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National and Global Impacts of Genetically Modified Crops[†]

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We estimate the impact of genetically modified (GM) crops on countrywide yields, harvested area, and trade using a triple-differences rollout design that exploits variation in the availability of GM seeds across crops, countries, and time. We find positive impacts on yields, especially in poor countries. Our estimates imply that without GM crops, the world would have needed 3.4 percent additional cropland to keep global agricultural output at its 2019 level. We also find that bans on GM cultivation have limited the global gain from GM adoption to one-third of its potential. Poor countries would benefit most from lifting such bans. (*JEL* O13, Q15, Q16, Q17, Q18)

According to their proponents, the commercialization of genetically modified (GM) crops promised a bright green future. Has it arrived? Surely not everywhere. GM crops remain controversial, and most countries ban farmers from cultivating them. Bans, and the fact that GM varieties are only available for a few crops, provide us with a quasi-experiment, which we use in this paper to assess the economic impact of GM crops in countries where they are allowed and the costs of banning them elsewhere.

GM crops do not have higher yields than conventional crops when grown under perfect conditions. Instead, most GM crops are designed to be resistant to herbicide, pests, or both, and they should consequently offer higher yields in actual growing conditions where pests and weeds take a toll on output. Most farm-level studies do indeed find that farms growing GM crops have higher yields than their peers, but the gains are not universal. Of the 168 peer-reviewed papers identified by Carpenter (2010), 128 reported higher yields of GM crops, but 45 reported unchanged or lower yields. Klümper and Qaim (2014) find similar variation in a meta-study that includes the gray literature.

Selection and general equilibrium effects mean that one cannot infer from farm-level studies how GM crops affect aggregate yields, and at the aggregate level, the evidence is both less clear and less abundant. The National Academies of Sciences, Engineering, and Medicine (NASEM 2016, 102) conclude that “the

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nation-wide data on maize, cotton, or soybean in the United States do not show a significant signature of genetic-engineering technology on the rate of yield increase." At a global level, a report commissioned by the United Nations and the World Bank concluded that "the pool of evidence of the sustainability and productivity of [GM crops] in different settings is relatively anecdotal, and the findings from different contexts are variable, allowing proponents and critics to hold entrenched positions about their present and potential value."[1] The cross-country studies published since the release of the report do not resolve the controversy. In a correlational study, Barrows, Sexton, and Zilberman (2014b) find that the uptake of GM varieties is associated with increases in countrywide yields, but Scheitrum, Schaefer, and Nes (2020), using a difference-in-difference strategy, find no significant effects on yields but large effects on harvested area.[2]

We bring new evidence to this debate. At the core of our analysis is a triple-differences (DDD) rollout design in which we exploit that GM varieties of cotton, maize, rapeseed, and soybean became commercially available in 1996, whereas GM varieties of rice, wheat, and other important crops have yet to be commercialized. Countries that ban GM cultivation constitute another natural control group. We use the two control groups and the staggered national approval of commercial GM cultivation to identify causal effects of GM adoption in a three-dimensional panel in which the unit of observation is a crop in a given country in a given year. We only include field crops in our analysis, whereby we exclude GM varieties of a few specialty crops, such as eggplant and papaya. This is no severe limitation, as cotton, maize, soybean, and rapeseed account for more than 98 percent of global GM production (ISAAA 2020).

Contrary to previous studies, our empirical strategy allows us to control for country-by-year fixed effects, which absorb potentially confounding variation in agricultural policies, climate, input prices, and so on. We also allow the estimated effect of GM adoption to depend on climate and income levels. Furthermore, we carefully inspect pre-trends in our outcomes, something that becomes important when considering the impact on land use. And contrary to Scheitrum, Schaefer, and Nes (2020), we exclude from our treatment group countries where GM cultivation is technically legal but commercial production remains effectively banned.

We find that cultivation of GM varieties significantly increases yields, particularly cotton yields. The yield gains are larger in countries with low incomes and many frost-free days, as warmer climates make pests and weeds more prevalent and poorer farmers have less resources to keep them in check (Oerke et al. 1994; Qaim and Zilberman 2003). Like NASEM (2016), we find no effect of GM adoption on maize and soybean yields in countries with climates and incomes similar to that of the United States, but the null finding cannot be extrapolated to poorer countries with warmer climates. In a country like India, we estimate that nationwide maize yields could increase by as much as 64 percent if cultivation of GM maize was allowed. Soybean yields could increase by almost as much.

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[1] McIntyre (2009, 40)

[2] A few recent papers study GM adoption across administrative subdivisions within a single country. See Qiao (2015) on China; Bustos, Caprettini, and Ponticelli (2016) on Brazil; and Hendricks, Tack, and Lusk (2019) on the United States.

Turning to land use, we find that of the four crops we study, only the harvested area of soybean increases after GM approval. And even in the case of soy, the increase is almost indistinguishable from a trend in soybean cultivation predating the introduction of GM varieties. Aggregate cropland also expands following GM approval, but again, the expansion reflects an ongoing underlying trend. While the adoption of GM varieties does not increase land use, the higher yields still increase production. We provide evidence that much of the resulting surplus is exported to countries that ban GM cultivation but allow import.

Aggregating to the global level, we find that GM varieties increased the value of global agricultural production by about US$39 billion in 2019, the last year in our sample. Without GM crops, the world would have needed 3.4 percent additional cropland to produce the same amount of output as in 2019, corresponding to an area the size of Spain. Only one-third of the potential of the currently available GM varieties has been achieved, however. We find that without any bans on GM cultivation, the value of global agricultural production could have been a further US$69 billion higher in 2019. Poorer countries, notably African ones, would have benefited the most. Not only have they most to gain in terms of yields, they also have large agricultural sectors. Lifting current GM bans could consequently support economic development of the poorest places on our planet while increasing agricultural production at a time when food security is a growing concern.

