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Diffusion of Genetically Modified Crop Technology

Charles de Grazia, Nicholas E. Rada, Gregory Graff

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Charles de Grazia, École de Management Léonard de Vinci♣
Paris, France

Nicholas E. Rada
Barcelona, Spain

Gregory Graff, Colorado State University
Fort Collins, Colorado

Abstract

Technology diffusion is central to the process of innovation, as new products or processes must be adopted for them to make meaningful contributions to societal welfare or economic growth. We focus here on the global diffusion of technology that has the potential to improve food insecurity and address challenges posed by climatic effects, genetically modified (GM) crops. We adopt a variety of sources and methods to demonstrate the reach and timing of genetically modified crop technology diffusion worldwide, relying primarily on national regulatory approval information. Specifically, we depict the international adoption of genetically modified crop technology over time and assess the rate at which GM cotton, maize, and soybeans have been adopted within countries. In addition, we examine two case studies that assess an underused information source—trademark data—to determine whether they provide an alternative measure of diffusion. The case studies focus on two different contexts: established branded technologies and nascent technologies. In addition to significant overlap with regulatory approval data for established branded technologies, trademarks appear to provide an indicator of pre-commercialization in countries where regulatory approval coverage can expand. We end with guidance on when trademarks may serve as an indicator of international technology diffusion.

Keywords: Technology diffusion, Agricultural innovation, Genetically modified crops, Trademarks, Diffusion measurement
JEL: O3, Q16, Q18

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♣ Corresponding author: cadegrazia@gmail.com.

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1 Motivation

How technology diffuses over time and space and the economic benefits that accompany it has long been a focus of economic research. Early studies into the diffusion of technology identified the importance of diffusing improved farm technologies (e.g., superior livestock breeds and crop varieties) for lifting productivity (Sauer 1969; Hayami and Ruttan 1971). The diffusion of hybrid corn technology was at the center of Zvi Griliches' (1957) seminal study exploring the economics of technological change. More recent studies have analyzed implications of technology diffusion for the general economy (Kalyani et al. 2025) and specific to agriculture (Moscona and Sastry 2025).

In the present working paper we analyze the global diffusion of genetically modified (GM) crops, a controversial technology that has transformed agriculture. The widespread diffusion of GM crops has the potential to mitigate food insecurity and address challenges posed by climatic effects. Genetically modified crops differ from traditional crops in that they have new genes coded for desirable traits inserted into the plant's DNA (Qaim 2009). These GM technologies include herbicide-tolerant and insect-resistant field crops, and evidence suggests that their adoption results in higher farm production and profit (Klumper and Qaim 2014). In their meta-analysis of 147 studies on the topic, Klumper and Qaim find that, on average, GM crops had 21% higher yields (due to effective pest control), 37% reduced pesticide usage, 39% lower total costs, and 69% higher farm profits despite the relatively more expensive GM crop seed.

Our present purpose is twofold. First, we use a variety of sources and methods to demonstrate the reach and timing of genetically modified crop technology diffusion worldwide. Specifically, we track how quickly three prominent GM crops (cotton, maize, soybeans) diffused across and within countries using regulatory approval and harvested area data for the cultivation of GM events in developing and developed countries since the early 1990s.[1] Studies that highlight technological diffusion tend to analyze adoption 'S-curves' (Griliches 1975; Hall 2004; Smyth 2014; Alston et al. 2023). These curves reflect the adoption of a given technology, which in agriculture, begins slowly as farmers encounter new developments and assess their usefulness, then rapidly accelerates as the technology is incorporated into more farm production systems, and tapers off as the technology nears full adoption among farms (Alston et al. 2023). Importantly, as pointed out by Hayami and Ruttan (1971, p. 258), these S-curves account for local adaptation, a critical aspect of international agricultural technology diffusion.

Our second purpose leverages GM regulatory approval data to evaluate a new approach for assessing global technology diffusion using trademark data. Studies of technology diffusion tend to focus on knowledge diffusion using patent data (Ji et al. 2019; Kalyani et al. 2025) or entry into foreign markets using proprietary data (Cockburn et al. 2016). Trademarks, however, are a commonly used form of intellectual property that protect brand names from imitation (Fink et al., 2022) and should in principle be closely aligned, if not intertwined, with a company's commercial activities. A recent study of diffusion using trademark data (von Graevenitz et al. 2022) exploits this relationship and the legal requirements that mandate use of the trademark in commerce to analyze regional technology diffusion within the

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[1] A GM event is defined as "the insertion of DNA into the plant genome as a result of a single transformation process" (Pilacinski et al. 2011).

United States from 1981 to 2012. Beyond the U.S. context, less is known about the use of trademarks as a measure of diffusion, particularly as a measure of international knowledge and technology flows.

To address this gap in the literature, our initial case study uses trademark filings for established GM brands[2] that are known to have a global reach. In particular, we track a set of first-generation *Roundup Ready* products across countries, analyze the similarities (differences) between the two diffusion indicators, and comment on what can be learned from them. We find that trademarks serve as a meaningful measure of commercial intent in most jurisdictions across the globe,[3] but can only be extended to a measure of commercialization under certain assumptions. We argue that the use of trademarks as a measure of commercialization and therefore diffusion is most appropriate in countries with stronger trademark use requirements (e.g., Mexico, the Philippines, and the United States). We further test the robustness of findings by extending the assessment to other prominent GM crop brands, including *Bollgard*, *LibertyLink*, and *Widestrike* in Appendix C.

The next case study focuses on the diffusion of frontier genome-editing (GE) technologies (e.g., Clustered Regularly Interspaced Short Palindromic Repeats, or CRISPR) that do not involve the insertion of foreign DNA to achieve the desired traits (e.g., drought resistance), precipitating a debate among governmental entities and other stakeholders over how GE crops should be regulated. While several countries and supranational organizations (e.g. the European Union) regulate GE crops in the same manner as GM crops, others, including the United States and Argentina, have less stringent commercialization restrictions on crops developed through gene editing (Tuncel et al. 2023). Like the regulatory debate on GM crops, the policy landscape of GE crops is uncertain and evolving. As governments and supranational organizations loosen restrictions on GE crops, however, new GE crop innovations may be less likely to appear in the regulatory approval data than GM crops that are developed through the introduction of foreign genes (e.g., glyphosate-tolerant seeds). Our objective is therefore to understand the degree to which GE crops are captured by regulatory approval data, and to analyze how frontier firms in the GE crop product space use trademark registrations to protect their brands. We link data from non-regulation or regulation exemption inquiries for firms developing genome-edited crops to global trademark data, presenting a partial view of the nascent technology's global diffusion as well as the advantages (disadvantages) of using trademark registration data to track the diffusion of frontier technologies.

2 Brief review of economic factors affecting technology diffusion

From an economics perspective, several factors influence the decision to adopt a specific technology, including demand (benefits), adoption costs, information and uncertainty, and the market and regulatory environment (Hall and Helmers 2024). Below we briefly discuss how these factors apply to our GM crop technology context and how they might impact the differential spread of these

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[2] According to the American Marketing Association (AMA), a brand, "is any distinctive feature like a name, term, design, or symbol that identifies goods or services," (https://www.ama.org/topics/brand-and-branding/. Trademarks are a form of intellectual property that protects others, including firms, from using these identifying brands.

[3] Although the prior literature on trademarks (Castaldi 2020) notes that many countries allow for a grace period before the 'use in commerce' requirement comes into effect, there is insufficient specificity to assess the applicability of a trademark-based diffusion measure on a country-by-country basis.

technologies across countries and regions. For a more in-depth discussion of the specific factors influencing international GM crop diffusion, see Falck-Zepeda (2026).

