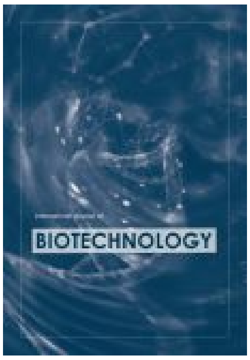


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# The yield and price effects of growing genetically modified corn: evidence from the US corn belt

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# The yield and price effects of growing genetically modified corn: evidence from the US corn belt

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**Abstract:** This study investigates the impact of GM corn adoption on yield and price for the US corn belt from 2014 to 2020. In addition, the study investigates the interaction effects of GM corn and yield on price and analyses the impact of both temporary and permanent shocks of growing GM corn on yield and price. The results indicated that the GM corn adoption had a positive impact on yield and a negative and statistically significant impact on price. Also, the interaction effect of GM corn and yield impacted positively on the price, suggesting that the adoption of GM corn should increase the negative effect of yield on price. The temporary shock of growing GM corn positively impacted yield and price while the permanent shock negatively affected yield and price. The study suggested that the adoption of GM corn has implications for improving producer and consumer welfare and global food security.

**Keywords:** genetically modified corn; price; yield; USA; corn belt.

**JEL codes:** Q16, Q18.

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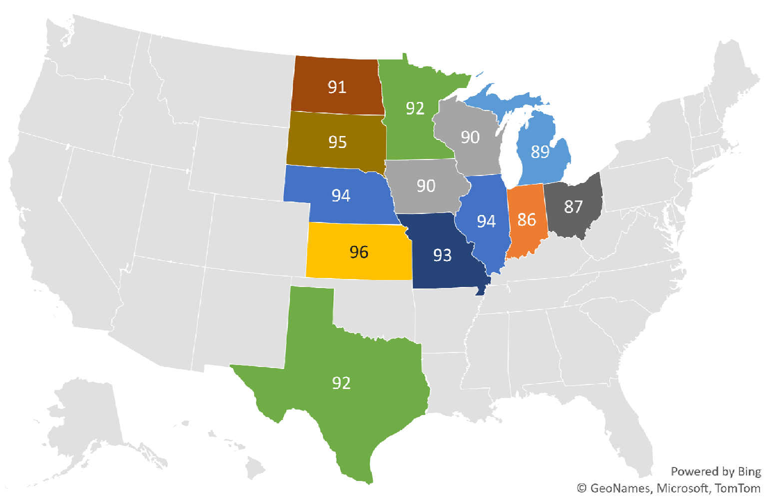
## 1 Introduction

Globally, over 820 million people suffer from hunger, and many more suffer from specific nutritional deficiencies, often related to insufficient intake of micronutrients (United Nations News, 2019). As a result, in 2015, the United Nations General Assembly launched the Sustainable Development Goals (SDGs) to improve people's lives by 2030 (Food Aid Foundation, 2020). SDG 2 aims to achieve zero hunger, food security, improve nutrition, and promote sustainable agriculture (United Nations, 2012). The adoption of GM crops played an important role in achieving this SDG goal (Qaim, 2020). The GM seed varieties were commercially introduced in 1996 (USDA, 2020). Since its adoption, GM crop production has experienced over a 100-fold increase (Brookes and Barfoot, 2013; Mathur et al., 2017; ISAAA, 2020). Also, as of 2019, farmers from 29 countries have grown 190.4 million hectares of GM crops (Turnbull et al., 2021; ISAAA, 2020).

The USA remained the world leader in developing and commercialising GM crops. Countries like Brazil, Argentina, and Canada also grow large quantities of GM crops (Turnbull et al., 2021; Genetic Literacy Project, 2018). In 2015, the USA grew 33 million hectares of corn (82 million acres); in 2019, the GM area in the USA stands at 71.5 million hectares, accounting for nearly 38% of the world market share in agricultural GM technology (Report Linker, 2020; Turnbull et al., 2021). Currently, the USA adoption rate of GM crops is around 95% (ISAAA, 2020). For instance, corn accounts for 33.17 million ha of GM crops planted, soybeans (30.43 million ha), cotton (5.31 million ha), canola (800,000 ha), sugar beets (454,100 ha), alfalfa (1.28 million ha), and potatoes (1,780 ha) (ISAAA, 2020).