I. Background and Descriptive Evidence

Genetic modification allows scientists to implant any genetic trait into crops, but almost all GM crops currently grown have only two such traits: resistance to glyphosate, a mild herbicide also known as Roundup, and genes from the bacterium Bacillus thuringiensis (Bt) that allow the modified plant to produce natural toxins that kill the larvae of certain insects but are harmless to other organisms. Neither modification increases yields in the absence of pests and weeds, so by how much GM crops increase actual yields depends on the prevalence of such maladies (Qaim 2009; Barrows, Sexton, and Zilberman 2014a).

Farmers in Argentina, Australia, Canada, China, Mexico, and the United States quickly adopted GM seeds when they became available in 1996 (see Figure A.1 in the online Appendix). Policymakers in many other countries, notably in the European Union (EU), Russia, and much of Africa, banned farmers from cultivating GM crops under pressure from unfavorable public opinion. The opposition to GM technology was orchestrated by NGOs and activists, notably British ones, citing public health concerns, environmental concerns, and ethical concerns about seeds being patented by the likes of Monsanto (Lynas 2018). Despite that concerns about human health were unfounded, that the scientific community considers GM crops net beneficial for the environment (NASEM 2016), and that Monsanto's patents expired years ago, cultivation of GM crops remains effectively banned in most countries. Only 29 countries currently approve commercial cultivation (Figure A.2 in the online Appendix). An additional 42 countries allow import of GM crops but not cultivation (ISAAA 2020).

Once settled on a policy toward GM crops, few countries change their minds, and how fiercely the public opposed GM crops when the question of approval first arose largely explains where they are banned today. GM crops arrived in Europe at a time when the mad cow disease (bovine spongiform encephalopathy, or BSE) scandal unfolded, whereas no comparable regulatory failures affecting public health had occurred in the United States in recent memory (Lynch and Vogel 2001). But just as important, the regulatory process in the EU meant that approval of GM crops took longer, allowing opposition from NGOs to build (Lynch and Vogel 2001; Bernauer and Meins 2003). Dargent and Urteaga (2019) find a similar pattern in Latin America. The regulatory regimes in Bolivia and Colombia permitted simultaneous risk assessments and field trials, allowing the countries to authorize GM crops before opposition to them spread from Europe. Peruvian law required sequential risk assessments and field trials, and the attempt to commercialize GM crops failed amid growing opposition.

By the mid-2000s, the global anti-GM movement had halted the global spread of GM crops almost entirely. Trade considerations added to the pressure on governments. Mexican legislators permitted soybean cultivation in 2012 but immediately withdrew the permission under pressure from Mexican honey producers fearing for their exports to the EU (USDA Foreign Agricultural Service 2012). Many African countries likewise ban GM crops with an eye on agricultural exports to Europe (Paarlberg 2010).

Besides trade considerations, economics seem to explain little of the variation in policies toward GM crops. There is, for instance, no reason why GM crops should be less profitable in Europe than in North America, and European farmers (and biotech companies) were as eager to introduce the new technology as their American counterparts (Lynch and Vogel 2001). At a more general level, we find that GM-approving countries and GM-banning countries had similar observable characteristics before GM crops were commercialized, including similar agroecologies, agricultural productivity levels, and GDP per capita levels (online Appendix Table A.1).

The simplest way to assess the economic gains from GM varieties is to divide the world into two regions: one in which GM crops are approved and one in which GM crops are effectively banned. In Figure 1, we compare trends in the two regions' yields of the four crops of which GM varieties are commercialized. As an additional comparison, the figure includes trends in the yields of rice and wheat, major crops of which no GM varieties are commercially grown in either region. We normalize yields to their 1995 levels to make them comparable across crops and report three-year moving averages to reduce annual fluctuations.

Panel A of Figure 1 shows that average cotton yields increased rapidly in the GM-approving region after GM cotton was commercialized in 1996 but not elsewhere. Yields of wheat and rice follow the same trend in the GM region as in the rest of the world, suggesting that the acceleration of cotton yields in the GM region does reflect the commercialization of GM cotton. We find a similar pattern for maize and rapeseed in panels C and D, although the impacts seem smaller. For soybean in panel B, no effect on yields is apparent.

That cotton is more prone to pests than the other three crops (Oerke 2006) is probably the main reason why cotton yields increase the most after GM approval. But most cotton-producing countries were also relatively poor and had comparably inefficient pest control before they introduced GM varieties. Soy is mostly grown in countries with more advanced agriculture, which to some extent explains why soy yields appear not to respond to the introduction of GM varieties. Our econometric framework, to which we turn next, can disentangle such composition effects from the inherent yield advantages of GM crops.