Various economic factors influence farm-level technological adoption decisions. Demand for GM crop technology by farmers is derived from the expected benefits relative to the existing available technology (e.g., traditional seeds). Location is especially important for agricultural technology adoption as local adaptation is required to account for the varied physical, biological, and socioeconomic environments in which farmers operate (Hayami and Ruttan 1971). Adoption of GM crop technology is driven by expected higher profitability (Klumper and Qaim 2014), which is affected by the local severity of such factors as weed or pest infestations, drought, infrastructural deficiencies limited access, or downstream consumer preferences. If expected costs (e.g. GM seed costs, learning and training costs, acquisition costs) outweigh expected benefits (e.g., higher yields and profit), farmers will choose to postpone adopting a given technology or not adopt at all.

The prices charged to farmers for purchase of GM seed are typically higher than for traditional seed, which some attribute to intellectual property rights (Qaim and de Janvry 2003; Basu and Qaim 2007). GM crop innovators --- typically large, private agricultural corporations[4] --- invested an average of $136 million in research to develop and commercialize a given GM crop between 2008 and 2012, and invested a slightly lower average of $115 million between 2017 and 2022 (AgbioInvestor 2022). These companies often seek intellectual property protection (e.g., patents and trademarks) to appropriate returns on this investment (Graff et al. 2003; Jefferson et al. 2015). Patent rights act as a partial solution to innovation-related market failures (Arrow 1962) but by creating time-delimited exclusive control over the claimed technology that solution leads to static inefficiency and to higher prices. Trademark rights act as a solution to the 'market for lemons' (Akerlof 1978) by serving as a source identifier that signals a product is of a certain and consistent quality (Greenhalgh and Rogers 2012), thereby reducing search costs but also allowing the seller to charge a higher price. To wit, Qaim and de Janvry (2003) find that higher prices for GM crops through stronger intellectual property protection act as a barrier to adoption of *Bt* (*Bacillus thuringiensis*) cotton in Argentina, but the observed timeframe is limited to the first three years following local product introduction. Our analysis below, using a more robust time series spanning 20+ years, suggests the benefits of Bt cotton adoption in Argentina outweighed that and any other barrier to on-farm adoption.

The regulatory and institutional environment surrounding GM crops also plays a key role in their diffusion. Commercializing a product in most countries requires prior regulatory approval from one or more local government agencies. The degree of regulatory oversight likely impacts the overall speed of diffusion. Strict regulatory requirements may raise the (expected) costs of regulatory approval, delaying the introduction of the technology into the jurisdiction by the innovator (Cockburn et al. 2016). Cultural attitudes towards food and GM crops may simultaneously impact demand for GM crops and the regulatory requirements for market entry --- as is the case in the European Union where the perception of food has deep cultural roots and is less utilitarian than in other countries (Runge et al. 2001).[5] The European Union, together with several other countries, is commonly viewed as adhering to the precautionary principle and pursuing more risk-averse health, safety, and environmental policies

[4] See Fuglie et al. (2011) for more information.

[5] Other studies approach the endogeneity of GM crop regulation from a political economy perspective (Graff et al. 2009).

than the United States (Vogel 2003).[6] Notably, these risk preferences and cultural attitudes towards genetically modified crops have led the EU to ban the cultivation of GM crops in most EU countries except Portugal and Spain.

Finally, we note that institutions, uncertainty, and availability of information affect the diffusion of GM crop technology. Extension services to farmers have been found to mitigate informational frictions and other uncertainties for farmers, but empirical evidence shows that their impact varies widely across projects (Anderson and Feder 2007; Kalogiannidis and Syndoukas 2024). Recent research suggests that extensions services could be improved through institutional reforms that embrace nongovernmental organizations, that adopt new information and communication technologies, and that improve knowledge, networks, and coordination skills of existing extension agents (Fuglie et al. 2020).

3 Data sources and descriptions

Our analysis of GM crop diffusion relies most heavily on the AgbioInvestor GM Monitor Approval database --- herein referred to as the Agbioinvestor approval data --- that contains global GM regulatory approval data compiled directly from governmental websites and publications.[7] We prioritized the AgbioInvestor approval data over The International Service for the Acquisition of Agri-biotech Applications, Inc. (ISAAA) data because it is more up-to-date with easier access. See Appendices A and B, respectively, for a comparison of GM crop adoption and regulatory approval information from both sources.[8]

To ensure consumer safety and prevent adverse environmental impacts, GM crops are highly regulated by countries --- or at the regional level in the case of Europe --- and in some cases are banned outright. Most jurisdictions that permit the cultivation or importation of GM crops require firms to apply for regulatory approval at one or more governmental agencies. The regulatory approval data compiled by AgbioInvestor includes detailed information on the jurisdiction (i.e., country or countries), crop, GM event, applicant, approval date, and brand name (if applicable), among other variables. For the purposes of our analysis, we focus on GM events that are given a unique identifier in the OECD BioTrack Product Database.[9] These combined data indicate diffusion of particular GM crops by tracking regulatory approvals of unique GM events across jurisdictions from 1992 to 2024.[10]

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[6] According to the Ministerial Declaration of the Third International Conference on the Protection of the North Sea (1990), the precautionary principle requires that governments, "take action to avoid potentially damaging impacts of substances that are persistent, toxic and liable to bioaccumulate even where there is no scientific evidence to prove a causal link between emissions and effects," (pg. 2, see https://www.ospar.org/site/assets/files/1239/3nsc-1990-hague_declaration.pdf). We note that other studies suggest that the relative precaution of the European Union compared to that of the United States varies across domains and over time (Wiener and Rodgers 2002).

[7] See https://gm.agbioinvestor.com/approvals-database. Version 2025V2, accessed 4 April 2025.

[8] We expand our comparison of regulatory approval datasets to include regulatory approval data from the Biosafety Clearing House and the Center for Environmental Risk Assessment (Mallah et al. 2017).

[9] See https://biotrackproductdatabase.oecd.org/.

[10] Countries/regional bodies with at least one regulatory approval in the AgbioInvestor Approval Database include Argentina, Australia, Australia & New Zealand, Bangladesh, Bolivia, Brazil, Canada, China, Colombia, Costa Rica, the European Union (EU), Ethiopia, Ghana, Honduras, India, Indonesia, Japan, Kenya, Malaysia, Mexico, Nigeria, Pakistan, Paraguay, Philippines, Russia, Singapore, South Africa, South Korea, Switzerland, Turkey, the United Kingdom (UK), the United States of America (USA), and Vietnam.

AgbioInvestor also compiles crop-level data on total cultivated area and the proportion planted to GM crops for several countries worldwide. From these data, we construct adoption S-curves for GM maize, soybeans, and cotton.

Our case studies rely on trademark data that "indicate the origin of a market offering" and are often associated with commercialization of new products (Morales et al. 2024, p. 925). Regulatory approval, on the other hand, is a necessary condition for market entry in most jurisdictions and therefore serves an intent to commercialize. As such, regulatory approval records provide a suitable empirical benchmark for assessing the accuracy of trademark data as a measure of diffusion across jurisdictions. In our two case studies, we compare regulatory data with trademark data to evaluate the overlap in these diffusion indicators across jurisdictions and comment on their applicability as diffusion indicators.

The first case study primarily employs data related to the diffusion of a single GM crop innovation: *Roundup Ready (RR)* products that were originally introduced by Monsanto (now Bayer). We query the AgbioInvestor Approval database for first-generation *Roundup Ready*-branded products. The set of queried *Roundup Ready*-branded crops includes alfalfa, canola, cotton, creeping bentgrass, maize, soybean, and wheat. We simplify our analysis by excluding from our query follow-on *Roundup Ready* products (e.g., *Roundup Ready 2* or *WideStrike III Roundup Ready Flex*).

