	23,800.0	88,808.0	163,540.0	28,138.8	123.6	**763,949**
2018	87.0%	0.0	331,125.5	42,891.0	27,718.2	7,308.0	79,535.4	119,103.0	29,623.8	0.0	**610,744**
	Estimated yield premium[c]	0.553	0.591[d]	0.986[d]	0.708[d]	0.700[d]	0.653[d]	0.370[d]	0.978[d]	0.727[d]	0.601[d]

[a]As derived by Equation 1.

[b]As derived by the summation of additional tons of white maize produced in each province.

[c]As derived from (Shew et al., 2021).

[d]Estimated yield premium associated with GM adoption in province *p* was statistically different (P < 0.01) from conventional maize yield.

[e]Calculated as the product of Table A2 and estimated yield premium on Table 1.

4.2. Estimation of welfare gains

To quantify changes in producer and consumer surplus attributable to the adoption of GM technology in white maize production in South Africa, a general EDM was employed (Equations 3-10). The resulting changes in consumer surplus, producer surplus, and net surplus (2018 USD) for the years 2001-2018 are presented in Table 2. The gains in consumer surplus are reflective of the benefits to consumers resulting from lower maize prices which emerge from an increase in quantity supplied to markets which emerge from the adoption of GM technology. The net surplus summed over 2001-2018 amounted to $694.7 million (2018 USD), and the average annual net surplus was $38.6 million (2018 USD) (Table 2).

Table A3 presents the resulting total net surplus sensitivity analysis attributed to the adoption of GM maize under various estimates of demand and supply elasticities for 2001-2018. The total net surplus estimates resulting from the sensitivity analysis range from $388.4 million to $905.9 million (2018 USD) with an average total net surplus of $668.9 million (2018 USD) (Table A3). By comparison, the total net surplus as reported in Table 2 was $694.7 million (2018 USD), indicating that our results gravitate towards the average of all scenarios.

Table 2. Changes in producer and consumer surplus (2018 USD) and additional annual maize rations attributable to the adoption of GM maize in South Africa: 2001-2018.

Year	Price/ton (2018 USD)[a]	Additional tons of maize[b]	Consumption of maize (kg/capita/yr)[c]	Additional annual rations[d]	Consumer surplus (2018 USD)[e]	Producer surplus (2018 USD)[e]	Net surplus (2018 USD)[e]
2001	307.26	3,271	111.96	29,215	82,180,175	-33,908,344	48,271,831
2002	154.86	28,834	112.64	255,982	46,112,148	-19,026,323	27,085,825
2003	161.85	93,426	113.48	823,280	55,302,640	-22,818,410	32,484,229
2004	107.04	78,059	110.71	705,077	37,057,731	-15,290,382	21,767,349
2005	182.16	260,596	108.03	2,412,253	69,101,679	-28,512,029	40,589,650
2006	236.20	244,723	101.17	2,418,930	70,667,153	-29,157,959	41,509,194
2007	224.15	538,825	100.05	5,385,559	60,422,812	-24,931,043	35,491,769
2008	180.29	531,307	96.67	5,496,093	62,922,961	-25,962,629	36,960,332
2009	132.96	635,555	94.15	6,750,447	44,707,871	-18,446,905	26,260,966
2010	200.69	698,350	101.19	6,901,375	79,807,036	-32,929,164	46,877,872
2011	240.68	557,516	100.43	5,551,288	85,766,089	-35,387,927	50,378,161
2012	217.63	711,845	99.4	7,161,419	72,160,333	-29,774,059	42,386,274
2013	200.87	737,642	100.1	7,369,046	55,213,235	-22,781,521	32,431,714
2014	248.53	712,222	101.31	7,030,123	87,212,112	-35,984,571	51,227,542
2015	350.62	708,864	101.95	6,953,051	98,573,343	-40,672,326	57,901,017
2016	159.06	505,862	102.46	4,937,167	43,798,015	-18,071,490	25,726,526
2017	154.80	763,949	103.4	7,388,287	68,200,467	-28,140,180	40,060,287
2018	163.07	610,744	103.4[f]	5,906,617	63,494,050	-26,198,266	37,295,784
			Average	**4,637,512**	**65,705,547**	**-27,110,752**	**38,594,796**
			Total	**83,475,209**	**1,182,699,850**	**-487,993,530**	**694,706,321**

[a](SAFEX, n.d.). [b]From Table 1. [c](FAO, 2020, 2017). [d]As derived by Equation 2. [e]The elasticity of demand of -0.149 (van Zyl, 1986) and the elasticity of supply of 0.36 (Shoko et al., 2016). The upward shift in supply was set at 7.05% assuming demand held constant. Prices and quantities varied with the year observed but elasticities remained constant (see Equations 3-10). [f]Maize consumption data for the year 2018 was not available, thus it was assumed maize consumption remained constant from the previous.