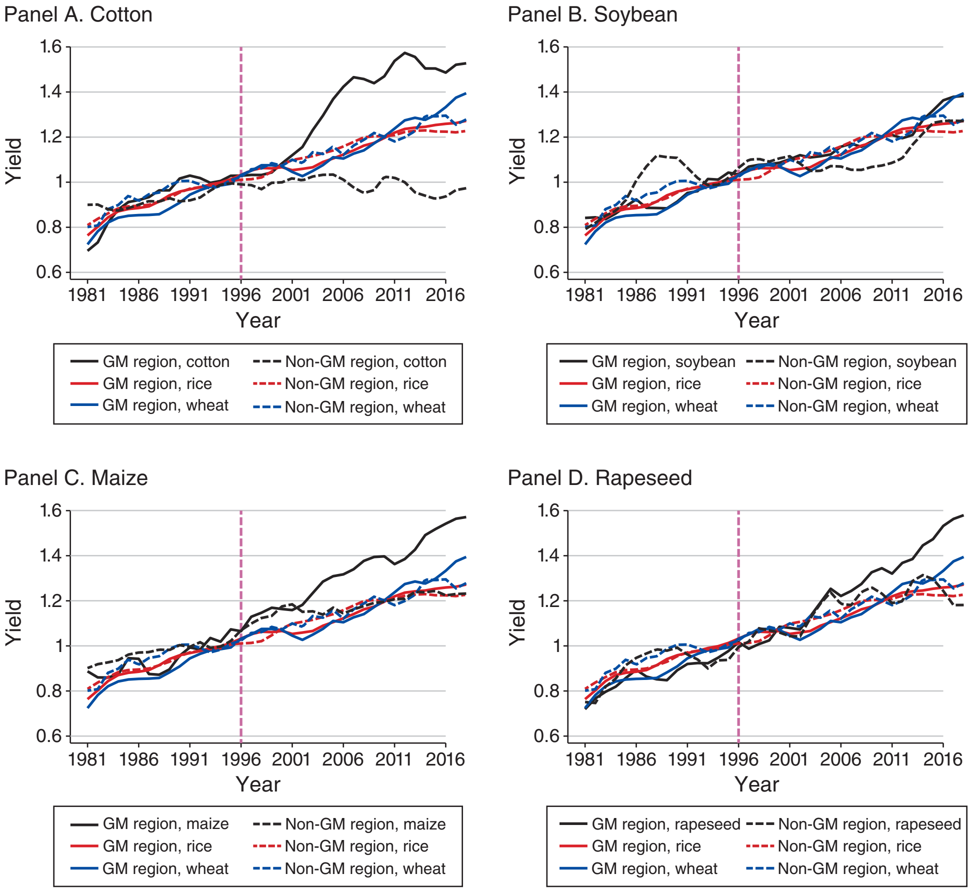

FIGURE 1. TRENDS IN CROP YIELDS IN GM- AND NON-GM REGIONS

Notes: The figure shows three-year moving averages of aggregate crop yields relative to 1995 in GM and non-GM regions. The GM region consists of countries eventually approving a given GM crop. All other countries are assigned to the non-GM region. The vertical red line indicates 1996, the year in which GM crops were commercialized. All panels include the non-GM crops rice and wheat as benchmarks. Online Appendix B lists the countries in the GM region.

II. Research Design

Our econometric analysis builds on the same logic as the descriptive Figure 1, but we now compare individual countries rather than GM and non-GM regions. The unit of observation is a specific crop (e.g., maize) in a given country in a given year. We exploit variation in when GM crops were approved in different countries in a DDD staggered rollout design, in which we compare yields (and other outcomes) of crops for which GM varieties are available to those of crops of which GM varieties are nonexistent or banned. We compare changes in such relative yields before and after national approval to the similar yield changes in countries that did not approve GM crops. Our event study estimation equation is

$$\ln y_{ict} = \delta_{it} + \gamma_{ci} + \lambda_{ct} + \sum_{j=-10}^{T} \alpha_j \mathbf{1}[t - E_{ic} = j] + \epsilon_{ict}, \tag{1}$$

where y_{ict} is the outcome of interest for crop c in country i and year t. The DDD design allows us to include both country-by-year fixed effects (δ_{it}), crop-by-country fixed effects (γ_{ci}), and crop-by-year fixed effects (λ_{ct}). The crop-by-year fixed effects capture global trends in, for example, technology or demand that affect a given crop. The crop-by-country fixed effects capture variation in how suitable different countries are for different crops, as well as country-and crop-specific productivity levels. The country-by-year fixed effects capture local weather shocks, economic growth, and policies that uniformly affect production of all crops. We denote the error term ϵ_{ict} and cluster standard errors at the country-crop level.

E_{ic} is the year when the first GM varieties are harvested, and $\mathbf{1}[t - E_{ic} = j]$ is an indicator being one j years after that event. A causal interpretation of α_j requires E_{ic} to be exogenous conditional on all three sets of fixed effects. Based on our reading of the qualitative evidence reviewed in Section I, we consider GM approval to be approximately exogenous. Using the strictly exogenous commercialization year, 1996, for all GM-adopting countries instead gives similar but less precise results (online Appendix Figure A.3).

Our baseline estimation window for treated units is ten years before the first harvest of GM crops $(j = -10)$ to ten years after $(j = T = 10)$. Treated units are excluded outside the event window. We balance the sample, such that we use the same set of treated units in all event years. Extending the event window beyond ten years would leave us with relatively few early adopters in the balanced sample or force us to unbalance the sample.[3]

Results based on the rollout estimator are sometimes difficult to interpret, as units treated early act as controls for units treated later, leading to bad comparisons (e.g., Goodman-Bacon 2018). Only 2 percent of the units in our regressions are ever treated, so the problem is mitigated by the many clean controls. Nevertheless, Figure A.7 in the online Appendix shows that we reach the same conclusions when using alternative estimators (Sun and Abraham 2021; Callaway and Sant'Anna 2021; Borusyak, Jaravel, and Spiess 2021; de Chaisemartin and d'Haultfoeuille 2020).

