The Effects of GM Technology on Maize Yield

Jean-Paul Chavas,* Guanming Shi, and Joseph Lauer

ABSTRACT

In the United States, maize (*Zea mays* L.) farmers have adopted genetic-modification technology rapidly since its first commercialization in 1996. By 2012, 88% of U.S. maize is planted with genetically modified (GM) hybrids. Our objective in the paper is to present an empirical analysis of the determinants of U.S. maize yield using experimental maize production data, with a focus on the interaction effects of GM technology, management, and risk. Genetic-modification technology had a stronger impact on the lower end of maize yield distribution within a trial thereby reducing exposure to downside risk. A strong interaction exists between GM technology and crop rotations: GM reduces the adverse effects of maize–maize rotation on yield. As such, GM technology is found to be a substitute for crop rotation. Genetic-modification technology increases the yield gains associated with higher planting density. This indicates that GM technology offers good prospects for future improvements in maize productivity.

J.P. Chavas, and G. Shi, Dep. of Agricultural and Applied Economics, Univ. of Wisconsin, Madison, WI 53706; and J. Lauer, Dep. of Agronomy, Univ. of Wisconsin, Madison, WI 53706. This research was supported by a USDA/AFRI grant and by a Hatch grant, College of Agricultural and Life Science, University of Wisconsin, Madison. Received 28 Nov. 2013. *Corresponding author (jchavas@wisc.edu).

Abbreviations: GM, genetically modified; pmaize, planted after maize.

Maize productivity has increased sharply during the last few decades. In the United States, average maize yields have gone from 1.26 tons per hectare in 1930 to 7.41 tons per hectare in 1985 and to 10.29 tons per hectare in 2009 (USDA–NASS, 2012). These large productivity gains have come from both plant breeding and improved management practices, each accounting for about 50% of the increase (Duvick, 2005).

Two examples of management changes during the last 20 yr have been the adoption by farmers of more acres planted to continuous maize and an increase in plant density in production fields (Duvick, 2005). Favorable maize prices and increased demand for biofuel have promoted a trend toward maize monoculture in the U.S. Corn Belt. Increasing plant densities have contributed to higher maize yields in recent years (Duvick, 2005; Stanger and Lauer, 2006).

Over the years, breeders have selected varieties for high yield as well as greater stress tolerance. As a result, while newer hybrids give higher average yield, they also often perform better than their predecessors under unfavorable growing conditions. This trend applies to conventional hybrids as well as GM hybrids (Edgerton et al., 2012; Shi et al., 2013; Xu et al., 2013).

In the United States, maize farmers have adopted GM technology rapidly since its first commercialization in 1996. By 2013, 90%

Published in Crop Sci. 54:1331–1335 (2014).
doi: 10.2135/cropsci2013.10.0709

of U.S. maize was planted with GM hybrids (USDA–ERS, 2013). It raises the following questions. How does GM technology affect maize yield? Does it contribute to reducing the adverse effects of unfavorable agroclimatic conditions? Does GM technology interact with management in its effects on maize yield?

Relying on data from field experiments, this paper presents an empirical analysis of the determinants of maize yield, with a focus on the interaction effects of GM technology, management, and production risk. Using quantile regression, we document that GM technology increases maize yield and reduces exposure to downside risk. While previous literature has typically studied yield response in terms of mean and variance (using classical regression and analysis of variance) (e.g., Qaim and Zilberman, 2003; Shi et al., 2013; Xu et al., 2013), the quantile approach provides a more refined analysis by estimating the distribution of yield. Our research examines the evolution of maize yield distribution and its determinants, with a focus on the effects of GM technology, management, and their interactions.

MATERIALS AND METHODS

Our empirical analysis relies on data from field experiments conducted annually in three sites in the northern U.S. Corn Belt. The three sites are Arlington, Janesville, and Lancaster, all in southern Wisconsin. All sites involve rainfed agriculture facing similar agroclimatic conditions. The experiments were conducted from 1990 to 2010 to evaluate the performance of maize hybrids submitted by seed companies and university researchers (see University of Wisconsin, 2014 for details). The data were collected by the University of Wisconsin in cooperation with Wisconsin Crop Improvement Association. They involved farmer cooperators in Janesville and the University of Wisconsin Agricultural Research Stations near Arlington and Lancaster. The focus on these sites simplifies our analysis because it avoids complications due to interactions between genetics and agroclimatic conditions that commonly vary across space.