Monsanto trademarked the phrase "Roundup Ready" in several jurisdictions to protect its product innovation---herbicide-resistant genetically modified seeds--- from imitation. Drawing on WIPO's Global Brand Database (GDB; accessed 15 July 2025), we collect the set of *Roundup Ready* trademarks associated with Monsanto. We again limit our query to first-generation *RR* products and exclude any follow-on product introductions. The Global Brand Database includes a broad geographic scope for this case study.[11]

The second case study employs data related to the diffusion of commercialized genome editing (GE) crop technology, including those crops edited with new genomic techniques such as CRISPR, in addition to more conventional genetic modification (GM) technology. First, we link a set of small agricultural biotechnology firms that have commercialized or are developing GE crops to the AgbioInvestor approval data to determine whether commercialized GE crops are included in these data and thus captured by the regulatory approval process. We then link these small agricultural biotechnology firms to the Global Brand Database at the firm level (i.e. not the product level) to determine the global reach of commercialization efforts by these firms. Finally, firms wishing to commercialize GE crops in the United States can inquire whether their GE crop is a regulated article under U.S. law or exempt from such regulation by the U.S. Department of Agriculture (USDA). These inquiries and corresponding decisions are contained in 'Am I regulated?' (AIR) data from the U.S. Department of Agriculture's Animal and Plant Health Inspection Service (APHIS) and are released publicly by the USDA. We identify all the inquiries filed by firms in our sample.

4 Technology diffusion using regulatory approval data

The countries with the most area planted to genetically modified crops are the United States, Brazil, Argentina, India, and Canada (Cheng, et al. 2024). These authors find relatively high adoption rates

[11] For a full list of countries and regional IP offices contributing data to the Global Brand Database, see https://branddb.wipo.int/en/coverage.

globally for GM cotton and soybeans (>70%) and lower adoption of maize (30%). The first country to initiate crop production with genetic modifications was the United States in 1994, followed by Canada in 1995, and Argentina, Uruguay, and Australia in 1996 (Ji, Barnett, and Chu 2019).

The technological development of GM crops is a long and difficult process. Alston et al. (2023) show that *Bt*, a protein-based pesticide, was scientifically discovered in the early 1900s and required another half century of research before *Bt* corn was commercialized in the U.S. Further, Graff, Zilberman, and Bennett (2010) find that of 560 product-quality genetic traits identified in a particular R&D process, only 5 were eventually commercialized for farmers.

4.1 Diffusion of genetically modified crops across countries

Most GM crop approvals --- defined at the event-jurisdiction-type level[12] --- were for importing as food or animal feed (Figure 1). Between 1992 and 2024, 74% of all approvals globally were specific to imported technologies, and 26% were specific to cultivated technologies.[13] Approvals for import grew rapidly from the early 2000s to 2013, then started declining after 2015 when 216 approvals were registered with authorities, the most in any year. Notably, while approvals have rebounded since the Covid years, they have not reached previous levels. Approvals for cultivation, on the other hand, also grew continuously to 2013, and also had a period of stagnant growth through 2019. However, in a departure from approvals for import, those for cultivation rebounded in 2019 to reach 59, followed by a covid downturn and revival in 2024 when there were a 1992-2024 maximum number of approvals for cultivation with 66.

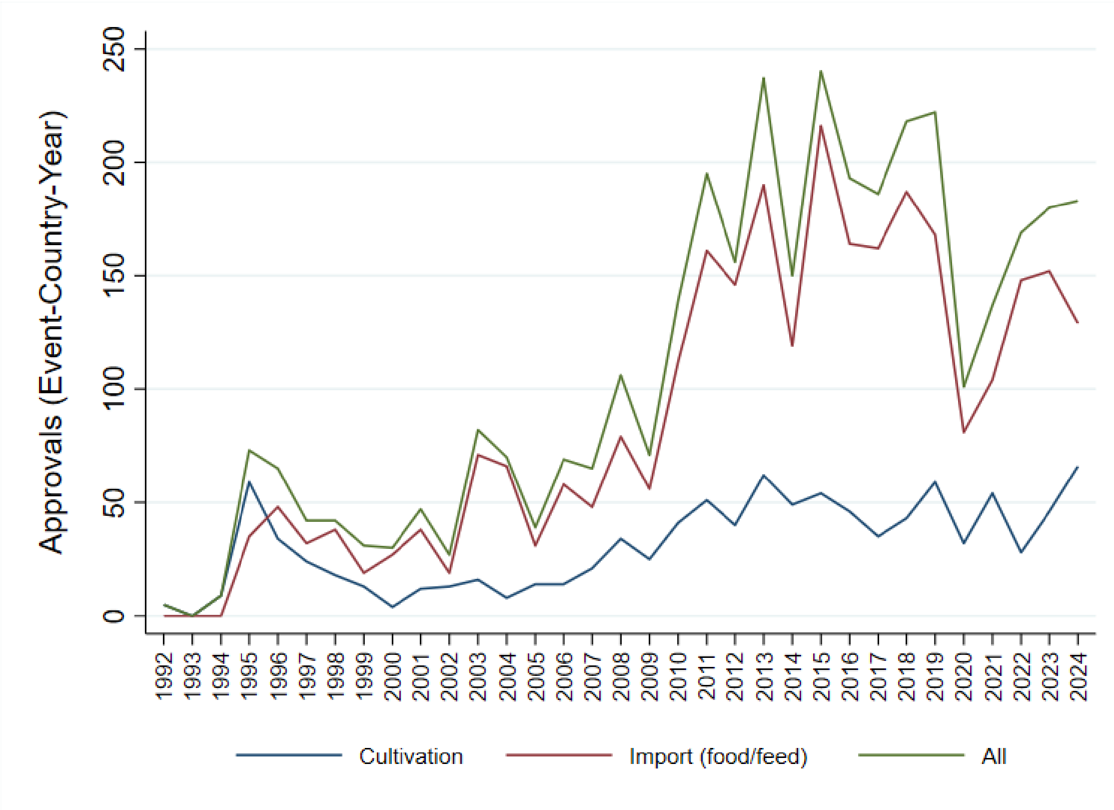
Cultivation approvals offer direct evidence of intent to introduce and diffuse a technology to agricultural end-users. Moreover, the AgbioInvestor database provides both total harvested hectares of cotton, soybean, and maize, as well as harvested hectares planted to GM varieties, thereby offering direct evidence of GM adoption across cropland.[14] Approvals for import lack such a direct connection because there is no recorded information that documents how much of the imported GM technology is used in food, feed, or fiber products. We therefore focus the remainder of our study on the diffusion of GM technologies approved for cultivation.

[12] Here the event refers to a GM event, the jurisdiction is defined as the country or supranational organization, and the type refers to the approval type (e.g. cultivation or food/feed).

[13] Please note that many GM events were approved for both cultivation and food/feed.

[14] Note that adoption rates using harvested cropland likely offers a different perspective on technology diffusion than rates using farms or seed sales. By assessing harvested cropland, the technology diffusion focus is on national aggregate grain supply. Assessing diffusion by farm adoption rates, the diffusion focus takes on a welfare and distributional perspective, where farm size becomes an important consideration, among other factors such as infrastructure and access to research and extension services. A third perspective that likely mirrors the by-cropland approach was offered by Smyth (2014) who used seed sales.

Figure 1. Unique approvals for cultivation or import of genetically modified crops, globally, 1992-2024



Source: AgbioInvestor Database.