While corn is grown in most states in the USA, it is predominantly grown in the corn belt (see Figure 1). Available data shows that between 2014 to 2020, Kansas grew the largest GM corn (96%), followed by South Dakota (95%), Nebraska (94%), Illinois (94%), Missouri (93%), Minnesota (92%), Texas (92%), North Dakota (91%), Iowa (90%), Wisconsin (90%), Michigan (89%), Ohio (87%), and Indiana (86%) (see Figure 1).

**Figure 1** Percent of GM corn (all varieties) grown in the US corn belt (2014–2020) (see online version for colours)




*Source:* Author's construct using data from the USDA (2021)

The rapid adoption of GM crops has raised considerable debate in the USA and overseas (Klümper and Qaim, 2014). Much of this debate has been driven by concerns over the potential adverse effects of GM corn, albeit some benefits have also been argued (Fosu, 2019; Anderson and Yao, 2003). Specifically, many of the issues around GM crop adoption have focused on consumer safety and health, implications for the environment, consumers' right to choose, and several economic issues (Maghari and Ardekani, 2011).

In their study, Pellegrino et al. (2018) found that GM corn varieties had lower percentages of mycotoxins (–28.8%), fumonisins (–30.6%), and thricotecons (–36.5%), all of which can lead to economic losses and also cause harm to human and animal health (Genetic Literacy Project, 2018; Pellegrino et al., 2018). Currently, there are two main types of GM corn seeds available to farmers, and these are herbicide-tolerant (HT) and insect-resistant (Bt) corn (Genetic Literacy Project, 2018). The HT corn allows farmers to control weeds better, whiles the Bt corn also fends off pests such as the corn borer (Genetic Literacy Project, 2018). In addition, HT corn incorporates genes from a soil bacterium into corn plants. The insect-resistant corn also includes genes from another soil bacterium, [i.e., *Bacillus thuringiensis* (Bt)] which is commonly sprayed on the farm as an approved natural pesticide (Genetic Literacy Project, 2018).

Several studies have analysed the impact of GM crops on various outcomes. Fernandez-Cornejo and Li (2005) employed a nationwide survey data in 2001 and investigated the effect of Bt corn on pesticide use and yield in the USA. Brookes et al. (2010) and Brookes and Barfoot (2013) examined the global income and production effects of genetically modified (GM) crops. Similarly, Brookes (2008) analysed the economic and environmental impact of Bt maize on yield and farm income in the European Union. Several other studies by have also examined the environmental, agronomic, and economic impact of GE technology for both developed and developing countries (Brookes and Barfoot, 2018; Gewin, 2003; Klümper and Qaim, 2014; Ayele, 2008; Smale et al., 2008). To my knowledge, an empirical study that examined the effects of GM corn adoption on yield and price focusing on the US corn belt has not been done, even though, the US corn belt is arguably the largest corn-growing area in the world. Thus, the objectives of this study are three-fold.

The first objective of this paper is to examine the impact of GM corn varieties on yield and price in the US corn belt. The second objective is to explore the interaction effect of GM corn adoption and yield on price. Lastly, it is assumed that growing GM corn is a favourable supply shock, so I decomposed this shock into temporary and permanent shocks and analysed their impact on yield and price. The paper contributes to the empirical literature because it is the first to examine the yield and price and the GM corn adoption nexus focusing specifically on the US corn belt. Also, it is the first empirical paper to investigate the impact of temporary and permanent shocks associated with growing GM corn on yield and price in the US corn belt. In addition, the outcome of this study not only contributes to the empirical literature on biotechnology but also forms the basis for making agricultural and global food policy decisions. The rest of the paper is organised as follows; Section 2 reviews the literature, Section 3 presents the methodology, and Section 4 presents results and discussion. The last section presents the conclusions.