Maize yields were recorded at each site for a set of hybrids, planting densities, and crop rotations. The experimental design was a randomized complete block in which each hybrid was grown in at least three separate plots (replicates) at each location to account for field variability. Management practices were typical of maize farming found in rainfed agriculture in the U.S. Corn Belt. The soil was prepared for seeding by fall chisel plowing followed by spring field cultivating. Fertilizers were applied as recommended using soil nutrient information from soil tests. Herbicides were applied for weed control and supplemented with cultivation when necessary. Insecticide was applied when the infestation level was above a threshold commonly used by farmers. Grain yields were measured and adjusted to moisture content of 155 g kg^{-1}.

A total of 2198 hybrids were tested between 1990 and 2010 at the three sites, of which 1250 were conventional hybrids and 948 were transgenic hybrids. All hybrids were tested in multiple locations and some for multiple years, resulting in 10,695 usable observations of yield (measured in tons per hectare) for a single hybrid at a single location for a single year, of which about 38% are from transgenic hybrids. Summary statistics for the data are presented in Table 1. On average, maize yield during our study period is 12.56 tons per hectare. For crop rotation, 68% of the fields are planted in maize after soybean [*Glycine max* (L.) Merr.], 26% maize after maize, and <6% maize after alfalfa (*Medicago sativa* L.) or wheat (*Triticum aestivum* L.). The average plant density is 70 thousand plants per hectare.

Table 1 Summary statistics.†

Variable	Mean	Minimum	Maximum
Maize yield (tons per hectare)	12.56	2.76	18.19
Rotation: after maize (*pmaize*)	0.2617	0	1
Rotation: after alfalfa (*palfalfa*)	0.0414	0	1
Rotation: after wheat (*pwheat*)	0.0176	0	1
Rotation: after soybean (used as benchmark)	0.6793	0	1
GM‡ technology	0.3776	0	1
Plant density (1000 plants per hectare)	70.23	53.07	79.87

† The total number of observations is 10,695.

‡ GM, genetically modified.

These data are used to assess the factors affecting the evolving distribution of maize yield via quantile regression conducted using the R software package (Koenker, 2005). Let maize yield y be represented by the production function $y = f(X, e)$, where X is a set of known factors affecting maize yield and e denotes random variables (e.g., weather shocks) with a given probability distribution. Then the distribution function of maize yield is given by $F(y|\ X) = Prob[f(X, e) \leq y]$. For a given k, $0 < k < 1$, the quantile of y is defined as the inverse of the distribution function: $Q(k, X) = inf\{y\colon F(y|\ X) \geq k\}$. Conditional on X, the quantile $Q(k, X)$ is the smallest yield level that can be attained with probability k. As a special case, the conditional median of y occurs when $k = 0.5$ and is given by $Q(0.5, X)$. In quantile regression, we assume that $Q(k, X) = X\beta_k$ and proceed to use data on (y, X) to estimate the parameters β_k (Koenker 2005). Applied to maize yield, the quantile function $(X\beta_k)$ provides the basis to investigate the distribution of yield risk and to analyze the factors affecting it. In contrast with classical regression, quantile regression allows the parameters β_k to vary across quantiles, thus providing information on how specific explanatory variables X affect the distribution of yield.

We focus on three sets of factors: GM technology, management, and the effects of other technological change over time. For that purpose, the explanatory variables X include a GM technology dummy variable, a time trend (capturing technological change), a location dummy (capturing local agroclimatic conditions), and management variables (including crop rotation and plant density). We allow all parameters β_k to vary between conventional hybrids and GM hybrids. We also introduce interaction effects between GM and crop rotation and between GM and plant density. By doing so, the effects of GM are allowed to vary over time and to change with crop rotations as well as plant density.

RESULTS AND DISCUSSION

The quantile parameters β_k are estimated for the conventional and GM hybrids separately. While the analysis was done for all quantiles k, $0 < k < 1$, selected results are presented in Table 2. They include three quantiles for each hybrids group: the bottom 20% ($k = 0.2$), the median ($k = 0.5$), and the top