The event studies give separate point estimates for each event year. To preserve degrees of freedom for our analysis of treatment heterogeneity, we assume that relative log yields increase approximately linearly after GM approval and estimate the following DDD equation where, contrary to in equation (1), α varies across crops rather than over time:

$$\begin{aligned} \text{(2)} \qquad \ln y_{ict} = {} & \delta_{it} + \gamma_{ci} + \lambda_{ct} + \alpha_c \mathbf{1}[E_{ic} \leq t](t - E_{ic} + 1) \\ & + \mathbf{X}_i' \beta [E_{ic} \leq t](t - E_{ic} + 1) + \kappa \ln area_{ict} + \epsilon_{ict}, \end{aligned}$$

where $\mathbf{1}[E_{ic} \leq t]$ is an indicator taking the value 1 if GM varieties are harvested. The interaction $\mathbf{1}[E_{ic} \leq t](t - E_{ic} + 1)$ consequently counts the number of years GM crops have been cultivated, including the current one. As in our event study equation, we exclude observations more than ten years after the first GM harvest (i.e., $t - E_{ic} > 10$), leaving us with 11 years of treatment. The estimation window

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[3] We show both alternatives in Figures A.5 and A.6 in the online Appendix.

is not a limitation: we show later that the gains from GM crops are almost fully phased in after a decade. Contrary to when we estimate our event study specification (equation (1)), we only estimate a single coefficient per crop (a trend break) in our DDD specification, so it becomes unnecessary to balance the sample in the treatment window.

The coefficient β captures how treatment depends on initial conditions, represented by the vector $\mathbf{X}_i$. In our baseline regression, we include in $\mathbf{X}_i$ initial GDP per capita and days of frost in a year. Motivated by the model in Gollin, Hansen, and Wingender (2021), we take into account that average yields decline when cultivation expands into less suitable areas by controlling for logged harvested area.

To quantify the effect of GM crops on global agricultural production, we first calculate crop-and-country-specific yield gains in percent:

$$\Delta_{ict} = \begin{cases} \exp\Big(\big(\hat{\alpha}_c + \mathbf{X}_i'\hat{\beta}\big) \times \min\{t - E_{ic} + 1, 11\}\Big) & \text{if } E_{ic} \leq t; \\ 0 & \text{otherwise.} \end{cases} \tag{3}$$

The hat variables are estimates of the parameters in equation (2). As when estimating equation (2), we assume that all yield gains have materialized after 11 years of treatment.

In the next step, we combine the yield effects with how much different countries produce of different crops to compute the total increase in crop production following GM adoption:

$$\textit{total production gain}_{it} = \frac{\sum_c \Delta_{ict} \times \textit{production}_{ict}^{NoGM}}{\sum_c \textit{production}_{ict}^{NoGM}}. \tag{4}$$

Equation (4) implicitly assumes no reallocation of land, which is not entirely unreasonable given that we do not find any clear effects on land allocation in our empirical analysis. Any reallocation of land not picked up by our empirical estimates would increase the total production gain as long as farmers maximize profits. We do not observe $\textit{production}_{ict}^{NoGM}$—that is, what production would have been without GM varieties. We therefore calculate $\textit{production}_{ict}^{NoGM}$ using equation (4) and observed production after GM approval:

$$\textit{production}_{ict}^{NoGM} = \frac{\textit{production}_{ict}^{GM}}{1 + \Delta_{ict}}. \tag{5}$$

We measure $\textit{production}_{ict}^{GM}$ in local producer prices to facilitate comparisons across different crops. We then use equation (5) to rewrite equation (4) in terms of observables:

$$\textit{total production gain}_{it} = \frac{\sum_c \Delta_{ict} \times \textit{production}_{ict}^{GM}}{\sum_c \frac{\textit{production}_{ict}^{GM}}{1 + \Delta_{ict}}}. \tag{6}$$

We aggregate the expression above across countries to obtain the increase in global agricultural production caused by GM varieties.

III. Data and Sample

We define the event year E_{ic} as the first year in which a GM variety of a given crop could be harvested and sold commercially for human consumption or animal feed without violating a ban. In the southern hemisphere, where the agricultural year does not follow the calendar year, the first GM harvest may be one or two years after GM crops are approved by the legislature. In countries with no legislation, or no enforcement of legislation, we use the year in which GM seeds became available through parallel imports from a neighboring country. A few countries allow GM crops but restrict their cultivation to an extent that it amounts to de facto bans. Honduras, for instance, only allows GM maize in 3 out of 18 administrative regions and only in certain areas within the 3 (USDA Foreign Agricultural Service 2020). We consider Honduras to have a de facto ban in our baseline regression. Using de jure approval dates or the year 1996 as the event year instead of the first harvest gives similar but less precise estimates; see online Appendix Figure A.4. We provide documentation for GM approval dates and the year of the first harvest in online Appendix B. The online Appendix also provides documentation for our data on GM adoption, which we have collected from multiple sources.

We use data on agricultural production, harvested area, producer prices, and agricultural trade from FAOSTAT and GDP data from Feenstra, Inklaar, and Timmer (2021). We use data on the share of frost days in the average year to proxy for the climatically determined exposure to pest and weeds. More frost means less pests and weeds. To avoid exaggerating frost exposure in the agricultural heartlands of arctic countries like Canada and Russia, we calculate the number of frost days for cultivated land only using gridded spatial data on frost and land use from FAO GAEZ v3.0.[4]

We restrict the sample to countries with more than 100,000 hectares of cropland, meaning essentially all countries with an agricultural sector. We balance the sample in our estimation window (1986–2019), which leaves us with a sample of 120 countries. In the crop dimension, we include all field crops, defined as 60 crops FAO categorizes as cereals, pulses, roots and tubers, oil crops, and fiber crops. We exclude fruits, nuts, and vegetables, which are biologically different from the four GM crops we study and produced by different methods. Our results are robust to using different samples of crops and countries (online Appendix Figure A.8).

IV. Results

In Figure 2, we report event study estimates for cotton, maize, rapeseed, and soybean together, implicitly assuming homogeneous treatment effects. Panel A shows how farmers gradually adopted GM varieties after they were approved. The high adoption rates a decade after the first permitted harvest (year 0) suggests that farmers consider GM varieties profitable despite GM seeds being costlier than conventional ones.