## 2 Literature review

The relevant body of literature concerns the impacts of new agricultural technologies, (i.e., GM crops) on welfare change and how economic surplus from adopting the technology is distributed between producers and consumers (Wu, 2004; Marra et al., 2002). For instance, in the USA, Falck-Zepeda et al. (2000) adopted the economic surplus approach presented by Marra et al. (2002) and found that the adoption of GM cotton leads to increases in global surplus, with much of the surplus going to US farmers that adopted the new technology. Several studies also emphasise the net economic benefits of Bt corn on yield to farmers that adopt the technology. Marra et al. (2002) estimated profit from yield improvement due to GM corn adoption and reported that Bt corn provides a significant yield increase to farmers in the US corn belt. Brookes et al. (2010) examined the production effects of GM crop adoption. Their study found that world prices of corn, soybeans, and canola would probably be 5.8%, 9.6%, and 3.8%, respectively, higher, on average, than if the technology were no longer available to farmers. Also, in the Philippines, Yorobe and Quicoy (2006) sought to determine the economic impact of the Bt corn variety among some selected corn farmers. They found that yield and income of Bt corn farmers were significantly higher than those of the non-Bt corn farmers. They also found that the expenditure on insecticide was considerably lower among Bt corn farmers. In a similar study, Brookes and Barfoot (2018) examined the environmental impact of GM crops. They found that adopting Bt and HT technology has reduced pesticide spraying costs by 671.4 million kg (8.2%), thus, reducing the environmental impact of herbicide and insecticide use on these crops. Colin et al. (2017) sought to determine whether yield benefits are associated with growing genetically engineered corn. Their study found that GM crops provide advantages over traditional varieties, such as reduced chemical load on the environment and reduced soil tillage.

Additionally, GM corn may provide a yield advantage. In their paper, Fernandez-Cornejo and Li (2005) developed an econometric model to examine the impact of Bt corn adoption on insecticide use and yields using a nationwide farm survey in 2001. They found a moderate insecticide reduction and a small yield increase associated with Bt corn compared to conventional corn varieties in 2001. Also, in their study, ‘the Bt corn in Spain – the performance of the EU’s first GM crop,’ Gomez-Barbero et al. (2008) found that conventional corn farmers, on average, applied 0.86 treatments/year between 2002 to 2004 compared with 0.32 treatments/year for Bt corn farmers. They also found a significant price premium of Bt corn seeds relative to conventional seeds in Zaragoza, Albacete, and Lleida. Using a meta-analysis, Klümper and Qaim (2014) analyse the agronomic and economic impacts of GM crops. They found that GM technology adoption has decreased chemical pesticide use by 37%, increased crop yield by 22%, and increased farmers’ profits by 68%. Using Vietnamese farm survey data conducted in 2018–2019, Brookes and Dinh (2021) assessed the farm-level economic and environmental impacts of GM corn. They showed that yield increased by 30.4% and decreased the cost of production by between US$26.47 per ha and US$31.30 per ha. In addition, they showed that for every US$1 spent on GM seed relative to convention corn, farmers gain an additional US$6.84 and US$12.55 in income. Furthermore, using data from 2001 to 2008, Ala-Kokko et al. (2021) found that the welfare benefits attributable to GM white maize cultivation were US$694.7 million in South Africa. The authors also found that GM white maize adopters received more profits than non-GM farmers in Free State and Northwest. More so, using farm survey data from Argentina, Qaim and De Janvry (2005) found that Bt cotton decreases pesticide use by 50% while significantly increasing yield. Vitale et al. (2010) also showed that Bt cotton farmers earn US$39.00 per ha and US$61.88 per ha increase in profit and income, respectively, more than non-Bt cotton farmers in Burkina Faso.

## 3 Methodology

### *3.1 The analytical model and data description*

The broader objective of this paper is to examine the impact of GM corn adoption on yield and price in the US corn belt. The basic econometric models of the relationship between GM corn and yield; GM corn and price are as follows:

$$\begin{aligned}\ln Yield_{st} &= \alpha_0 + \alpha_1 GMcorn_{ALL,st} + \alpha_2 GMcorn_{Bt,st} + \alpha_3 GM_{Ht,st} \\ &\quad + \alpha_4 \ln Yield_{st-1} + \mu_s + \lambda_t + \varepsilon_{it}\end{aligned} \tag{1}$$

$$\begin{aligned}\ln Price_{st} &= \beta_0 + \beta_1 GMcorn_{ALL,st} + \beta_2 GMcorn_{Bt,st} \\ &\quad + \beta_3 GMcorn_{Ht,st} + \beta_4 \ln Yield_{st} + \beta_5 GMcorn_{AL,st} \ln Yield_{st} \\ &\quad + \beta_6 \ln Price_{st-1} + \mu_s + \lambda_t + \varepsilon_{it}\end{aligned} \tag{2}$$