Table 2. Parameter estimates of the *k*-th quantile of maize yield.†

Variable‡	Conventional (*n* = 6657)			GM§ (*n* = 4038)		
	k = 0.2	k = 0.5	k = 0.8	k = 0.2	k = 0.5	k = 0.8
Intercept	1.932***	2.927***	2.573***	−1.040	3.939***	6.881***
Year	2.397***	2.071***	1.491***	1.043***	0.212	−0.193
pmaize	−0.930***	−0.715***	−0.517***	0.242**	−0.600***	−0.785***
palfalfa	2.667***	3.062***	2.793***	1.070***	1.132***	1.098***
pwheat	1.130***	0.718***	0.192**			
Janesville, WI	0.471***	0.416***	0.348***	0.176**	0.507***	0.792***
Lancaster, WI	−0.753***	−0.018	0.568***	−0.149*	0.381***	0.813***
Density, WI	0.138***	0.138***	0.159***	0.184***	0.130***	0.101***
Year × density	−0.032	−0.027***	−0.020***	−0.013***	−0.002	0.002
Year × *pmaize*	−0.020	0.016	0.092***	−0.026	0.129***	0.150***

* Significant at the 0.05 probability level.

** Significant at the 0.01 probability level.

*** Significant at the 0.001 probability level.

† Note: we also analyzed the effects of specific genetically-modified (GM) genes. But we did not have enough data points to obtain reliable estimates for specific patented genes. As a result, our research focuses on contrasting GM maize versus conventional maize.

‡ *palfalfa*, planted after alfalfa; *pmaize*, planted after maize; *pwheat*, planted after wheat.

§ GM, genetically modified.

20% ($k = 0.8$). Most parameters are statistically significant. In particular, the time trend variables are often positive and statistically significant, reflecting the rapid rate of yield growth for maize during the last two decades.

A number of statistical tests were performed on the quantile model. First, we tested whether the regression parameters were the same across three quantiles: $\beta_{0.2} = \beta_{0.5} = \beta_{0.8}$. Using a Wald test, the test statistic was 28.00 (with 18 degrees of freedom) for conventional hybrids and 12.17 (with 16 degrees of freedom) for GM hybrids, with corresponding p-values < 0.01. These results provide strong evidence that the parameters β_k change across quantiles, thus justifying our quantile approach. From Table 2, the impact of having maize as the previous crop (*pmaize*) is much more negative in the lower quantile ($k = 0.2$) than in the higher quantile ($k = 0.8$). Thus, crop rotation has a larger impact on maize yield in the lower portion of the distribution (corresponding to unfavorable growing conditions). The time trend variable also has a stronger positive effect on yield in the lower quantile. Thus, part of the maize yield growth comes from reducing exposure to downside risk. Planting density has a much stronger positive effect on GM yield in the lower quantile than in the upper quantile. Genetically-modified maize hybrids tend to demonstrate strengthened yield gains from higher density under unfavorable conditions. These results suggest that it would be inappropriate to assume that the regression parameters are constant across quantiles (as done in a standard regression analysis).

Second, we tested the null hypothesis that the management variables (crop rotation and plant density) have no effect on maize yield. Using a Wald test (with 2 degrees of freedom), the test statistics are as follows: for conventional hybrids, 54.01 for crop rotation and 316.1 for plant density; and for GM hybrids, 12.15 for crop rotation and 117.49 for plant density. In all cases, the p-values are < 0.01. Thus, we strongly reject the null hypotheses, providing strong evidence of the important role of management.

Finally, we tested whether the regression parameters were the same for conventional and GM hybrids. Using a Wald test (with 9 degrees of freedom), the corresponding test statistic is 39.62, with a p-value <0.01. Thus, as far as maize yield is concerned, we strongly reject the null hypothesis that GM technology and conventional technology are the same.

To examine the effects of GM technology and its interactions with management, the estimated model was simulated to obtain the distribution function of maize yield under alternative scenarios. We consider the following situations: (i) years 2000 and 2005; (ii) two crop rotations: after soybean (treated as the base case) and after maize (*pmaize*); and (iii) two plant densities (measured in 1000 plants per hectare): the sample mean of 70.23 (treated as the base case) and a higher density of 77.25 (corresponding to a 10% increase compared with the base case). The simulated distribution functions are presented in Fig. 1, 2, and 3.