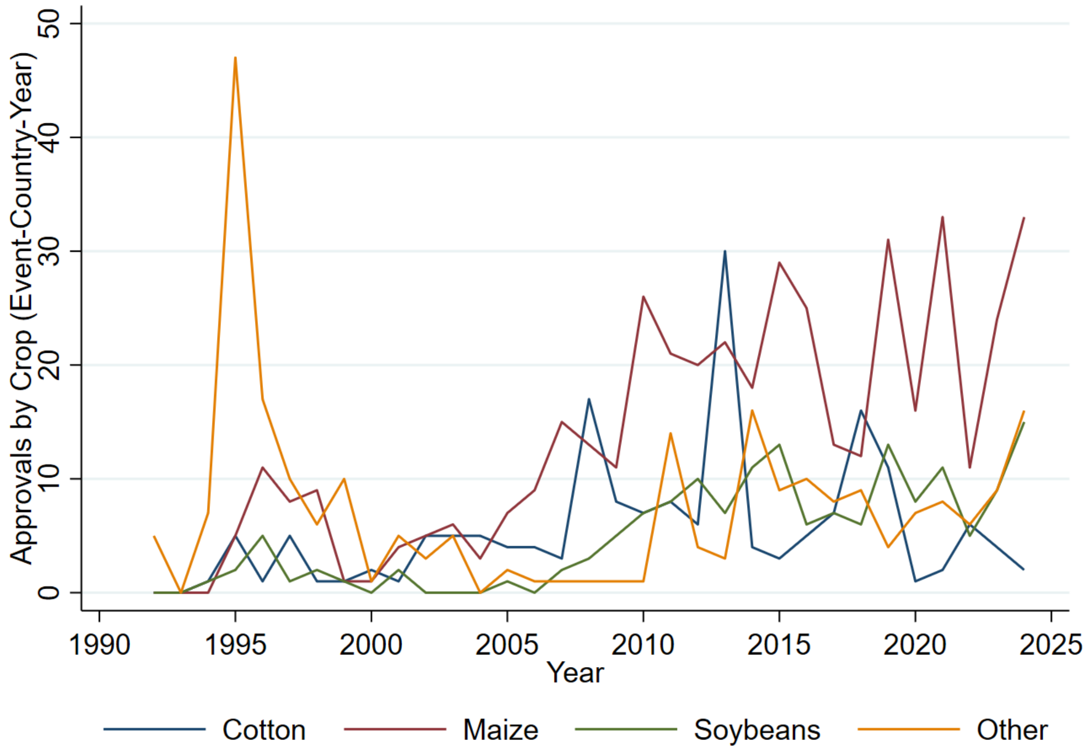
The year 1992 was the first in which a GM crop was approved, the Flavr Savr tomato with a delayed ripening trait, developed by Calgene (subsequently acquired by Monsanto) (Figure 1). As depicted by Figure 1, there were 5 cultivation approvals in 1992 (all related to the Flavr Savr tomato), followed by a spike of activity in 1995 when Argentina approved Roundup Ready soybeans, Canada approved GM canola, potatoes, tomatoes, and the aforementioned Roundup Ready soybeans, and the U.S. approved canola, cotton, maize, potatoes, (more) soybeans, squash, and (more) tomatoes.

Cotton and soybeans were first approved for cultivation in 1994, and maize was first approved in 1995 (all in the U.S.). Cultivation approvals for these crops did not start rising in the long-term until the mid-2000s (Figure 2). In fact, between 1992 and the 2008 financial crisis, 41% of all cultivation approvals were in the "Other" category,[15] while 20% of were for GM cotton, 33% for GM maize, and only 7% for GM soybeans. In the 2009-2024 period, however, GM maize approvals for cultivation jumped to 47%, GM soybeans rose to second position with a 19% share among all approvals, globally, while both GM

[15] The Other category includes alfalfa, apples, bananas, beans, camelina, canola, cantaloupe, cassava, chicory, chrysanthemum, cowpea, creeping bentgrass, eggplant, eucalyptus, flax, grapefruit, mustard, papaya, pea, pennycress, pineapple, plum, potato, rice, rose, safflower, squash, sugar beet, sugarcane, sweet orange, tobacco, tomato, and wheat.

cotton and Other GM food crops had a 16% and 17% share, respectively. Despite the 2013 spike, GM cotton approvals for cultivation have been declining since 2008. GM maize approvals for cultivation, conversely, have risen since 2000.

Figure 2. Global cultivation approvals of genetically modified crops, by crop, 1992-2024

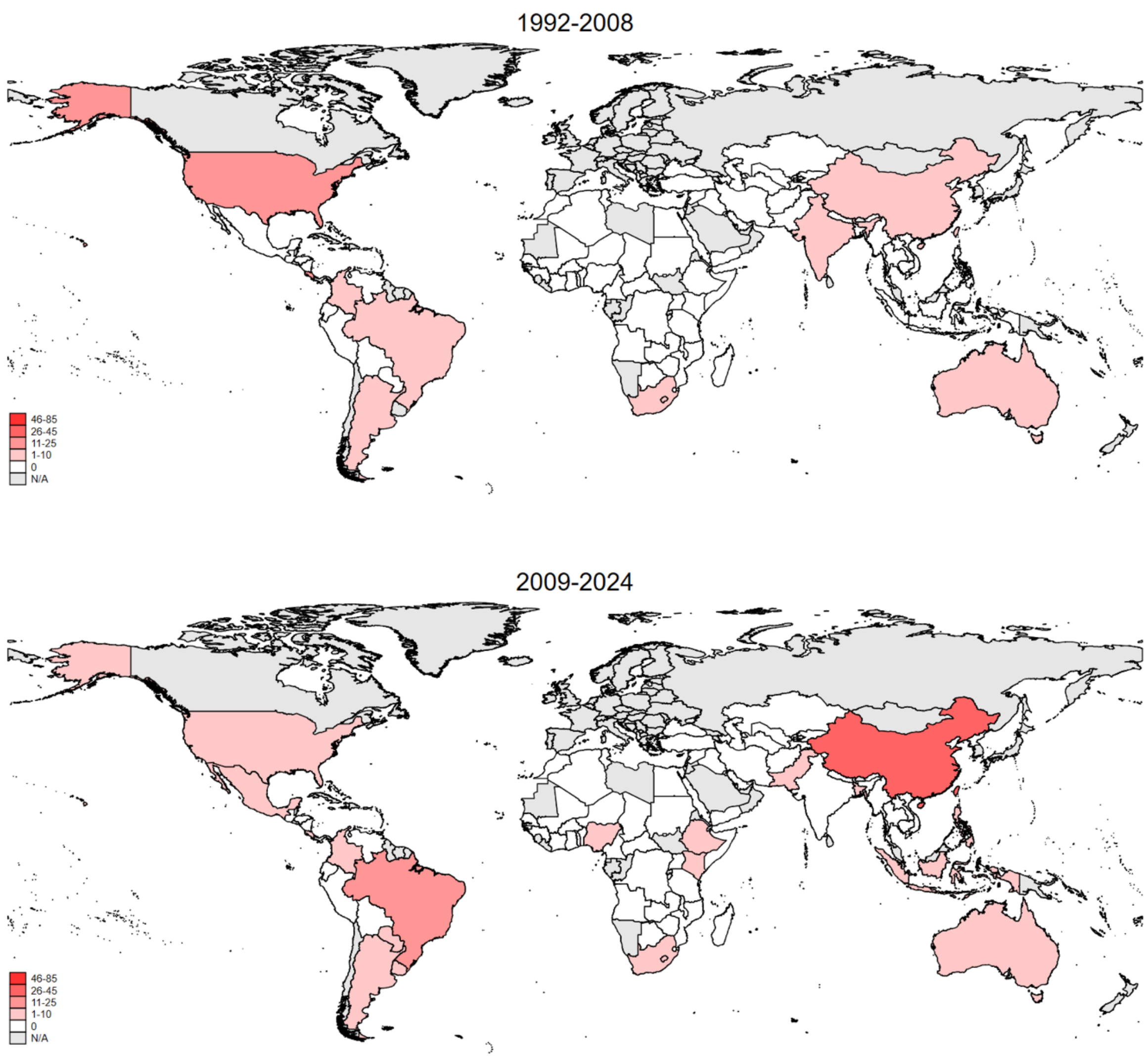


Source: AgbioInvestor Database.
Notes: Other includes alfalfa, apples, bananas, beans, camelina, canola, cantaloupe, cassava, chicory, chrysanthemum, cowpea, creeping bentgrass, eggplant, eucalyptus, flax, grapefruit, mustard, papaya, pea, pennycress, pineapple, plum, potato, rice, rose, safflower, squash, sugar beet, sugarcane, sweet orange, tobacco, tomato, and wheat.