4.3. Ecosystem impacts of GM maize adoption

The ecosystem impacts of GM maize adoption are presented in the counterfactual argument. That is, we ask, how much more environmental damage would have occurred if GM white maize was not adopted in South Africa from 2001-2018? The main differences between conventional and GM maize production include the yield (i.e., yields associated with conventional dryland maize and GM dryland maize were estimated at 3.998 and 4.421 tons per hectare, respectively) and the pesticides requirements (Table 3). For example, conventional maize production uses seven different herbicides (e.g., glyphosate, atrazine, terbuthylazine, S-metolachor, mesotrione, 2,4-D, and terbuthylazine) while GM maize production solely uses glyphosate, albeit three times as much than conventional maize production. Both conventional and GM maize production use a pyrethroid compound as a means of pest control. Conventional maize production, however, uses about twice as much pyrethroid in a growing season compared to GM maize production. Commercial maize production in South Africa involves more inputs than those listed on Table 3, but all other inputs in maize production are assumed to be identical for conventional and GM maize, implying that the differences in ecosystem impacts would manifest themselves through the different inputs on Table 3.

Table 3. Pesticide active ingredients for one hectare of conventional and GM white maize production in South Africa for the 2019/2020 production season.[a]

	Conventional dryland maize	GM dryland maize
Herbicides (g/ha)		
Glyphosate	1,155.00	3,465.00
Atrazine	978.20	N/A
S-metolachlor	966.60	N/A
2,4-D (phenoxy compound)	120.00	N/A
Pesticide, unspecified[b]	517.20	N/A
Insecticides (g/ha)		
Pyrethroid	9.05	4.38

[a]Derived from maize production budget from Grain SA and personal communication with Ernest Dube at Nelson Mandela University (Grain SA, 2019a).
[b]Includes pesticides that do not have built unit process in ecoinvent database (Wernet et al., 2016). 497.2 g/ha of terbuthylazine and 20.0 g/ha of mesotrione is accounted for as an unspecified pesticide in the conventional dryland maize unit process.

The functional unit for comparison is one hectare of production under both seed technologies (stacked GM and non-GM). Table 4 presents the results associated with each Stepwise impact category. The total cost reflects the sum of all impact categories in terms of monetary cost (2018 USD). The total costs for one hectare of conventional dryland white maize production and GM dryland white maize production are estimated at $9.11 (2018 USD) and $8.77 (2018 USD), respectively. The total costs can be viewed as the costs to mitigate the environmental damage associated with the production of a hectare of conventional and GM white maize in South Africa, respectively. Respiratory inorganics and effects associated with global warming from fossil fuels are the major contributors to the economic costs associated with both conventional and GM white maize production in South Africa. All other environmental costs combined accounted for under nine and ten percent of the total costs for conventional and GM white maize, respectively (Table 4).

Table 4. Environmental impact scores using Stepwise LCIA method for one hectare of conventional and GM dryland maize production. The total cost is the sum of monetary cost of all impact categories.

Impact category	**Conventional dryland maize (USD 2018)**	**GM dryland maize (USD 2018)**
Total Cost	$9.1133	$8.7746
Respiratory inorganics	$4.9214	$4.1431
Global warming, fossil	$3.4222	$3.7473
Human toxicity, carcinogens	$0.2297	$0.1758
Human toxicity, non-carc.	$0.1302	$0.1555
Photochemical ozone, vegetat.	$0.1029	$0.1383
Acidification	$0.0711	$0.0283
Ecotoxicity, terrestrial	$0.0666	$0.0692
Eutrophication, aquatic	$0.0653	$0.1714
Eutrophication, terrestrial	$0.0400	$0.0420
Nature occupation	$0.0356	$0.0605
Ecotoxicity, aquatic	$0.0153	$0.0267
Respiratory organics	$0.0072	$0.0100
Ozone layer depletion	$0.0019	$0.0011
Global warming, non-fossil	$0.0000	$0.0000
Non-renewable energy	$0.0000	$0.0000

Inputs were derived from Table 5. The mean yield for conventional dryland white maize for 2001-2018 was estimated at 3.998 tons per hectare (Grain SA, 2020). The yield for GM dryland white maize was estimated as 4.421 tons per hectare and was calculated as the sum of the mean yield for conventional dryland white maize (3.998 tons per hectare) (Grain SA, 2020) and the estimated yield premium for GM dryland maize (0.423 tons per hectare) (Shew et al., 2021).