where $\mu_s$ and $\lambda_t$ denote the unobservable state and year fixed effects, respectively. $Yield_{st}$ is yield measured in bushel per acre. $Price_{st}$ is price measured in \$ per bushel. $GMcorn_{ALL,st}$ is GM corn (all varieties), $GMcorn_{Bt,st}$ is insect-resistant (Bt) corn, $GMcorn_{Ht,st}$ is HT corn. All types of GM corn are measured as a percentage of acres planted. $GMcorn_{AL,st}\ln Yield_{st}$ is the interaction term between GM corn and yield. The coefficient of $\alpha_1$, $\alpha_2$ and $\alpha_3$ are expected to be positive. As GM corn (all varieties), Bt corn, and Ht corn increase, everything else equal should increase yield. Thus, the adoption of GM corn is expected to increase corn production and hence increase yield. I anticipate a positive $\alpha_4$ coefficient as increases in lagged yield ($Yield_{s-1}$) should increase the current yield because the knowledge farmers gain from previous farming activities can translate into current farming. The coefficients $\beta_1$, $\beta_2$ and $\beta_3$ are expected to be negative as an increase in GM corn (all varieties), Bt, and Ht corn, ceteris paribus, should decrease price. The intuition is that adopting GM corn increases yields, thereby leading to a lower price. Also, a higher yield, ceteris paribus, is expected to decrease the price. Therefore, the coefficient of yield ($\beta_4$) is expected to impact price negatively. The interaction term ($\beta_5$) is expected to be positive as the adoption of GM corn should increase the negative effect of yield on price. The coefficient of lagged price ($\beta_6$) can have either a positive or negative impact on the current price as farmers form rational expectations. Thus, a lower (higher) price in the previous year can positively (negatively) affect today's price.

The goal of this paper was to include all the US states in the analysis. However, it was difficult getting data on GM corn (i.e., percent of acres planted) for all the US states, so the study is limited to only the US corn belt. Specifically, the data include a panel of 13 US states (Illinois, Indiana, Iowa, Kansas, Michigan, Minnesota, Missouri, Nebraska, Ohio, North Dakota, South Dakota, Texas, and Wisconsin) from 2014 to 2020. Data on all variables and the US states were obtained from USDA, National Agricultural Statistics Service (NASS) website (USDA/NASS QuickStats Ad-hoc Query Tool). It is assumed that growing GM corn is a favourable supply shock because growing GM corn should increase yield and corn supply and decrease price. So, I decomposed this shock into temporary and permanent shocks using the Hodrick-Prescott (HP) filter and examined their impact on yield and price. The temporary shock is the cycle component, while the permanent shock is the trend component of GM corn. I then analysed how temporary and permanent shocks from growing GM corn affect price and yield. The empirical models with the effect of temporary shocks and permanent shocks on yield and price are specified below:

$$\ln Yield_{st} = \vartheta_0 + \partial_1 GMcorn_{ts,st} + \partial_2 GMcorn_{ps,st} + \partial_3 \ln Yield_{st-1} + \mu_s + \lambda_t + \varepsilon_{st} \tag{3}$$

$$\begin{aligned} \ln Price_{st} = {} & \delta_0 + \delta_1 GMcorn_{ts,st} + \delta_2 GMcorn_{ps,st} + \delta_3 \ln Yield_{st} \\ & + \delta_4 GMcorn_{ts,st} \ln Yield_{st} \\ & + \delta_5 GMcorn_{ps,st} \ln Yield_{st} + \delta_6 \ln Price_{st-1} + \mu_s + \lambda_t + \varepsilon_{st} \end{aligned} \tag{4}$$

$GMcorn_{ts,st}$ and $GMcorn_{ps,st}$ are the temporary and permanent shocks from growing GM corn, respectively. One potential challenge to the econometric strategy in this study standard omitted variable bias. This concern is the central motivation for pursuing first and foremost panel analyses that allow us to control for persistent state characteristics connected to yield and price over time.

## 4 Results and discussion

This section of the paper presents the empirical results. Table 1 reports the summary statistics. The summary statistics describe and examine the patterns in the dataset. From Table 1, it can be observed that the average acres of GM corn planted in the US corn belt are around 92.15%, with the minimum and maximum area planted equal to 82% and 98%, respectively. The average acres of BT corn and HT corn in the US corn belt is 3.36% and 11.42%, respectively. Out of the 92.15% average acres of total GM corn planted, BT and HT corn only constitute 14.78%, while the remaining 77.37% represent GM corn with both traits (stacked gene). These statistics on GM corn varieties are also presented in Figure 2. The average corn price in the US corn belt is around \$3.64 per bushel, with the minimum and maximum prices equalling \$3.01 per bushel and \$4.5 per bushel. The average yield is about 165.08 bushels per acre.