Figure 1 shows the yield distribution functions of conventional and GM hybrids for 2000 and 2005. The year 2000 was chosen as benchmark for our analysis (to avoid issues related to the early stages of GM hybrids introduction starting in 1996). The five-year lapse period between 2000 and 2005 is chosen to evaluate the evolution of maize productivity over time. We also use as benchmark "after soybean" for crop rotation and a plant density of 70.23 thousand plants per hectare. Both conventional and GM hybrids have experienced large yield growth over time, translating to a right shift in their respective distribution functions. In 2000, comparing GM versus conventional hybrids, the distribution of GM hybrid yield was uniformly better (shifting to the right of the distribution of conventional hybrid yield), with a larger difference around the median quantile. In 2005, the differences are more nuanced: the performance

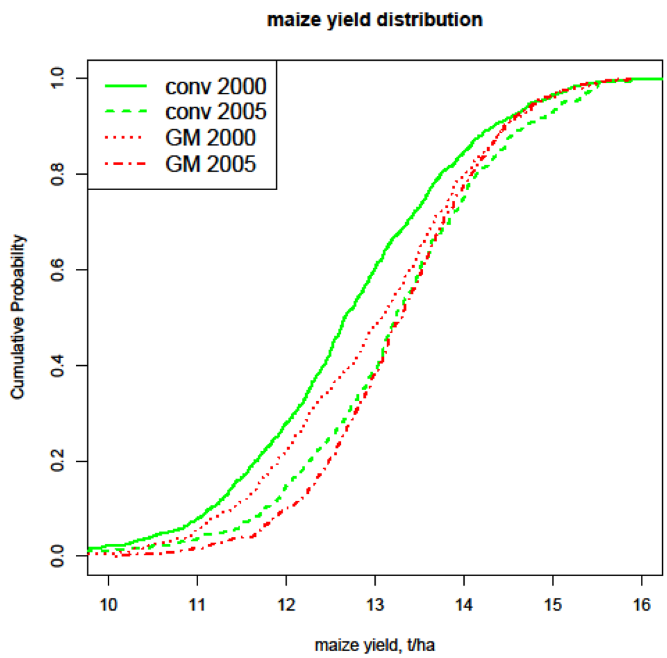


Figure 1. Distribution of maize yield in southern Wisconsin under alternative scenarios. Maize yield is measured in tons per hectare. The scenarios include two years (2000 and 2005) and two types of seeds (conventional seeds [conv] and seeds with GM genes [GM]).

of GM hybrids is better than the conventional hybrids in the lower part of the yield distribution only. It indicates that the benefits of GM technology on yield are largely due to a reduction in the exposure to downside risk.

Since current GM technology has focused on improving weed and pest control in maize production, our findings indicate that GM technology helps protect yield and reduces yield losses associated with weed infestation and/or pest damages. However, in 2005, the difference in distributions between GM and conventional hybrids became small around the median yield. As discussed by Hutchison et al. (2010), the widespread use of GM technology may have reduced pest populations in the U.S. Corn Belt, thus possibly reducing the yield benefits from GM technology.

Figure 2 presents the yield distribution functions of conventional and GM hybrids, with a focus on the effects of crop rotation. It compares the distribution functions under two crop rotations: "after soybean" (treated as the base case) versus "after maize." Growing maize after maize is not good for yield compared with growing maize after soybean. Such crop rotation effects are observed for both conventional and GM hybrids in 2000. Note that this negative impact is much smaller for the GM maize than for the conventional maize for the lower end of the distribution. To the extent that crop rotation contributes to reducing pest infestation, our results suggest that GM technology tends to be a substitute for crop rotation. By 2005, while the negative "maize after maize" effect still exists for the conventional hybrids, it has mostly disappeared for the GM technology, especially for the lower end of the yield distribution. Again,