To estimate the ecosystem externalities attributed to GM white maize adoption, the difference between the conventional dryland white maize total cost and the GM dryland white maize total cost, $0.34 (2018 USD), was multiplied by the area of GM white maize in South Africa annually (Equation 11). Table 5 indicates that GM white maize adoption has resulted in environmental benefits valued at $5.3 million (2018 USD) for 2001-2018 and $292,282 (2018 USD) on average annually. The net surplus attributable to GM white maize (Table 2) was subsequently added to the environmental externalities from GM white maize adoption, resulting in the net impacts of GM white maize adoption (Equation 12). As indicated in Table 5, the total net impacts of GM maize adoption for 2001-2018 was $700 million (USD 2018). On average, the net impacts of GM maize adoption were $38.9 million (USD 2018). While $292,282 (USD 2018) in annual environmental benefits is marginal compared to the revenue gains, these findings are contrary to the claim that GM crops are detrimental to the environment (Hakim, 2016; Heinemann, 2009; UNCTAD, 2013).

Table 5. Total benefits attributable to GM maize adoption: 2001-2018.

Year	**Net Surplus Change (2018 USD)**[a]	**Environmental Externalities (2018 USD)**[b]	**Net Impacts (USD 2018)**[c]
2001	$48,271,831	$2,116	$48,273,947
2002	$27,085,825	$18,720	$27,104,545
2003	$32,484,229	$60,482	$32,544,712
2004	$21,767,349	$49,904	$21,817,253
2005	$40,589,650	$166,957	$40,756,607
2006	$41,509,194	$153,925	$41,663,119
2007	$35,491,769	$341,153	$35,832,921
2008	$36,960,332	$329,416	$37,289,748
2009	$26,260,966	$398,363	$26,659,329
2010	$46,877,872	$436,788	$47,314,660
2011	$50,378,161	$345,778	$50,723,939
2012	$42,386,274	$448,826	$42,835,100
2013	$32,431,714	$460,045	$32,891,759
2014	$51,227,542	$441,270	$51,668,811
2015	$57,901,017	$441,350	$58,342,367
2016	$25,726,526	$309,285	$26,035,810
2017	$40,060,287	$472,977	$40,533,264
2018	$37,295,784	$373,620	$37,669,404
Average	**$38,594,796**	**$291,721**	**$38,886,516**
Total	**$694,706,321**	**$5,250,974**	**$699,957,295**

[a]From Table 2.
[b]Calculated by subtracting the conventional dryland maize total cost and GM dryland maize total cost (Table 4, $0.34) and multiplying by total white maize area found on Table A2 (Equation 11).
[c]Calculated as the sum of the net surplus change and environmental externalities (Equation 12).

4.4. Profitability and profit margin differentials between GM and non-GM white maize

Given that GM white maize production is associated with greater up-front costs to producers, yield gains alone are not a sufficient metric when evaluating the producer benefits of GM maize adoption. The mean yield and yield variance for conventional and *Bt* cultivars in 18 locations in Free State and North West were derived from Shew et al. (2021). Only the top ten yielding dryland conventional and dryland *Bt* maize cultivars for 2000-2017 (Table A5). Table A5 shows the average yields in Free State province for both conventional and *Bt* cultivars were higher than those of North West province, 5.04, 5.47, 4.41, and 4.67 tons per hectare, respectively. The yield variance estimates in North West province were higher (1.99 for conventional and 2.11 tons per hectare for *Bt*), on average, compared to the yield variance estimates in Free State province (1.43 for conventional and 1.81 tons per hectare for *Bt*).

Table A6 presents the variable costs associated with one hectare of conventional and *Bt* maize production in Free State and North West provinces. Table 6 presents the breakeven results and the relative profit margins for conventional and *Bt* maize cultivars in 18 locations in Free State province and 18 locations in North West province. In Free State, *Bt* adopters, on average, were estimated to breakeven or make a profit more frequently ($P < 0.05$) 83.80% of the time, compared to their conventional counterparts at 76.70%. Similarly, in North West, *Bt* adopters, on average, breakeven more frequently ($P < 0.05$) at 89.33% of the time compared to their conventional counterparts who breakeven 88.74% of the time.

Table 6. Breakeven and relative profit margins for conventional and Bt maize cultivars in Free State and North West provinces: 2000-2017.