To explore the geographic breadth of governmental GM crop approvals for cultivation, we exhibit below global maps of cultivation approvals by country for GM cotton, soybeans, and maize. To depict growth, we again bifurcate the data along the 2008 global financial crisis. The darkest red in Figures 3-5 below indicates between 46 and 85 approvals for cultivation were granted, the orange color indicates between 26 and 45 approvals were granted, the peach color between 11 and 25 approvals, the next lightest shade from 1 to 10 approvals. White indicates the country produced the crop but had zero related approvals, and gray indicates the country does not produce that crop. We rely on the Food and Agricultural Organization's FAOSTAT 2023 data (accessed 30 0ctober 2025) to delineate countries that do and do not produce a given crop.

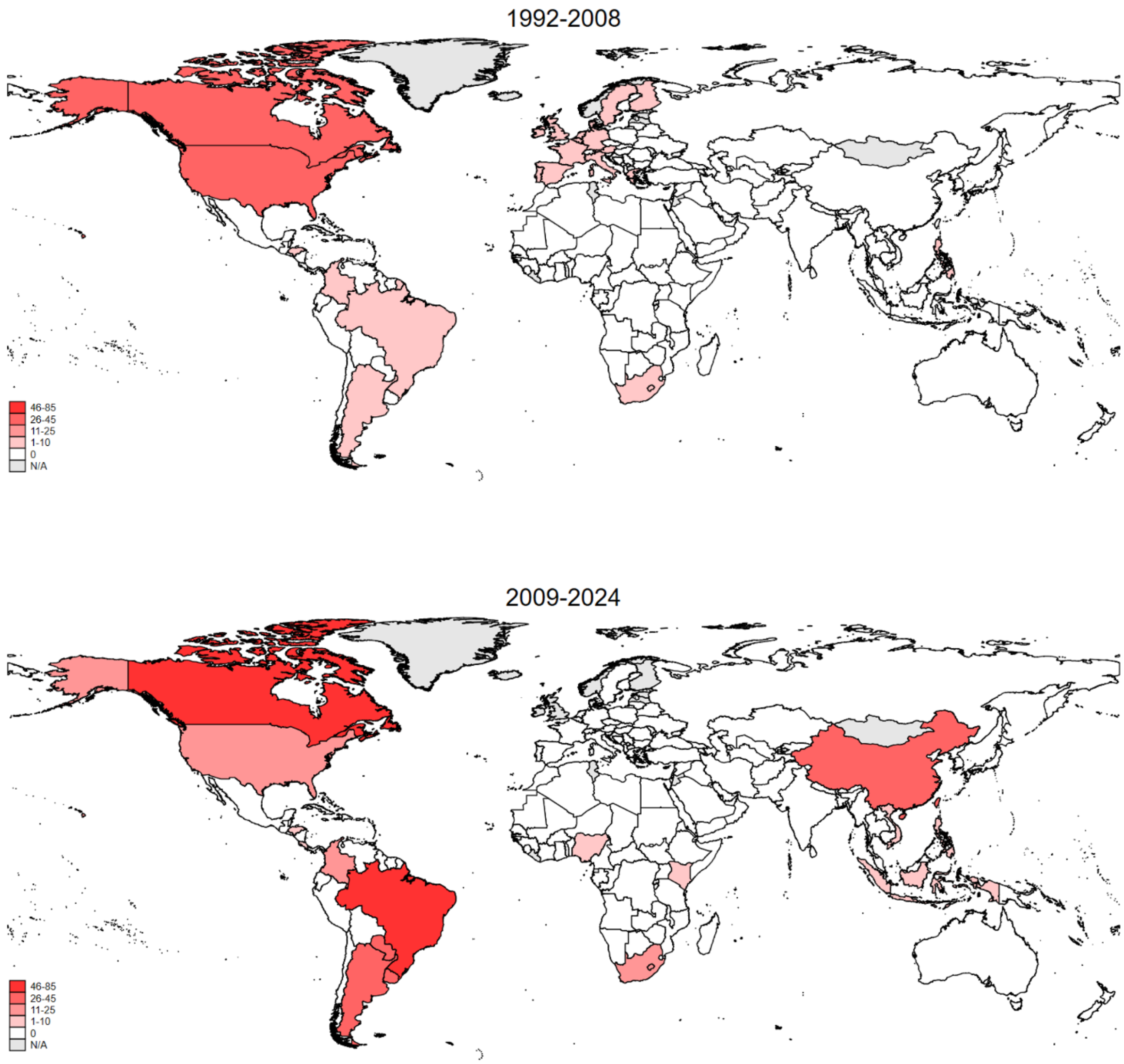
In the early period of 1992-2008, we observe the most GM cotton approvals for cultivation in the United States with 17. At this point, the U.S. was the global leader in approving GM cotton for farmers. Costa Rica in this period was in second position with 12 approvals, while Australia and South Africa were in third position with 7 approvals each. In the latter period of 2009-2024, cultivation approvals intensified in China (31 approvals, up from 3 in the prior period). Of those 31 approvals in China, the vast majority were approved in 2013. Brazil also exhibits substantial growth, with 3 GM cotton cultivation approval in the 1992-2008 period but with 23 approvals since then.

Figure 3. Genetically modified cotton approvals for cultivation, by country, 1992-2008 & 2009-2024



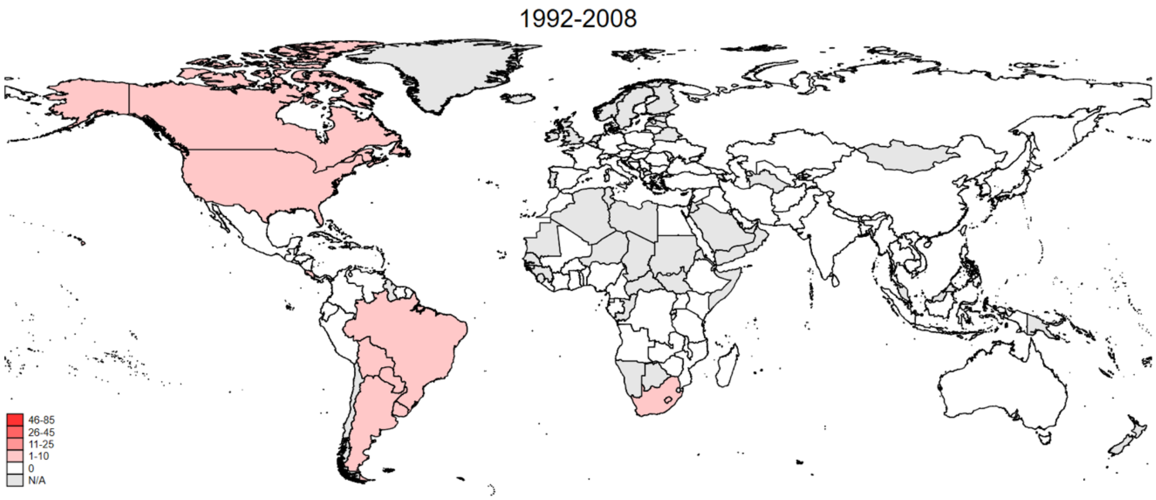
Source: AgbioInvestor Database provide cultivation approvals, and FAOSTAT 2023 data delineate countries that do (i.e., in White) and do not (i.e., in Gray) produce a given crop. FAOSTAT data were accessed in October 2025.