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[4] Using geographic information system software, we calculate the number of frost days in grid cells with at least 20 percent cultivated land. Our conclusions are robust to alternative cutoffs. The frost data are for 1961–1990. The data on cultivated land are for the year 2000.

Panel B reveals that before GM varieties are approved in a country, yields of treated crops relative to other crops followed the same trend as in other countries. Visually, there is no clear trend in the estimated pre-GM coefficients, and all of them are statistically insignificant, both individually (see the figure) and jointly ($p = 0.98$). After approval, relative yields of treated crops significantly increase in sync with adoption rates. Transformed from logs to levels, the magnitude of $\hat{\alpha}_{10}$ implies that GM varieties increase average yields by approximately 40 percent ten years after approval. The GM adoption rate is 80 percent after ten years (panel A), so the yield gain at adopting farms would be about 25 percent larger than the estimated average effect.

Beyond the first ten years, relative yields plateau as adoption rates do not have much scope to rise further. In the smaller subsample of countries that have cultivated GM crops since the 1990s, adoption rates reach just above 90 percent after 20 years, at which point yields are only marginally higher than after ten years (online Appendix Figure A.5). The ten-year window we use in our main analysis consequently captures almost all gains from GM adoption, and it has the added benefit of a larger sample.

Panel C of Figure 2 shows that the harvested area of a treated crop, on average, increases by 50 percent relative to other crops in the ten years after the first approved GM harvest (again, we transform our estimates from logs to levels). We cannot attribute the increase to GM adoption, however, as it appears to be a continuation of an existing trend. We probe this trend further in Section IVB.

Many countries that ban cultivation of GM crops still allow imports. One could suspect that such policy induces countries without bans on cultivation to specialize in crops of which GM varieties are available and export the resulting surplus. Panel D reinforces the suspicion: after GM approval, the net export of the affected crops increases relative to total agricultural trade (measured in current prices).[5] The figure may even underestimate the effect as the data only cover raw materials and lightly processed goods and not, for instance, cotton textiles. In other words, international trade partly compensates for the economic costs of banning GM cultivation. Still, while international trade in GM cotton is relatively unfettered, GM feed and particularly GM food face substantial regulatory obstacles (e.g., Disdier and Fontagné 2010; Kalaitzandonakes, Kaufman, and Miller 2014). A recent study by Nes, Schaefer, and Scheitrum (2022) finds considerable gains from further liberalization of GM food imports.

GM adoption rates are fairly uniform across crops and countries, but the effects of GM approval on yields, harvested area, and trade we report in Figure 2 mask interesting heterogeneities, which we explore in the next subsections.[6]

A. *Heterogeneous Effects on Yields*

In Table 1, we report DDD estimates for yields based on equation (2), which allows for separate coefficients for the four crops. Column 1 shows a substantial

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[5] We aggregate product-level data to the crop level using a crosswalk provided by FAO. Total agricultural trade (import + export) includes meat and dairy products.

[6] We also report event studies for all four outcomes by crop in online Appendix Figures A.9–A.12.

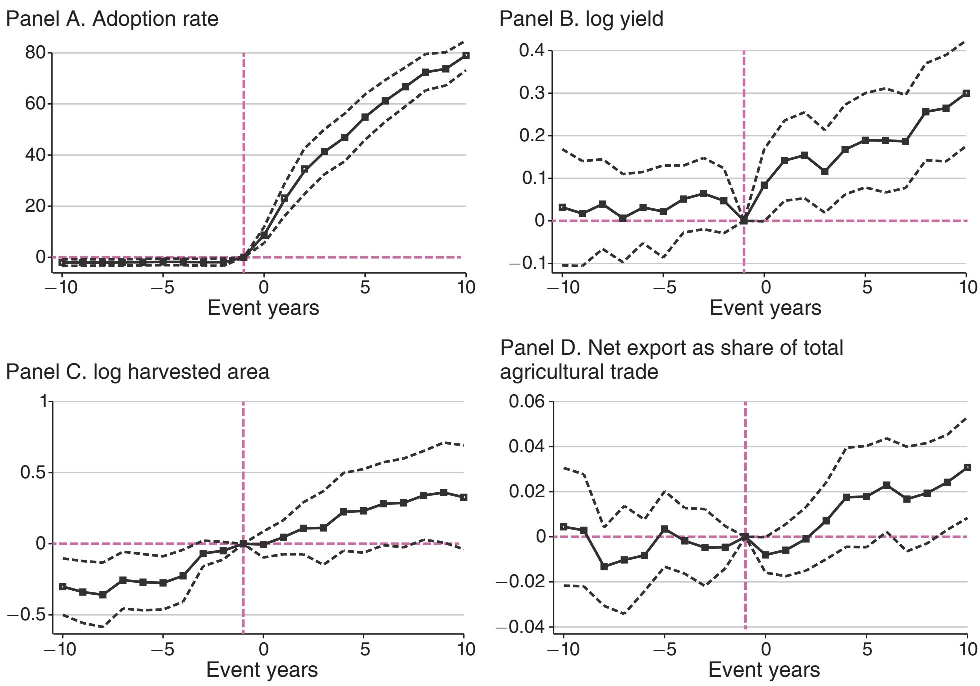


Figure 2. Baseline DDD Event Study Estimates

Notes: This figure reports DDD event study estimates based on equation (1). We assume homogeneous treatment effects across GM crops. The event window is ten years before/after the first approved harvest of GM varieties. The estimation window is 1986–2019. The sample contains 120 countries and 60 crops. We omit country-crop combinations treated in 2010 or later in order to balance the sample. The dashed lines are 95 percent confidence bands based on standard errors clustered at the country-crop level.

increase in cotton yields following GM adoption. The estimate implies that after GM cotton is introduced, cotton yields increase 4.6 percent faster per year in our ten-year estimation window than yields of untreated crops. Such a large effect is not implausible: on-farm field trails in India found Bt cotton to have 80 percent higher yields than conventional varieties (Qaim and Zilberman 2003). We also find a substantial effect on maize yields, whereas effects on soybean and rapeseed are small and insignificant.