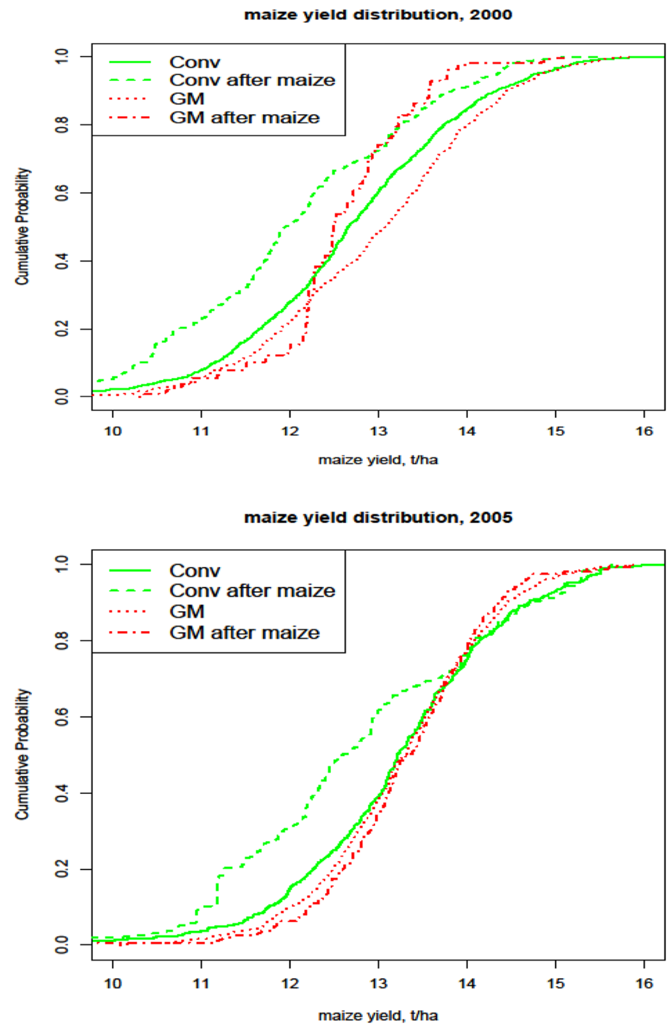
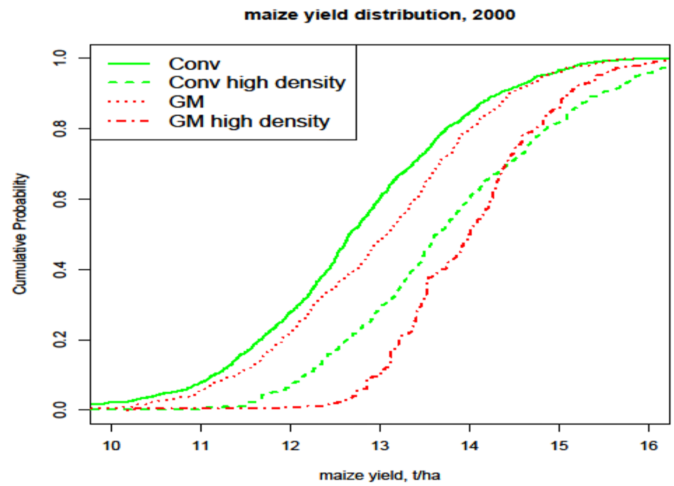


Figure 2. Distribution of maize yield in southern Wisconsin under alternative scenarios. Maize yield is measured in tons per hectare. The scenarios include two years (2000 and 2005), two types of seeds (conventional seeds [Conv] and seeds with GM genes [GM]); and two types of crop rotation (maize after soybean [the base case] and maize after maize ["after maize"]).

it is consistent with Hutchison et al.'s (2010) findings: if the widespread adoption of GM technology has reduced pest populations, it also yielded lower benefits from crop rotation (maize after soybean versus maize after maize).

Figure 3 shows the yield distribution functions of conventional and GM hybrids, with a focus on the effects of plant density. It evaluates the distribution functions under two plant densities: 70.23 thousand plants per hectare (treated as the base case) versus 77.25 thousand plants per hectare (corresponding to a 10% increase over the base case). Higher density contributes to higher yield for both conventional and GM hybrids in 2000, and the effects are present across all parts of the distribution. However, while the density effects still exist for GM maize in 2005, they have mostly disappeared for conventional maize. Thus, compared with the conventional maize, GM maize exhibits higher productivity under high planting density. It is



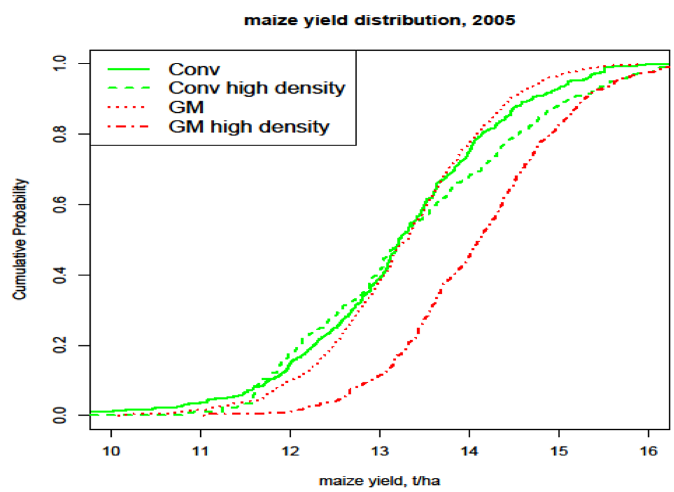


Figure 3. Distribution of maize yield in southern Wisconsin under alternative scenarios. Maize yield is measured in tons per hectare. The scenarios include two years (2000 and 2005), two types of seeds (conventional seeds [Conv] and seeds with GM genes [GM], and two plant densities (70.23 thousand plants per hectare [the base case] and 77.25 thousand plants per hectare ["high density"]).

probably due to healthier stalk and root systems for GM maize (Ciampitti and Vyn 2011; Stanger and Lauer 2006). To the extent that most of the historical increases in maize yields are due to density effects (Duvick 2005), our result indicates that GM technology offers good prospects for future productivity improvements.