		Breakeven (%)†		**Relative Profit Margin (%)**	
	Location	**Conventional**	***Bt***	**Conventional**	***Bt***
Free State	Bethlehem	92.04%^{a}	93.88%^{b}	36.27%^{x}	42.95%^{y}
	Blesbokfontein	29.97%^{a}	52.13%^{b}	-6.60%^{x}	0.88%^{y}
	Bothaville	84.36%^{a}	88.61%^{b}	24.73%^{x}	31.30%^{y}
	Bultfontein	78.23%^{a}	85.57%^{b}	10.56%^{x}	17.54%^{y}
	Clocolan	23.15%^{a}	49.84%^{b}	-7.54%^{x}	-0.03%^{y}
	Frankfort	39.15%^{a}	52.10%^{b}	-6.14%^{x}	1.32%^{y}
	Kroonstad	99.81%^{a}	99.80%^{a}	34.75%^{x}	41.04%^{y}
	Leribe	19.54%^{a}	49.56%^{b}	-7.62%^{x}	-0.12%^{y}
	Marquard	91.35%^{a}	93.86%^{b}	20.85%^{x}	27.53%^{y}
	Maseru	60.47%^{a}	71.30%^{b}	5.32%^{x}	12.44%^{y}
	Memel	100.00%^{a}	100.00%^{a}	43.63%^{x}	49.67%^{y}
	Nampo	94.41%^{a}	95.83%^{b}	22.09%^{x}	28.73%^{y}
	Reitz	99.65%^{a}	99.54%^{a}	34.97%^{x}	41.25%^{y}
	Tweeling	99.43%^{a}	99.48%^{a}	39.80%^{x}	45.95%^{y}
	Viljoenskroon	89.67%^{a}	92.30%^{b}	36.30%^{x}	42.54%^{y}
	Vrede	93.34%^{a}	94.88%^{b}	17.83%^{x}	24.59%^{y}
	Wesselsbron	86.26%^{a}	89.89%^{b}	27.39%^{x}	33.88%^{y}
	Windfield	99.86%^{a}	99.88%^{a}	56.18%^{x}	61.87%^{y}
	Average	**76.70%^{a}**	**83.80%^{b}**	**21.27%^{x}**	**27.96%^{y}**
North West	Athole	97.84%^{a}	97.87%^{a}	71.31%^{x}	69.17%^{x}
	Coligny	98.57%^{a}	98.46%^{a}	41.43%^{x}	40.75%^{x}
	Delareyville	85.14%^{a}	85.97%^{b}	25.18%^{x}	25.43%^{x}
	Gerdau	93.23%^{a}	93.53%^{a}	43.03%^{x}	42.26%^{x}
	Glaudina	75.12%^{a}	76.67%^{b}	16.69%^{x}	17.49%^{x}
	Grootpan	96.05%^{a}	96.28%^{a}	66.88%^{x}	64.94%^{x}
	Hartbeesfontien	84.52%^{a}	85.24%^{b}	20.84%^{x}	21.36%^{x}
	Kameel	67.99%^{a}	70.29%^{b}	4.32%^{x}	5.92%^{x}
	Koster	86.93%^{a}	87.45%^{a}	23.21%^{x}	23.59%^{x}
	Leeudoringstad	98.63%^{a}	98.57%^{a}	51.92%^{x}	50.70%^{x}
	Lichtenburg	87.72%^{a}	88.21%^{a}	52.30%^{x}	51.05%^{x}
	Ottosdal	98.13%^{a}	98.12%^{a}	44.76%^{x}	43.90%^{x}
	Potchefstroom	87.36%^{a}	87.82%^{a}	21.72%^{x}	22.19%^{x}
	Schweizerreineke	92.57%^{a}	92.77%^{a}	31.00%^{x}	30.91%^{x}
	Setlagole	63.19%^{a}	65.69%^{b}	7.62%^{x}	9.00%^{x}
	Tweebuffels	85.71%^{a}	86.45%^{b}	25.68%^{x}	25.90%^{x}
	Ventersdorp	99.80%^{a}	99.73%^{a}	47.47%^{x}	46.47%^{x}

Table 6 (Cont.)

	Breakeven (%)†		Relative Profit Margin (%)	
Location	**Conventional**	***Bt***	**Conventional**	***Bt***
Wolmaranstad	98.83%[a]	98.78%[a]	51.57%[x]	50.36%[x]
Average	**88.74%[a]**	**89.33%[b]**	**35.94%[x]**	**35.63%[x]**

†Based off of the mean yield and yield variance in Table A5 assuming an average price of 147.12 (2019 USD) and average total cost of 17.06 (2019 USD) for Free State and 14.17 (2019 USD) for North West simulated 1000 times using @Risk.

[b]Breakeven percentage for *Bt* maize cultivars in location *l* was statistically different (P < 0.05) from conventional maize cultivars.