One reason for the modest effects on soybean and rapeseed yields is that cultivation of the two crops expanded into less suitable land in the period we study, putting downward pressure on aggregate yields. When we control for harvested area in column 2, the estimated coefficients for soybean and rapeseed increase, and the former becomes significant with $p < 0.02$. The coefficients can be thought of as the yield gains in areas where soybean and rapeseed were already cultivated before the introduction of GM varieties.

GM varieties should have greater impacts in places where pests and weeds cause greater crop losses. Cold weather keeps both in check, and, indeed, the negative coefficient on the interaction term in column 3 implies lower yield gains in countries with many days of frost. When we include the interaction, the estimates in the first four rows correspond to yield gains in a frost-free country such as Brazil. We here assume that frost affects the four crops in the same way, which may be justified

Table 1—DDD Trend Break Estimates for Crop Yield

Variables	ln yield (1)	ln yield (2)	ln yield (3)	ln yield (4)	ln yield (5)	ln yield (6)
GM-cotton × *yr*	0.046	0.047	0.052	0.062	0.062	0.018
	(0.011)	(0.011)	(0.012)	(0.013)	(0.014)	(0.011)
GM-soy × *yr*	0.006	0.012	0.014	0.030	0.036	−0.008
	(0.005)	(0.005)	(0.007)	(0.012)	(0.014)	(0.009)
GM-maize × *yr*	0.027	0.027	0.034	0.051	0.050	0.007
	(0.007)	(0.007)	(0.007)	(0.012)	(0.014)	(0.008)
GM-rapeseed × *yr*	0.004	0.008	0.019	0.042	0.048	0.005
	(0.009)	(0.008)	(0.014)	(0.017)	(0.018)	(0.009)
ln *harvested area*		−0.036			−0.036	−0.036
		(0.008)			(0.008)	(0.008)
GM × *yr* × *frost days*			−0.040		−0.016	−0.016
			(0.019)		(0.022)	(0.022)
GM × *yr* × *income*				−0.013	−0.013	−0.013
				(0.005)	(0.006)	(0.006)
Observations	67,306	67,306	67,306	67,306	67,306	67,306
Benchmark	Sample avg.	Sample avg.	No frost	India	India	USA

Notes: This table reports DDD trend break estimates based on equation (2). We interact a before-after GM approval indicator with a linear year trend ("*yr*") with a "*GM-crop type*" indicator to allow for heterogeneous treatment effects. We use a linear trend to reflect the gradual uptake of GM varieties visible in panel A of Figure 2. The estimates in the table should be interpreted as the marginal effect of one additional year with GM varieties. In columns 1 and 2, the estimates in the first four rows are yield gains in the average country cultivating GM crops. In column 3, the interaction term makes the estimates in the first four rows correspond to the yield gains in a frost-free country (e.g., Brazil). In columns 4 and 5, we use frost days and income relative to India such that the estimates in the first four columns correspond to yield gains in a country similar to India in these dimensions. Column 6 is identical to column 5 except that we measure frost days and GDP per capita in 1995 relative to the United States instead of India. Frost days are measured as the shares of days during a year with frost. Standard errors clustered at the country-crop level are in parentheses.

given that all four have the same genes implanted. At a more practical level, we have an insufficient number of GM-approving countries to accurately estimate treatment heterogeneity by crop.

We should also expect GM varieties to have bigger impacts in poorer places with limited use of modern methods for keeping pests and weeds in check. To capture such heterogeneity, we interact GM approval with log GDP per capita relative to India in 1995 (column 4). The resulting coefficients in the first four rows can be interpreted as the yield gain from GM varieties in a country with an income level similar to India's. The negative coefficient on the interaction shows that richer countries gain significantly less from GM adoption.

In columns 5 and 6, we include both interactions as well as log harvested area in the regressions. The estimated coefficient on frost days declines numerically as richer countries tend to be colder. In column 5, we stick to India as the baseline country, whereas in column 6, we redefine frost days and income to be relative to the United States. The results show that in relatively poor and warm places similar to India, GM varieties substantially boost yields of all four crops. According to our estimates, maize yields would be 50 log points higher ten years after GM crops are introduced, corresponding to 64 percent. In richer, colder places similar to the United States, only GM cotton offers higher yields. GM varieties of the other three crops are nevertheless widely cultivated in the United States, as they still reduce the costs of fighting pests and weeds even if yields are unchanged.

B. *Harvested Area and Global Demand*

While no acceleration is visible in Figure 2, one might still wonder whether the harvested area of the four crops would have expanded at the same pace in the absence of genetic modification. We investigate the question further in this section, as it is important for understanding the impact of GM crops. It would, for instance, add to the economic gains if the increase in harvested area reflects that GM varieties profitably replace crops of which no GM varieties are available.

When we allow for separate effects on the harvested area of the four crops, we find that only soybean cultivation increases after GM adoption (Figure 3, Panel A). It follows that the adoption of GM varieties in general does not increase harvested area—if that had been the case, we would have seen effects on all four crops. GM soybean may be different, however, as soybean cultivation seems to have accelerated somewhat after GM adoption. Yet the steep pre-trend makes us cautious to interpret the acceleration without further consideration of the factors behind the expansion of soy production.