CONCLUSIONS

Our study suggests that GM technology has a stronger impact on the lower end of maize yield distribution. As such, it helps reduce exposure to downside risk. In addition, the impacts of GM maize hybrids interact with management practices such as crop rotation and planting density. Genetic-modification technology is found to be a substitute for crop rotation. But while the negative "maize after maize" effect still exists for the conventional hybrids, it has nearly disappeared for the GM technology in the lower end of the yield distribution. Higher planting density contributes to higher yield, such effects being particularly strong for GM hybrids. Finally, these results were obtained for selected sites in the northern U.S. Corn Belt. To the extent that the effects of GM technology vary across agro-climatic conditions, our findings may not apply elsewhere.

Acknowledgments

This research was supported in part by a U.S. Department of Agriculture Hatch grant from the College of Agriculture and Life Sciences, University of Wisconsin, Madison, and a U.S. Department of Agriculture AFRI grant.

References

Ciampitti, I.A., and T.J. Vyn. 2011. A comprehensive study of plant density consequences on nitrogen uptake dynamics of maize plants from vegetative to reproductive stages. Field Crops Res. 121:2–18. doi:10.1016/j.fcr.2010.10.009

Duvick, D. 2005. The contribution of breeding to yield advances in maize. Adv. in Agr. 86:84–145.

Edgerton, M.D., J. Fridgen, J.R. Anderson, J. Ahlgrim, M. Criswell, P. Dhungana, T. Gocken, Z. Li, S. Mariappan, C.D. Pilcher, A. Rosielle, and S.B. Stark. 2012. Transgenic insect resistance traits increase corn yield and yield stability. Nat. Biotechnol. 30:493–496. doi:10.1038/nbt.2259

Hutchison, W.D., E.C. Burkness, P.D. Mitchell, R.D. Moon, T.W. Leslie, S.J. Fleischer, M. Abrahamson, K.L. Hamilton, K.L. Steffey, M.E. Gray, R.L. Hellmich, L.V. Kaster, T.E. Hunt, R.J. Wright, K. Pecinovsky, T.L. Rabaey, B.R. Flood, and E.S. Raun. 2010. Areawide suppression of European corn borer with Bt maize reaps savings to non-Bt maize growers. Science 330:222–225. doi:10.1126/science.1190242

Koenker, R. 2005. Quantile Regression. Cambridge Univ. Press, Cambridge, UK.

Qaim, M., and D. Zilberman. 2003. Yield effects of genetically modified crops in developing countries. Science 299:900–902. doi:10.1126/science.1080609

Shi, G., J.P. Chavas, and J. Lauer. 2013. Commercialized transgenic traits, maize productivity and yield risk. Nat. Biotechnol. 31:111–114. doi:10.1038/nbt.2496

Stanger, T.F., and J.G. Lauer. 2006. Optimum plant population of Bt and non-Bt corn in Wisconsin. Agron. J. 98:914–921. doi:10.2134/agronj2005.0144

University of Wisconsin. 2014. Wisconsin corn hybrid trials. Corn Agronomy. University of Wisconsin. http://corn.agronomy.wisc.edu/HT/Default.aspx (accessed 13 Dec. 2013).

USDA–NASS. 2012. National Agricultural Statistics Service. U.S. Department of Agriculture, Washington, DC. www.nass.usda.gov/index.asp (accessed 13 Dec. 2013).

USDA–ERS. 2013. Adoption of genetically engineered crops in the U.S. United States Department of Agriculture–Economic Research Service. www.ers.usda.gov/data-products/adoption-of-genetically-engineered-crops-in-the-us/recent-trends-in-ge-adoption.aspx#.Uo_0zSf3PMY (accessed 13 Dec. 2013).

Xu, Z., D.A. Hennesy, K. Sardana, and G. Moschini. 2013. The realized yield effect of genetically engineered crops: U.S. maize and soybean. Crop Sci. 53:735–745. doi:10.2135/cropsci2012.06.0399