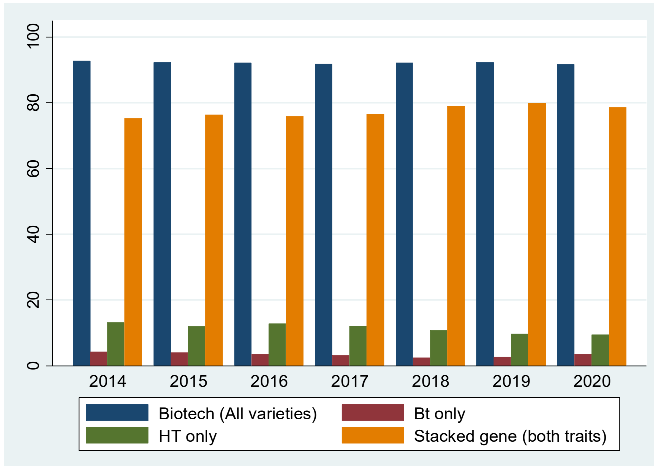
**Table 1** Summary statistics

| *Variable* | *Observation* | *Mean* | *Std. dev* | *Min* | *Max* |
|---|---|---|---|---|---|
| $GMcorn_{ALL,st}$ | 84 | 92.155 | 3.4831 | 82 | 98 |
| $GMcorn_{Bt,st}$ | 84 | 3.3571 | 1.867 | 1 | 12 |
| $GMcorn_{Ht,st}$ | 84 | 11.417 | 4.475 | 4 | 25 |
| $GMcorn_{ts,st}$ | 84 | 1.18E–08 | 1.183 | –3.853 | 3.142 |
| $GMcorn_{ps,st}$ | 84 | 92.155 | 3.276 | 84.683 | 97.783 |
| $Price_s$ | 84 | 3.644 | 0.373 | 3.01 | 4.5 |
| $Yield_s$ | 84 | 165.833 | 23.222 | 108 | 210 |

*Source:* Author's construct

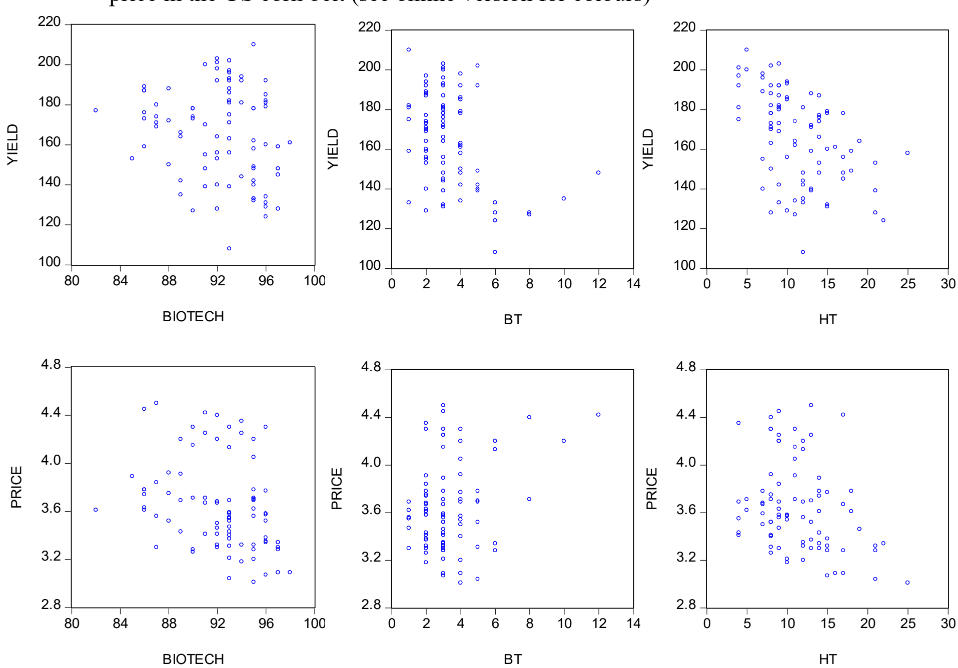
Figure 3 presents the correlation analysis between GM corn (all varieties), insect-resistant (Bt), HT, and yield and price for the US corn belt. The rationale for presenting the correlation analysis is to determine the associations between these variables. Figure 3 shows a negative linear correlation between GM corn (all varieties) and yield and price. Bt corn had a positive association with price but negatively correlated with yield. Also, HT corn had a negative association with yield and price.