[y]The relative profit margin for *Bt* maize cultivars in location *l* was statistically different (P < 0.05) from conventional maize cultivars.

In Free State, *Bt* adopters, on average, have a greater relative profit margin compared to their conventional counterparts at 27.96% and 21.27%, respectively (P < 0.05). These results suggest, on average, *Bt* cultivars return 0.07 Rand and more profit for each Rand invested than conventional cultivars return in Free State. In North West, it was found that there is not a statistical difference (P > 0.1) between the relative profit margin of *Bt* and conventional maize production (Table 6). The results presented in Table 6 suggest that the higher upfront costs associated with *Bt* white maize are offset by the ability for producers to breakeven more frequently, and for producers in Free State, offset by higher relative profit margins. These findings are contrary to the frequent criticism of GM crops that producers' higher yields are offset by higher input costs (Heinemann, 2009).

5. Conclusions

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Despite South Africa's upper-middle-income country classification, food insecurity is an ongoing concern for a large segment of the population, as evident from 2014-2015 when over a fourth of households experienced food insecurity due to severe drought and subsequent food price shocks (STATSA, 2016). Concerns surrounding food security are also amplified by the threat of climate change and its subsequent effects on sub-Saharan agricultural production and maize production particularly. Given the present and future concerns, producers, agricultural scientists, and policymakers alike are considering a wide range of options to reduce the present, as well as mitigate future food insecurity in the region, including GM technology adoption.

Three of the most common criticisms of GM adoption are that GM crops do not increase the food supply, do not make producers more profitable, and do not reduce the environmental impact of agricultural production. Using a combined economic (province-level yield benefits of GM and adoption rates) and environmental (LCA) approach, we estimate the total welfare benefits attributable to GM white maize adoption in South Africa for 2001-2018 are $694.7 million. Food security benefits attributable to GM white maize also manifest through an average of 4.6 million additional rations annually. To achieve these additional rations using conventional maize, the production area in South Africa would have to increase by up to 217,788 hectares. The LCA results indicate that GM maize reduces environmental damage by $0.34 per hectare or $291,721 annually, compared to conventional hybrid white maize. Our analysis of producer profitability focuses on the main production regions in the North West and Free State provinces, and we find that GM hectares breakeven more often than non-GM hectares. Given that GM is often associated with higher upfront costs, relative profitability was also compared, and we find that GM adopters in Free State, but not in North West, had higher relative profit margins. While the results of this study indicate that GM maize adoption in South Africa can increase maize rations, it is naive to think that increasing food supply is the only element of food security. Markets, incomes, purchasing power, and international trade all factors in food security. While this paper only analyzes one aspect of food security, its results indicate that adoption of GM maize in South Africa has contributed to additional maize supply which may have improved local and regional food security.

Unlike previous studies, we focus on one of the only field-to-plate GM crops, which has direct food security implications. Studies such as this provide important information for consumers, producers, NGOs, and agricultural policy makers about what GM crops can and cannot (e.g., completely alleviate food insecurity) achieve in South Africa. As we face a hotter and drier future, agricultural technologies such as GM may be one of the most salient ways to combat food insecurity while simultaneously reducing the environmental impact of agricultural production. Without metrics and effective communication about what and who the benefits and benefactors are, public confidence and trust surrounding GM technology is likely to remain low. Global food security necessitates an interdisciplinary approach among economic, scientific, and technical disciplines as demonstrated in this study.

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Appendix

Appendix A

Table A1. Area sown to white maize by province in South Africa in thousands of hectares: 1999-2018.