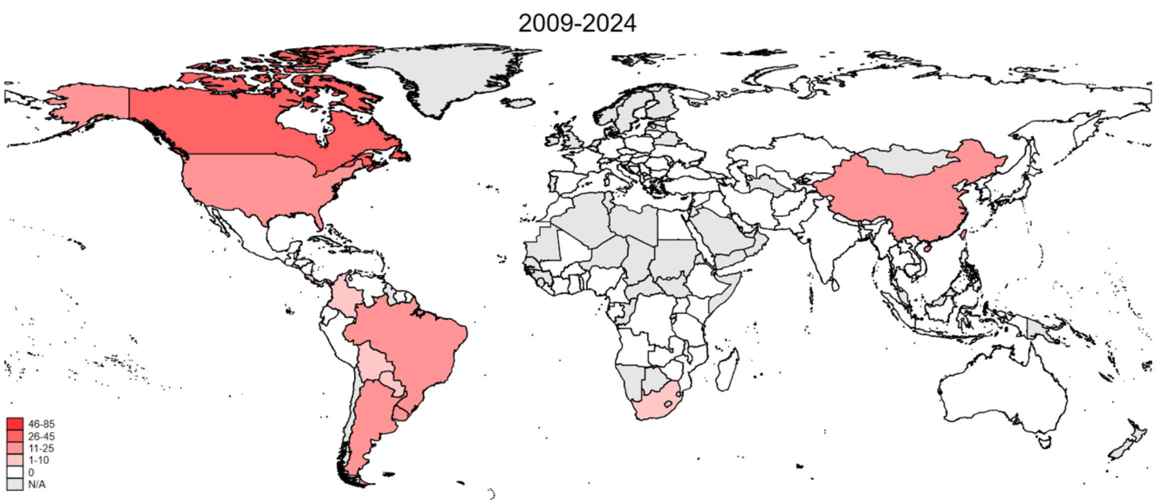
Figure 4. Genetically modified maize approvals for cultivation, by country, 1992-2008 & 2009-2024



Source: AgbioInvestor Database provide cultivation approvals, and FAOSTAT 2023 data delineate countries that do (i.e., in White) and do not (i.e., in Gray) produce a given crop. FAOSTAT data were accessed in October 2025.

Figure 5. Genetically modified soybean approvals for cultivation, by country, 1992-2008 & 2009-2024





Source: AgbioInvestor Database provide cultivation approvals, and FAOSTAT 2023 data delineate countries that do (i.e., in White) and do not (i.e., in Gray) produce a given crop. FAOSTAT data were accessed in October 2025.

Notably, the U.S. and Costa Rica experienced a decrease in approvals in this latter period with 10 and 7, respectively. We do observe growth in Africa, with a handful of countries (Ethiopia, Kenya, Nigeria, and South Africa) approving GM cotton for cultivation in small numbers. By the latter period, China emerged as the global leader of GM cotton approvals for farm cultivation. In total, we find the number of GM cotton approvals globally doubled between the two periods, from 60 in the 1992-2008 period to 120 in the 2009-2024 period.

Across the three crops, most notable in Figure 4 is the immense amount of white space reflecting countries that grow maize but have not had any cultivation approvals. In the early 1992-2008 period, most GM maize approvals were in Canada (38) and the U.S. (29). Similar to our map of GM cotton (Figure 3), most countries in this period had 10 or fewer GM maize approvals for cultivation. By the 2009-2024 period, growth in cultivation approvals is evident in China, Brazil, Uruguay, and Paraguay. For example, Brazil had only 6 GM maize approvals through 2008, but by 2024 the country had 72; China had no known approvals in the 1992-2008 period, but by 2024 it had 27. The U.S. has had fewer approvals over time, and the European Union banned GM maize for cultivation in 2003. Aggregating approvals globally, we find substantial growth of 212%, from 111 in the 1992-2008 period to 346 in the 2009-2024 period.

We observe the greatest growth in the total number of global approvals in GM soybeans. We find relatively few GM soybean approvals in the 1992-2008 period (Figure 5). The most were in the U.S. (10) with Canada in second position (3). By the 2009-2024 period, Canada had the most GM soybean cultivation approvals (29), with Brazil in second position with 25, then Argentina with 20, the U.S. with 18, Uruguay with 17, and China had 11 (all approved since 2020). Despite the slower growth of approvals in the U.S., we observe 28 total approvals there, only second behind Canada's 32. The total number of approvals for GM soybeans grew 605%, from 20 in the early period to 141 in the latter.

4.2 Diffusion of GM crops within countries

The global diffusion maps above provide insight into the countries that approved GM crop technologies for farm production, but they do not communicate how quickly these technologies diffused within a given country or from one country to the next. To this end, we assess the share of cropland in selected countries that planted these agricultural technologies. Our analysis focuses on countries in South America (Argentina, Brazil, Uruguay, Colombia, Paraguay, Bolivia), North America (U.S., Canada), Sub-Saharan Africa (Burkina Faso, South Africa), and Asia (China, India, Pakistan), as well as Australia, pending data availability. Note, AgbioInvestor provides adoption data of some GM technologies in these countries; however, coverage is incomplete, even conditional on positive production values of the focal crop (FAOSTAT 2025). For example, data on GM cotton are available in China, whereas data on GM maize and soybeans are not, possibly due to the limited domestic production of these GM crops.[16] Moreover, cultivation of GM maize in Canada from the AgbioInvestor data starts in 1998 but Smyth (2014) using national data shows that adoption started in 1996. We approximate those two years of data from Smyth in our estimates below.

In the below assessment, we develop adoption S-curves based on the share of harvested area planted to GM crop technology. The S-curves are modern versions of Griliches' (1957) assessment of hybrid corn in which he fit an S-shaped logistic trend function to the share of corn area planted to hybrid

[16] According to (Chu and Cao 2025), GM percentage of total maize planting area in China is expected to reach only 7 percent in 2025 --- below the diffusion origin (i.e., a 10 percent adoption rate).

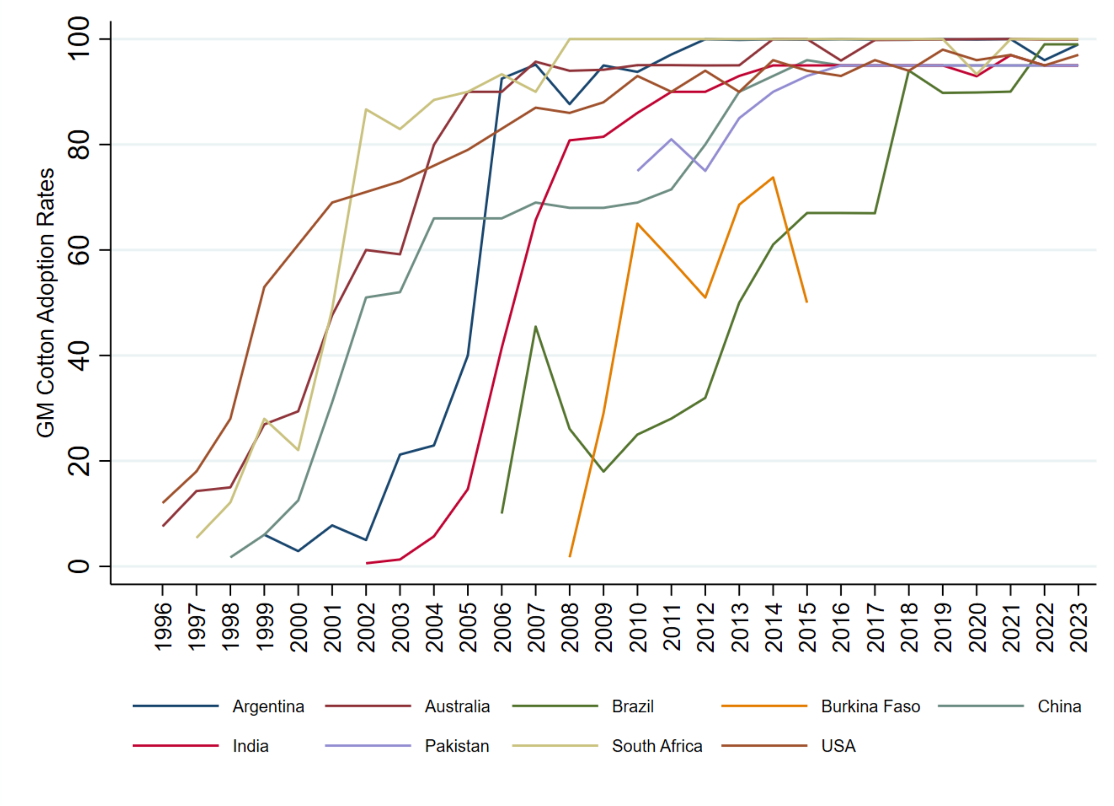
varieties (Hayami and Ruttan 1971). The logistic trend provides three parameters, an origin, slope, and ceiling. The origin is the date at which an area achieves 10% adoption and reflects an agricultural technology that has passed through the experimental stage and were widely commercially available. The slope reflects the rate of acceptance, and the ceiling is the stabilized adoption rate.