Soybean is mainly used for animal feed and vegetable oil, and increased consumption of meat, eggs, and cooking oil in emerging markets—particularly in China—has caused soybean demand to soar (Brown 2012). Besides potentially GM crops, there are several reasons why increased global demand mainly has been met by increased soybean production in the GM-adopting countries in the Americas. First, soy is more profitable in sparsely populated areas because it requires little labor (Bustos, Caprettini, and Ponticelli 2016; Gale, Valdes, and Ash 2019). Second, conventional breeding of soy has since the 1960s resulted in varieties adapted to new climates and soils. Soybean cultivation has, as a consequence, expanded into both colder regions in North America (Gale, Valdes, and Ash 2019) and tropical ones in South America (Alves, Boddey, and Urquiaga 2003). Third, with the new conventional varieties, soybean cultivation could easily be expanded in much of South America where the climate permits a double-cropping system with soy being the second crop. Fourth, Chinese tariffs have since the Chinese ascension to the WTO in 2001 favored soybean import (3 percent tariff) over cereal import (65 percent tariff). China has consequently gone from importing no soy in 1995 to importing about one-third of the total global production (Gale, Valdes, and Ash 2019; see also Figure 3, panel B). Domestic production has, by contrast, stagnated (panel C). The Chinese WTO membership and the boom in Chinese soy imports coincided with South American countries starting to cultivate GM soy. The Chinese demand for soybean imports is not entirely unrelated to genetic modification, however, as China's ban on GM soybean cultivation gives producers in the Americas a competitive advantage. Regulatory arbitrage may consequently have contributed to the slight acceleration of soybean cultivation in the GM-adopting countries visible in panel A of Figure 3.

We have so far only estimated effects on harvested area relative to other crops. Moreover, harvested area counts a piece of land twice if it yields two harvests per year. The increase in harvested area can consequently reflect other crops being substituted

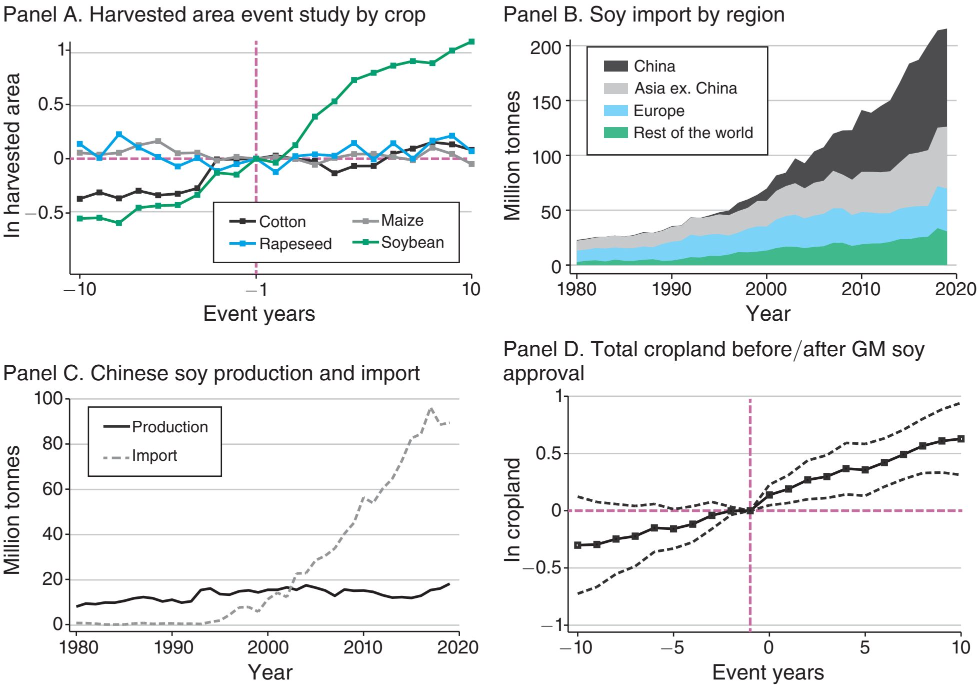


Figure 3. Trends in Soybean Production and Demand

Notes: Panel A: event study based on a version of equation (1) with heterogeneous treatment effects. We report confidence bands in online Appendix Figure A.11 but omit them here for readability. See the notes to Figure 2 for further details. Panels B and C use data from FAOSTAT. Panel D: event study at the country level using approval of GM soy as the event and total cropland as outcome. We aggregate to the country level using the methodology of Gollin, Hansen, and Wingender (2021).

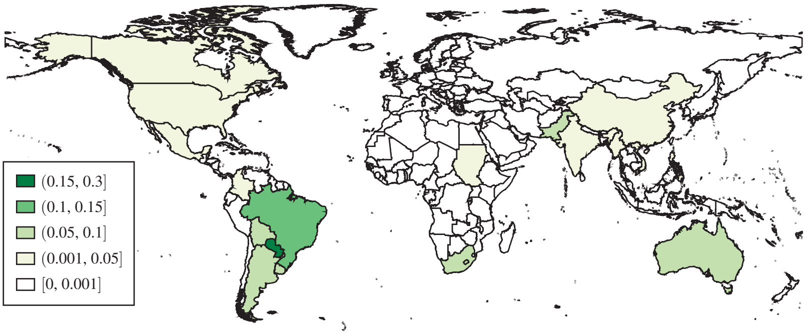
for soy, increased double cropping, or a genuine expansion of cropland into previously uncultivated areas. Only the latter causes deforestation and loss of habitat. In panel D of Figure 3, therefore, we report a country-level difference-in-difference event study with total cropland as the outcome and treatment being years since the first harvest of GM soy interacted with soy's share in agricultural output. The result shows that cropland expands after GM soy is introduced, but, again, the expansion is statistically indistinguishable from the pre-trend.