Year	Eastern Cape	Free State	Gauteng	Kwazulu-Natal	Limpopo	Mpumalanga	North West	Northern Cape	Western Cape	South Africa
1999	6.5	805.0	70.0	32.0	41.0	290.0	900.0	4.0	0.0	2148.5
	(0.3)	(37.5)	(3.3)	(1.5)	(1.9)	(13.5)	(41.9)	(0.2)	(0.0)	(100)
2000	4.9	610.0	56.0	25.5	32.0	180.0	650.0	3.5	0.1	1562.0
	(0.3)	(39.1)	(3.6)	(1.6)	(2.0)	(11.5)	(41.6)	(0.2)	(0.0)	(100)
2001	2.5	688.0	60.5	32.5	36.0	232.0	787.0	4.0	0.1	1842.6
	(0.1)	(37.3)	(3.3)	(1.8)	(2.0)	(12.6)	(42.7)	(0.2)	(0.0)	(100)
2002	3.5	805.0	75.5	45.0	51.5	280.0	960.0	11.9	0.1	2232.5
	(0.2)	(36.1)	(3.4)	(2.0)	(2.3)	(12.5)	(43.0)	(0.5)	(0.0)	(100)
2003	5.0	660.0	80.0	35.7	33.0	262.0	760.0	6.2	0.1	1842.0
	(0.3)	(35.8)	(4.3)	(1.9)	(1.8)	(14.2)	(41.3)	(0.3)	(0.0)	(100)
2004	4.0	660.0	60.0	35.0	34.0	224.0	680.0	3.0	0.0	1700.0
	(0.2)	(38.8)	(3.5)	(2.1)	(2.0)	(13.2)	(40.0)	(0.2)	(0.0)	(100)
2005	3.0	345.0	50.0	32.0	12.0	156.0	420.0	15.0	0.0	1033.0
	(0.3)	(33.4)	(4.8)	(3.1)	(1.2)	(15.1)	(40.7)	(1.5)	(0.0)	(100)
2006	3.0	640.0	60.0	38.0	40.0	220.0	620.0	3.8	0.0	1624.8
	(0.2)	(39.4)	(3.7)	(2.3)	(2.5)	(13.5)	(38.2)	(0.2)	(0.0)	(100)
2007	3.0	690.0	80.0	41.0	41.0	268.0	610.0	3.0	1.0	1737.0
	(0.2)	(39.7)	(4.6)	(2.4)	(2.4)	(15.4)	(35.1)	(0.2)	(0.1)	(100)
2008	3.0	565.0	69.0	40.0	33.0	215.0	560.0	2.5	1.5	1489.0
	(0.2)	(37.9)	(4.6)	(2.7)	(2.2)	(14.4)	(37.6)	(0.2)	(0.1)	(100)
2009	3.2	690.0	85.0	46.0	26.0	232.0	635.0	2.0	0.5	1719.7
	(0.2)	(40.1)	(4.9)	(2.7)	(1.5)	(13.5)	(36.9)	(0.1)	(0.0)	(100)
2010	3.0	595.0	74.0	39.0	25.0	180.0	500.0	2.0	0.3	1418.3
	(0.2)	(42.0)	(5.2)	(2.7)	(1.8)	(12.7)	(35.3)	(0.1)	(0.0)	(100)
2011	3.5	710.0	74.0	44.0	32.0	160.0	610.0	2.2	0.5	1636.2
	(0.2)	(43.4)	(4.5)	(2.7)	(2.0)	(9.8)	(37.3)	(0.1)	(0.0)	(100)

Table A1 (Cont.)

Year	Eastern Cape	Free State	Gauteng	Kwazulu-Natal	Limpopo	Mpumalanga	North West	Northern Cape	Western Cape	South Africa
2012	3.7	725.0	74.0	47.0	30.0	170.0	565.0	2.2	0.3	1617.2
	(0.2)	(44.8)	(4.6)	(2.9)	(1.9)	(10.5)	(34.9)	(0.1)	(0.0)	(100)
2013	2.5	730.0	65.0	43.0	30.0	168.0	510.0	2.2	0.5	1551.2
	(0.2)	(47.1)	(4.2)	(2.8)	(1.9)	(10.8)	(32.9)	(0.1)	(0.0)	(100)
2014	2.60	710.00	44.00	40.00	28.50	154.00	465.00	3.50	0.45	1448.1
	(0.2)	(49.0)	(3.0)	(2.8)	(2.0)	(10.6)	(32.1)	(0.2)	(0.0)	(100)
2015	2.00	390.00	49.00	38.00	31.50	160.00	340.00	3.75	0.50	1014.8
	(0.2)	(38.4)	(4.8)	(3.7)	(3.1)	(15.8)	(33.5)	(0.4)	(0.0)	(100)
2016	4.40	805.00	60.00	50.00	40.00	160.00	520.00	3.50	0.20	1643.1
	(0.3)	(49.0)	(3.7)	(3.0)	(2.4)	(9.7)	(31.6)	(0.2)	(0.0)	(100)
2017	3.50	644.00	50.00	45.00	12.00	140.00	370.00	3.60	0.00	1268.1
	(0.3)	(50.8)	(3.9)	(3.5)	(0.9)	(11.0)	(29.2)	(0.3)	(0.0)	(100)
2018	3.80	650.00	48.00	45.00	12.80	145.00	390.00	3.40	0.40	1298.4
	(0.3)	(50.1)	(3.7)	(3.5)	(1.0)	(11.2)	(30.0)	(0.3)	(0.0)	(100)

Parenthesis values represent the percentage of area devoted to growing white maize out of the total area grown (white and yellow maize).