**Figure 2** Average GM corn percent of acres planted in the US corn belt by type (see online version for colours)




*Source:* Author's construct using data from USDA (2021)

**Figure 3** Correlation between GM corn (all varieties), insect-resistant (Bt), HT, and yield and price in the US corn belt (see online version for colours)




*Source:* Author's construct using data from USDA

**Table 2** The effect of GM corn on Yield and Price

| *Estimation method* | *RE* (1) | *FE* (2) | *RE* (3) | *FE* (4) | *RE* (5) | *FE* (6) |
|---|---|---|---|---|---|---|
| $GMcorn_{ALL,st}$ | –0.0005 | 0.0001 | –0.0078** | –0.0041*** | –0.0578 | –0.1201** |
| | (0.0032) | (0.0032) | (0.0033) | (0.0013) | (0.1585) | (0.0545) |
| $GMcorn_{Bt,st}$ | –0.0188** | –0.0220*** | –0.0059 | –0.0005 | | |
| | (0.0073) | (0.0073) | (0.0077) | (0.0031) | | |
| $GMcorn_{Ht,st}$ | –0.0019 | –0.0028 | –0.0099*** | –0.0033*** | | |
| | (0.0030) | (0.0030) | (0.0029) | (0.0012) | | |
| $lnYield_{st}$ | | –0.1654* | –0.0898** | –1.0027 | –2.1673** | |
| | | | (0.0864) | (0.0342) | (2.8848) | (0.9934) |
| $lnYield_{st-1}$ | 0.6481*** | 0.65301*** | | | | |
| | (0.0955) | (0.0950) | | | | |
| $lnPrice_{st-1}$ | | | 0.2812 | 0.595069*** | 0.5647*** | 0.6821*** |
| | | | (0.1809) | (0.0838) | (0.1671) | (0.0655) |
| $GMcorn_{AL,st}lnYield_{st}$ | | | | | 0.0103 | 0.0229*** |
| | | | | | (0.0309) | (0.0106) |
| Constant | 1.9208*** | 1.8633*** | 2.5931*** | 1.4135*** | 6.1915 | 11.8095** |
| | (0.6458) | (0.6399) | (0.7250) | (0.3072) | (14.8413) | (5.1011) |
| R-squared | 0.6110 | 0.6683 | 0.3943 | 0.9208 | 0.2802 | 0.9164 |
| F-statistic | 26.3102*** | 13.8805*** | 8.5940*** | 70.9472*** | 6.5214*** | 75.5422*** |
| DW-statistic | 2.2698 | 2.2358 | 1.7871 | 2.4971 | 1.6154 | 2.2425 |
| State and year fixed effects | Yes | Yes | Yes | Yes | Yes | Yes |
| Observations | 72 | 72 | 72 | 72 | 72 | 72 |
| Hausman test: ($\chi$) | 78.7892*** | | 8.5581 | | 3.6794* | |
| Prob. | 0.0000 | | 0.1280 | | 0.0511 | |

Notes: Dependent variables are $Yield_s$ and $Price_s$. $Yield_s$ are measured in bushel per acre, while $Price_s$ are measured in $ per bushel.
Standard errors in parentheses ***$p < 0.01$, **$p < 0.05$, *$p < 0.1$.