International comparison of GM crop adoption ‘S-curves’ enables two ways to evaluate technology diffusion. First, they depict how quickly a technology spreads across a country’s cropland. To assess that pace of diffusion, we adopt Griliches’ origin measure of 10% to ensure wide commercial availability to farmers, and we pair it with a 90% ceiling that reflects market saturation. Slope in our case is defined as the number of years between the origin and ceiling thresholds. Second, the adoption S-curves exhibit how quickly these technologies diffused from first cultivation in the U.S. to first cultivation in other countries. We measure this as the number of years between each country’s measure of origin.

Focusing first on GM cotton, we find that the time required to adopt and diffuse the technology within countries varied widely (Figure 6). The fastest within-country diffusion of GM cotton --- represented by the slope estimate that measures the time from 10% to 90% adoption on havested area --- occurred in Argentina (Figure 6, Table 1). Argentina first adopted GM cotton in 1999 but did not hit 10% adoption on harvested area until 2003, when we identify 21% of cultivated area included GM technology. By 2005 it reached 40%, and by 2006, 92.5% of cultivated area was planted to GM cotton – a total of 3 years from origin to ceiling. The growth of GM area in the 2005-2006 period is remarkable. AgbioInvestor documents GM cotton harvested area in Argentina rose from 120,000 hectares in 2005 to 370,000 hectares in 2006.

The longest within-country diffusion period of GM cotton was suprisingly found in the U.S. and China. The U.S. appoved herbicide tolerant cotton varieties by Calgene in 1994 and adoption started in 1996 when we find 12% of cotton harvested area was planted to GM technology. By 1999, we find 53% of U.S. cotton cropland was planted to GM technologies, yet it wasn’t until 2010 when that share reached 93%. This diffusion period aligns with what we find in Alston et al.’s (2023) figure 3 of GM cotton’s adoption by U.S. farms. In total, it took 14 years for U.S. cultivated area of GM cotton to achieve a 90% share. China has the second sloweset adoption of our sample. In 2000, China adopted GM cotton on at least 10% of total cotton cropland, which rose to 31% in 2001, 51% in 2002, and 66% in 2004. Following this period of rapid adoption, there is a period of little to no further adoption in 2004-2010 when GM cotton’s share rose only to 69%. Adoption soon accelerated, such that 90% was planted to GM technology by 2013, 13 years after the origin threshold was achieved.

Figure 6. Adoption rates of GM cotton in selected countries, harvested area, 1996-2023



Source: AgbioInvestor Database.

Brazil's adoption of GM cotton shows substantial variation, with adoption starting in 2006 at 10%, rising to 45% in 2007 but dipping down to 18% by 2009, then rising again rather rapidly to 61% by 2014 and 94% by 2018. Burkina Faso rapidly adopted GM cotton starting in 2008, but cotton ginning machines extracted less lint from harvested GM cotton bolls than from conventional bolls, leading to disadoption.[17] According to Dowd-Uribe and Schnurr (2016), Burkina Faso's cotton companies planned to reduce availability of the GM (Bt) cottonseed gradually from from 2015 to 2017, transitioning back to non-GM, conventional cottonseed by 2018. Pakistan shows nearly 80% adoption in 2010, its first year of data availability from any database.

Figure 6 and Table 1 can also provide insight regarding how quickly GM cotton technologies diffused over countries' first-use in cultivation. In our case, we focus on the year in which each country achieved 10% GM share of cotton harvested area. GM cotton was first cultivated in the U.S. and Australia in 1996, with the U.S. achieving 10% GM share in 1996 and Australia in 1997, a one-year lag. While the U.S. cultivation in 1996 is expected, given that the technology was developed there first, the rapid diffusion to Australian farmers is interesting. One the one hand, it is somewhat surprising given that most agricultural technologies require adaptation to local environments, thus one might not expect such quick diffusion across countries. Yet, on the other, Australia had less strict, voluntary regulatory approval standards until 2000, which accelerated early diffusion. South Africa achieved a 10% GM

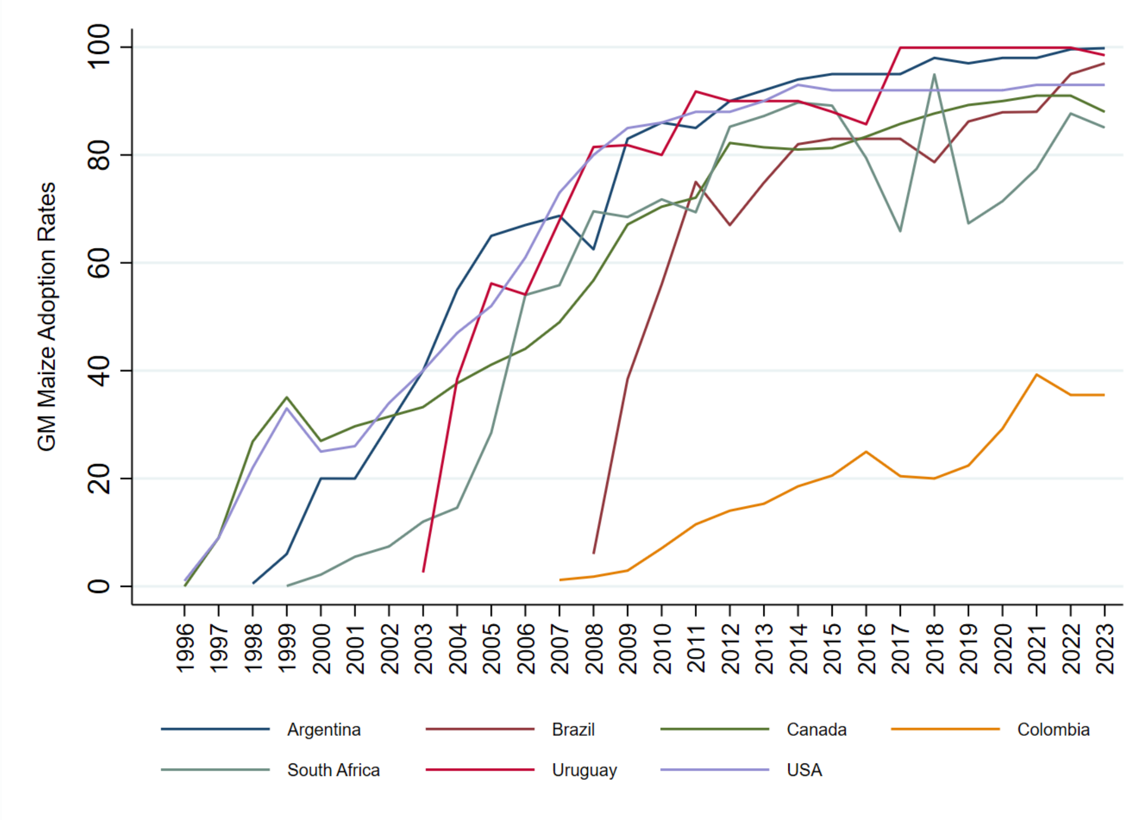
[17] See: https://source.colostate.edu/how-power-shaped-the-success-story-of-genetically-modified-cotton-in-burkina-faso/.

cotton share in 1998, and China in 2000, lags of two and four years. Longer lags are observed in Argentina (7 years), India (9 years), and Brazil (10 years) had the longest among countries in our sample.