Table A2. GM white maize area harvested in South Africa by year by province in thousands of hectares: 2001-2018.

Year	Eastern Cape	Free State	Gauteng	Kwazulu-Natal	Limpopo	Mpumalanga	North West	Northern Cape	Western Cape	South Africa	% White Maize that is GM
2001	0.0	2.4[a]	0.2	0.1	0.1	0.7	2.6	0.0	0.0	6.2	0.4%[b]
2002	0.1	20.6	1.8	1.0	1.1	7.0	23.6	0.1	0.0	55.3	3.0%[b]
2003	0.3	64.4	6.0	3.6	4.1	22.4	76.8	1.0	0.0	178.6	8.0%[b]
2004	0.4	52.8	6.4	2.9	2.6	21.0	60.8	0.5	0.0	147.4	8.0%[b]
2005	1.2	191.4	17.4	10.2	9.9	65.0	197.2	0.9	0.0	493.0	29.0%[b]
2006	1.3	151.8	22.0	14.1	5.3	68.6	184.8	6.6	0.0	454.5	44.0%[b]
2007	1.9	396.8	37.2	23.6	24.8	136.4	384.4	2.3	0.0	1,007.4	62.0%[b]
2008	1.7	386.4	44.8	23.0	23.0	150.1	341.6	1.7	0.6	972.7	56.0%[b]
2009	2.4	446.4	54.5	31.6	26.1	169.9	442.4	2.0	1.2	1,176.3	79.0%[b]
2010	2.4	517.5	63.8	34.5	19.5	174.0	476.3	1.5	0.4	1,289.8	75.0%[b]
2011	2.2	428.3	53.3	28.1	18.0	129.6	360.0	1.4	0.2	1,021.0	72.0%[b]
2012	2.8	575.1	59.9	35.6	25.9	129.6	494.1	1.8	0.4	1,325.3	81.0%[c]
2013	3.1	609.0	62.2	39.5	25.2	142.8	474.6	1.8	0.3	1,358.4	84.0%[c]
2014	2.1	613.2	54.6	36.1	25.2	141.1	428.4	1.8	0.4	1,303.0	84.0%[c]
2015	2.3	639.0	39.6	36.0	25.7	138.6	418.5	3.2	0.4	1,303.2	90.0%[d]
2016	1.8	351.0	44.1	34.2	28.4	144.0	306.0	3.4	0.5	913.3	90.0%[d]
2017	3.7	684.3	51.0	42.5	34.0	136.0	442.0	3.0	0.2	1,396.6	85.0%[e]
2018	3.0	560.3	43.5	39.2	10.4	121.8	321.9	3.1	0.0	1,103.2	87.0%[f]

[a]Calculated as the product of Table A1 and percentage of white maize that is GM on Table A2. [b](Abidoye and Mabaya, 2014). [c](Esterhuizen, 2015). [d](ISAAA, 2016). [e](ISAAA, 2017). [f](ISAAA, 2018).

Table A3. Total net surplus sensitivity analysis attributed to the adoption of GM maize under various estimates of South African maize supply and demand elasticities: 2001-2018.

Own Price Elasticity	Supply Elasticity		
	0.32[b]	0.36[c]	0.46[d]
-0.200[e]	$388,428,755	$480,371,644	$661,520,375
-0.149[f]	$611,208,538	$694,706,321[a]	$855,492,634
-0.137[g]	$670,826,485	$751,502,900	$905,920,937

[a]As calculated in Table 2. [b]Long-run supply elasticity for maize from IMPACT 2020 (Rosegrant et al., 1995). [c]Long-run supply elasticity for maize in South Africa (Shoko et al., 2016). [d]Long-run supply elasticity for maize in South Africa (Poonyth et al., 2000). [e]Own price elasticity for grain crops in South Africa (Dimaranan et al., 2006). [f]Own price elasticity for white maize in South Africa (van Zyl, 1986). [g]Own price elasticity for white maize in South Africa (Meyer, 2006).

Table A4. Impact categories used in the LCA for conventional and GM maize production (Stepwise LCIA).