**Table 3** The impact of temporary and permanent shock from GM Corn on yield and price

| *Estimation method* | *RE* (1) | *FE* (2) | *RE* (3) | *FE* (4) | *RE* (5) | *FE* (6) |
|---|---|---|---|---|---|---|
| $GMcorn_{ts,st}$ | 0.0044 | 0.0068 | 0.0005 | 0.0010 | –0.4629 | –0.0095 |
| | (0.0064) | (0.0094) | (0.0091) | (0.0032) | (0.3263) | (0.1133) |
| $GMcorn_{ps,st}$ | –0.0011 | –0.0008 | –0.0064 | –0.0040*** | 0.0713 | –0.1882*** |
| | (0.0025) | (0.0037) | (0.0039) | (0.0014) | (0.1933) | (0.0676) |
| $lnYield_{st}$ | | | –0.0523 | –0.0414 | 1.3636 | –3.3936*** |
| | | | (0.0792) | (0.0281) | (3.5146) | (1.2302) |
| $lnYield_{st-1}$ | 0.7536*** | 0.7801*** | | | | |
| | (0.0549) | (0.7801) | | | | |
| $lnPrice_{st}$ | | | 0.5639*** | 0.6887*** | 0.5518*** | 0.6661*** |
| | | | (0.1595) | (0.0668) | (0.1650) | (0.0649) |
| $GMcorn_{ts,st}lnYield_{st}$ | | | | | 0.0916 | 0.0020 |
| | | | | | (0.0645) | (0.0224) |
| $GMcorn_{ps,st}lnYield_{st}$ | | | | | –0.0153 | 0.0359*** |
| | | | | | (0.0377) | (0.0132) |
| Constant | 1.360859*** | 1.1997*** | 1.431004** | 0.9979*** | –5.7506 | 18.19424*** |
| | (0.4037) | (1.1998) | (0.7135) | (0.2661) | (18.0714) | (6.3092) |
| R-squared | 0.5721 | 0.6211 | 0.2843 | 0.9129 | 0.3079 | 0.9228 |
| F-statistic | 30.3086*** | 12.9062*** | 6.6552*** | 72.2470*** | 4.8188*** | 65.2259*** |
| DW-statistic | 2.4294 | 2.4591 | 1.6510 | 2.2790 | 1.6054 | 2.2986 |
| State and year fixed effects | YES | YES | YES | YES | YES | YES |
| Observations | 72 | 72 | 72 | 72 | 72 | 72 |
| *Hausman test* ($\chi$) | 92.2486*** | | 6.4105*** | | 6.653226**** | |
| Prob. | 0.0000 | | 0.1705 | | 0.3541 | |

Notes: Dependent variables are $Yield_s$ and *Prices*. $Yield_s$ are measured in bushel per acre, while $Price_s$ are measured in $ per bushel.
Standard errors in parentheses ***$p < 0.01$, **$p < 0.05$, *$p < 0.1$.

The random effects (RE) and fixed effects (FE) estimations are presented in Table 2 to analyse the impact of various GM corn adoption on yield and price. The yield model is given by models 1 and 2, the price model without the interaction term is presented by models 3 and 4, while the price model with the interaction term is given in models 5 and 6. The Hausman test indicates that the FE model is the preferred model for the yield model and the price model with the interaction term, while the RE is the preferred model for the price model without the interaction term. The DW statistic test close to 2 indicates that the empirical models are free from serial correlation. Also, the model passes the goodness of fit test as indicated by the significance F-statistic. The R-squared shows that the explanatory variables account for about 66.83%, 39.43%, and 91.64% of the total variations in the yield and the price models. In model 2, GM corn (all varieties) had a positive effect on yield. Unexpectedly, insect-resistant (Bt) and HT corn had a negative and statistically insignificant impact on yield. This negative effect may be attributed to Bt corn suffering from yield drag – a decrease in yield due to the plant producing the Bt protein in its tissues (Hurley et al., 2004; Elmore et al., 2001). In addition, the first generation of the European corn borers (ECB) is damaging corn in the Central Midwest of the USA (Edwards et al., 1993).[1]

In model 4, it was observed that GM corn (all varieties) had a negative and statistically significant effect on price. Insect resistant (Bt) and HT corn also had a negative impact on yield; however, their effect was statistically insignificant. These results suggest that the adoption of GM corn has a yield advantage and price premium because it increases both consumers' and producers' welfare. The intuition is that GM corn mitigates yield losses from insects and weeds and thus, leading to increase yield and lower price. Consumers gain an increase in their real income due to lower prices from GM corn adoption. In addition, since GM corn increases yield, the result indicates that GM corn increases producer surplus. The result is consistent with Klümper and Qaim (2014), who found that GM crops adoption decreased chemical pesticide use by 37%, increased crop yields by 22%, and increased farmers' profits by 68%. The result is also consistent with the work of Fosu (2019), Fernandez-Cornejo and Li (2005), Yorobe and Quicoy (2006) and Ferrell and Witt (2002). The lagged yield had a positive and statistically significant effect on yield. Also, the coefficient of lagged price had a positive and statistically significant impact on the current price. In model 6, I examined the interaction effect of yield and GM corn on price. The interaction of yield and GM corn had a positive and statistically significant impact on price. The positive interaction term suggests that the adoption of GM corn should increase the negative effect of yield on price.