The observed expansions of soybean cultivation and total cropland following GM adoption are too confounded by other trends to draw strong conclusions. Still, we find that GM cotton, maize, and rapeseed have no effect on harvested area. Previous episodes of agricultural innovation have even reduced land use (Byerlee, Stevenson, and Villoria 2014a, b; Gollin, Hansen, and Wingender 2021), so it appears likely that GM soy would not have drawn additional land into agriculture in the absence of Chinese demand.

C. *Realized and Potential Gains*

How important are GM varieties for total agricultural production? Panel A of Figure 4 shows realized production gains for 2019 as defined by equation (6).

Panel A. Realized gains



Panel B. Counterfactual gains

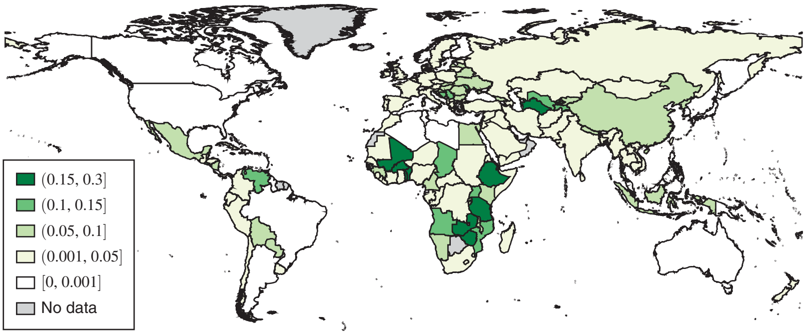


Figure 4. Estimated Realized and Counterfactual Gains Ten Years after GM Adoption

Notes: Panel A shows how many percent higher crop production is in 2019 than it would have been had GM crops not been adopted. The calculation is based on equation (6). Panel B shows how much higher crop production would have been in 2019 had countries with GM bans counterfactually approved GM crops before 2009. The calculations are based on equation (4). Some countries have both realized and counterfactual gains because they approve some GM crops but not others. A few countries do not have the required GDP data for the calculation in panel B. To complete the map, we assign to them a GDP per capita level of a reasonable comparison country (e.g., Sudan in the case of Somalia). We only use these assumed values for the map. We omit countries with missing data from the calculations reported in the main text.

Aggregate yields in Paraguay have increased the most following GM adoption: about 19 percent. The maize-soybean double-cropping system that is widespread in Paraguay and elsewhere in South America explains the comparatively large gains in the region. Turning to the individual crops, we find that without genetic modification, the world would have produced 33 percent less cotton, 7 percent less maize, 2 percent less rapeseed, and 5 percent less soybean in 2019 (assuming that other inputs stayed the same). Combined, the implied output gains amounted to US$39 billion in current US producer prices. Alternatively, without genetic modification, we would have needed to expand global cropland by 3.4 percent (48 million hectares) to produce the same amount of output.[7]

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[7] We assume that land use is reduced to keep production fixed in each country. Within countries, we assume that the least productive land is abandoned first. We use the estimated coefficient on harvested area in Table 1 to calculate how much average yields rise when the least productive land is taken out of production. See Gollin, Hansen, and

How costly are GM bans? To find out, we calculate by how much yields would have been higher in 2019 had all bans on cultivation been lifted ten years before.[8] The result, depicted in panel B of Figure 4, shows that GM bans mainly hurt Sub-Saharan Africa. Not only because the region is relatively poor and warm, but also because it grows substantial amounts of cotton and maize. Moreover, Sub-Saharan Africa and other low-income countries have large agricultural sectors, so the cost of GM bans relative to their total economies would be disproportionately larger than in richer countries.

At the global level, we find that cost of GM bans in terms of lost output was about US$69 billion in 2019. As our estimated realized gain was $39 billion, it follows that only one-third of the potential of the currently available GM varieties has been realized. The one-third is an average for the four crops, however. Without bans, the world would have produced 13 percent more cotton, 28 percent more maize, 26 percent more rapeseed, and 4 percent more soybean in 2019. A comparison to the realized gains reported above shows that while most of GM cotton's potential has been realized, the opposite is true for GM maize. The difference comes down to regulation. Cotton is not used for feed or food, and growers can freely export GM cotton fibers to other countries without special permission.

V. Concluding Remarks

The economic potential of genetic modification is larger than the potential of the currently cultivated pest-tolerant and herbicide-resistant GM varieties we study in this paper. GM varieties of wheat, rice, and other important crops might be commercialized in the future, as may GM varieties with different genetic traits, such as drought resilience or increased nutritional value (Parisi, Tillie, and Rodríguez-Cerezo 2016; Qaim 2020). Developing new GM varieties, and approving currently banned existing ones, may also alleviate concerns about low crop diversity in GM-adopting countries insofar as the low diversity reflects regulatory arbitrage leading to specialization.

Although our study mainly deals with economic aspects of GM technology, the fact that the associated yield gains can be land saving also implies environmental benefits. Reduced conversion of natural land to grow crops prevents both biodiversity losses and greenhouse gas emissions. Kovak, Blaustein-Rejto, and Qaim (2022) calculate that were Europe to adopt GM crops, emissions could be cut by 33 million tonnes per year, most of which would come from reduced land use. Our results suggest that the scope for reducing emissions this way is even greater in developing countries, where the yield advantage of GM crops is larger. So although valid concerns about their environmental impact remain, our study reinforces the current scientific consensus that GM crops are net positive for the environment.

Wingender (2021) for the theoretical background for this calculation. Assuming that land with average productivity is taken out of production instead only marginally decreases our estimate.

[8] We include all countries with the required data, not just the balanced sample we use to estimate the parameters.

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