Impact category	Units	Description
Acidification	m2 UES	Terrestrial acidification driven by acid gases
Ecotoxicity, aquatic	kg TEG-eq w	Ecosystem toxicity associated with emissions to water
Ecotoxicity, terrestrial	kg TEG-eq s	Ecosystem toxicity associated with emissions to land
Eutrophication, aquatic	kg NO3-eq	Freshwater and marine eutrophication driven by nutrient runoff
Eutrophication, terrestrial	m2 UES	Excess nutrients on land
Global warming, fossil	kg CO2-eq	Accumulated greenhouse gas emissions (IPCC 2006 characterization factors)
Global warming, non-fossil	kg CO2-eq	Accumulated greenhouse gas emissions (IPCC 2006 characterization factors)
Human toxicity, carcinogens	kg C2H3Cl-eq	Human toxicity from carcinogens (e.g., pesticides and chemicals)
Human toxicity, non-carc.	kg C2H3Cl-eq	Human toxicity from non-carcinogens (e.g., heavy metals)
Nature occupation	m2-years agr	Agricultural land occupation; a proxy for effects to biodiversity
Non-renewable energy	MJ primary	Nonrenewable energy consumption
Ozone layer depletion	kg CFC-11-eq	Accumulated ozone-depleting compounds emissions
Photochemical ozone, vegetat.	m2*ppm*hours	Damage to vegetation estimated from ozone emissions
Respiratory inorganics	kg PM2.5-eq	Primary and secondary particulate emissions
Respiratory organics	pers*ppm*h	Human health effects from volatile organic compounds

UES = Unprotected Ecosystems

Table A5. Mean yield and yield variance (tons per hectare) for dryland conventional and Bt maize in the Free State and North West provinces from the National Maize Cultivar trials: 2000-2017.

	Location	**Conventional Mean Yield**	**Conventional Yield Variance**	***Bt* Mean Yield**	***Bt* Yield Variance**
Free State	Bethlehem	6.07	3.23	6.54	3.80
	Blesbokfontein	3.14	0.57	3.58	0.94
	Bothaville	5.19	2.67	5.63	3.04
	Bultfontein	4.21	0.74	4.65	1.11
	Clocolan	3.09	0.38	3.52	0.75
	Frankfort	3.17	1.83	3.60	2.20
	Kroonstad	5.95	0.59	6.39	0.96
	Leribe	3.08	0.28	3.52	0.65
	Marquard	4.92	1.02	5.35	1.39
	Maseru	3.87	1.55	4.31	1.92
	Memel	6.67	0.71	7.11	1.08
	Nampo	5.00	0.85	5.44	1.22
	Reitz	5.97	0.79	6.40	1.16
	Tweeling	6.36	1.23	6.79	1.60
	Viljoenskroon	6.08	4.01	6.51	4.38
	Vrede	4.70	0.60	5.14	0.97
	Wesselsbron	5.39	2.86	5.82	3.23
	Windfield	7.78	1.86	8.22	2.23
	Free State	**5.04**	**1.43**	**5.47**	**1.81**
North West	Athole	6.85	4.79	7.11	4.91
	Coligny	4.66	1.04	4.92	1.16
	Delareyville	3.69	1.49	3.95	1.61
	Gerdau	4.76	2.47	5.03	2.60
	Glaudina	3.23	1.45	3.49	1.58
	Grootpan	6.49	5.33	6.75	5.45
	Hartbeesfontein	3.45	1.04	3.71	1.16
	Kameel	2.61	0.19	2.88	0.31
	Koster	3.58	1.08	3.84	1.20
	Leeudoringstad	5.36	1.78	5.63	1.90
	Lichtenburg	5.39	6.54	5.65	6.66
	Ottosdal	4.88	1.38	5.14	1.50
	Potchefstroom	3.50	0.90	3.76	1.02
	Schweizerreineke	4.02	1.24	4.28	1.36
	Setlagole	2.77	1.14	3.03	1.26
	Tweebuffels	3.72	1.49	3.98	1.61
	Ventersdorp	5.06	0.80	5.32	0.93
	Wolmaranstad	5.34	1.63	5.60	1.75
	North West	**4.41**	**1.99**	**4.67**	**2.11**

As estimated from (Shew et al., 2021).

Table A6. Variable costs associated with one hectare of conventional and Bt maize production in Free State and North West provinces: 2019-2020.

	Variable Costs (R/ha)	Conventional Maize	*Bt* Maize
Free State	Seed	1,329.90	1,774.68
	Fertilizer	549.90	549.90
	Lime	530.00	530.00
	Fuel	897.08	875.95
	Reparation	896.74	871.44
	Herbicide	876.24	798.71
	Pest control	908.68	557.95
	Grain hedging	450.76	450.76
	Interest on production	498.41	498.41
North West	Seed	886.60	1,183.12
	Fertilizer	501.65	501.65
	Lime	166.50	166.50
	Fuel	983.18	994.21
	Reparation	668.74	662.10
	Herbicide	696.28	837.07
	Pest control	473.82	305.40
	Grain hedging	339.94	352.58
	Interest on production	246.80	255.97

Production budgets obtained from (Grain SA, 2020).