It is assumed that growing GM corn is a favourable supply shock because growing GM corn should increase yield and corn supply and decrease price. So, the study decomposed this shock into temporary and permanent shocks and examined their impact on yield and price. In addition, the study examined the interaction effect of these shocks from growing GM corn and yield on price. The empirical results of this analysis from RE and FE estimations are presented in Table 3. Table 4 has six models. Models 1 and 2 estimate the effect of temporary and permanent shocks associated with growing GM corn on yield, while models 3 and 4 estimate the impact on price. For models 5 and 6, I analysed the interaction effect of GM corn (temporary and permanent shocks) and yield on price. The Hausman test shows that the FE model is the best model for the yield equation and the price models. The DW statistic test close to 2 indicates that overall, the empirical models are free from serial correlation. Also, the model passes the goodness of fit test as indicated by the significance F-statistic. The R-squared suggests that overall, the explanatory variables account for 62.11%, 91.29%, and 92.28% of the total variations in the yield and price models, respectively. From model 2, it can be observed that the temporary shock of growing GM corn had a positive impact on yield; however, unexpectedly, the permanent shock had a negative impact on yield. The possible explanation for this relationship may be linked to diminishing marginal return as permanent use of the GM technology may decrease yield. For example, using United Nations data, Hakim (2016) showed that farmers in the USA and Canada had gained no discernible advantage in yields compared to their counterparts in Western Europe like France and Germany. Hakim (2016) also indicated that in France, where GMOs are not permitted, pesticide use has significantly declined; meanwhile, in the USA, the major grower of GM crops, farmers are using more weed killers. As farmers incur additional costs to fight weeds and seed costs, their overall production cost increases, decreasing their productivity because they will not be competitive when they face high production costs.

Also, lagged yield had a positive and statistically significant effect on current yield. In model 4, it was observed that temporary shock associated with growing GM corn positively impacted the price; however, the permanent shock had a negative and statistically significant effect on price. As expected, the results revealed a negative and statistically insignificant effect of yield on price. Lagged price had a positive and statistically significant effect on the current price. The coefficients of the interaction terms are positive, suggesting that both the temporary and permanent shocks from growing GM corn should increase the negative effect of yield on price. These results also reinforce the negative effect of GM corn adoption on price.

## 5 Conclusions and policy recommendations

The broad objective of the paper was to examine the impact of GM corn varieties on yield and price for 13 US states, (i.e., the corn belt) from 2014 to 2020. In addition, the interaction effects of GM corn and yield on price were analysed. Lastly, the impact of the temporary and permanent shocks of growing GM corn on yield and price were analysed. The results indicated that GM corn (all varieties) had a positive effect on yield and a negative and statistically significant impact on price. Furthermore, Bt and HT corn had a negative impact on yield and price, although these effects were unexpected. In addition, the interaction effects of GM corn and yield on price were positive thus, suggesting that the adoption of GM corn should increase the negative impact of yield on price. The temporary shock of growing GM corn positively impacted yield and price, while the permanent shock negatively affected yield and price. These results suggest that the adoption of GM corn has a yield advantage and price premium. Given these results, this study has larger implications for improving quality of life and food security. The quality of life is viewed in four different ways. First, consumers experience an increase in real income due to lower price from GM corn. Second, the yield increase associated with GM corn increases producers' profits. Third, GM increase corn supply available for industrial consumption. More so, GM corn enables increased corn export to developing countries that are food insecure or governments wanting to improve their renewable energy sector. The main limitation of this study is getting enough data on GM corn percent of acres planted for all the US states. As a result, this study is limited to only a few US states and years. As enough data becomes available, future research can include other crops such as soybeans and cotton and incorporate other control variables to analyse the effects of GM crop adoption on yield and price for US states and other developed and developing countries. In addition, future research can perform a natural experiment to examine how the adoption of GM crops has impacted yield and price for US states that have adopted the GM technology and compare the outcome with US states that have not adopted the technology. The same natural experiment can also be done at the country level, like comparing the yield in the USA with France or Germany before and after the GM adoption.

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## Notes

1 The ECB tunnelling weakens the stalk, increasing the potential for lodging in the fall before harvest. Furthermore, tunnelling creates avenues for the introduction of plant pathogens, which may produce stalk rots that have further negative yield effects (Hyde et al., 1999).