Adoption curve slopes for GM maize are less steep than those observed for GM cotton (Figure 7, Table 1). Like GM cotton, the U.S. was the first country to adopt GM maize for cultivation in 1996 as shown in Figure 7, when 1% of all maize cultivated area was planted with the GM technology. The U.S. achieved 10% adoption in 1998 and 90% adoption in 2013, 15 years later. Longer, flatter adoption curves for GM maize than seen in GM cotton are also observed in Canada (22 years), South Africa (15 years), Brazil (13 years), and Argentina (12 years) (Table 1). Only Uruguay stands alone in adopting GM maize to at least 90% of its total maize cropland in under a decade (Figure 7, Table 1).

Transitioning to the diffusion from the U.S. to other countries' first use in cultivation, we find adoption lags of GM maize diffused from the U.S. and Canada in 1998 to Argentina in 2000 and to South Africa in 2003 and Uruguay in 2004. In our sample there is then a pause until 2009 when Brazil achieved 10% GM maize adoption, and 2011 when Colombia also achieved initial market availability. It total, the GM maize adoption lag from 10% of total harvested area achieved in the U.S. to 10% in Colombia was 13 years.

Figure 7. Adoption rates of GM maize in selected countries, harvested area, 1996-2023

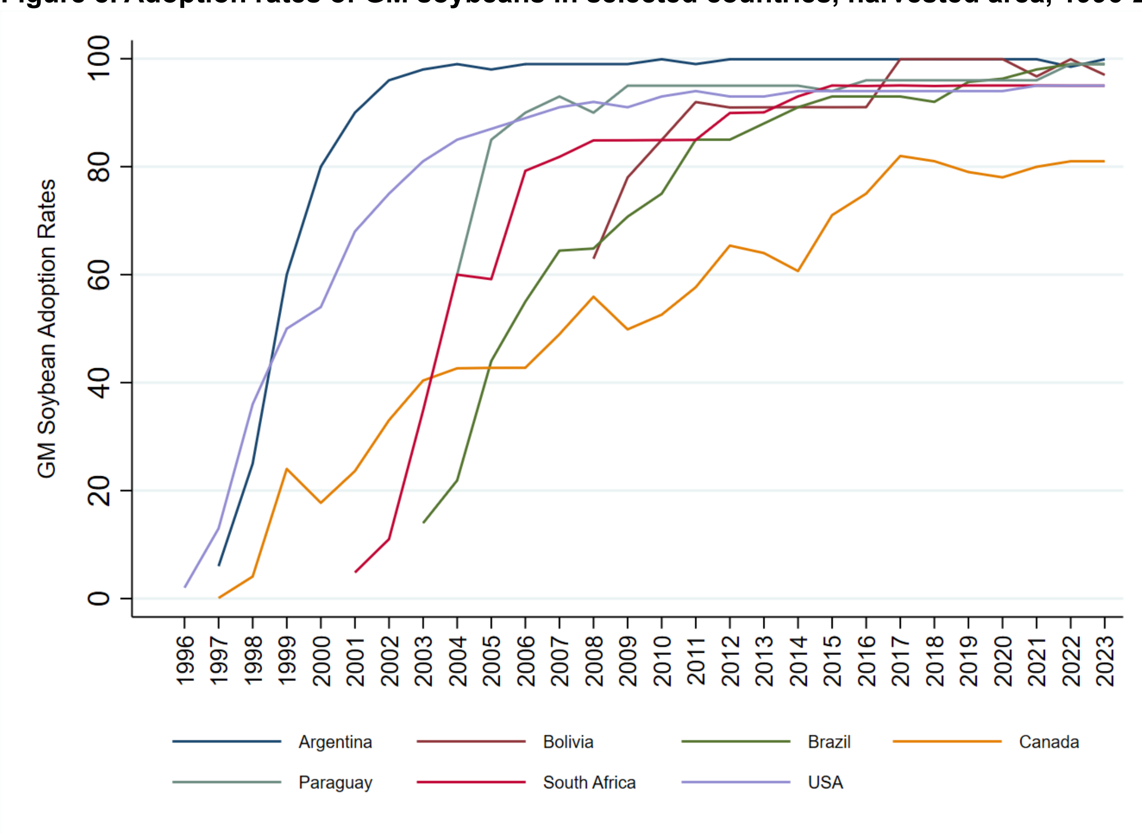


Source: Authors' estimates using AgbioInvestor database and Smyth (2014).

Figure 8 below presents the adoption S-curves for the available GM soybean data, which present both relatively rapid and slow adoption curve slopes, ranging from 3 years in Argentina to 11 years in Brazil and South Africa (Table 1). On the relatively rapid side, Argentina's diffusion of GM soybean technology started at 6% in 1997, and then jumped to 25% in 1998, 60% in 1999, 80% in 2000, and to 90% by 2001. The 3 years between origin and ceiling represents the fastest diffusion of any GM crop technology within any country in our sample. Conversely, Canada shows the relatively slowest diffusion, with 0.1% of total cropland planted to GM soybeans in 1997, 4.1% in 1998 and 24% in 1999. But then the pace of adoption slows and never exceeds 82% in any year.

Paraguay and Bolivia in Figure 8 present similar within-country diffusion trends. Both countries' first data point is well into their adoption process: Paraguay's data starts in 2004 with 60% adoption, while Bolivia starts in 2008 with 63% adoption. Bolivia cultivated over 90% of its soybean cropland to GM by 2011, only three years after entering our data sample. Paraguay, reach 90% diffusion in 2006, just 2 years after its first adoption data point.

Figure 8. Adoption rates of GM soybeans in selected countries, harvested area, 1996-2023



Source: AgbioInvestor Database.

Analyzing the diffusion lag across first use in cultivation, we start with the U.S.'s 10% share achieved in 1997. One year later Argentina achieves 10% adoption, and two years later Canada achieves it, followed by South Africa in 2002 and Brazil in 2003. As briefed in Section 2 and discussed in detail by Falck-Zepeda (2026), crop-specific factors contributing to adoption lags across countries span a range of supply- and demand-side considerations, including affordability, the regulatory and institutional environment (notably intellectual property regimes), observability and awareness, and infrastructure.

Table 1. Adoption origins, slopes, and ceilings for selected countries, by GM crop, 1996-2023

	Argentina	Australia	Brazil	Canada	China	Colombia	India	South Africa	Uruguay	USA
Maize										
origin year	2000	-	2009	1998	-	2011	-	2003	2004	1998
slope	12	-	13	22	-	n/a	-	15	7	15
ceiling year	2012	-	2022	2020	-	n/a	-	2018	2011	2013
Soybeans										
origin year	1998	-	2003	1999	-	-	-	2002	-	1997
slope	3	-	11	n/a	-	-	-	11	-	10
ceiling year	2001	-	2014	n/a	-	-	-	2013	-	2007
Cotton										
origin year	2003	1997	2006	-	2000	-	2005	1998	-	1996
slope	3	8	12	-	13	-	6	7	-	14
ceiling year	2006	2005	2018	-	2013	-	2011	2005	-	2010

Notes: Table 1 results rely on both AgbioInvestor and ISAAA databases, using the earliest and latest data from each to create the rates. Pakistan, Bolivia, Paraguay, and Burkina Faso are excluded from the table due to an insufficient time-series dimension of the data. Origin year is the year at which GM harvested area was equal to or greater than 10% of the total harvested area for that crop. Ceiling year is the year at which GM harvested area was equal to or greater than 90% of total harvested area for that crop. Slope is defined as the difference between origin year and ceiling year. Areas with " - "' have no GM data for that crop and country.

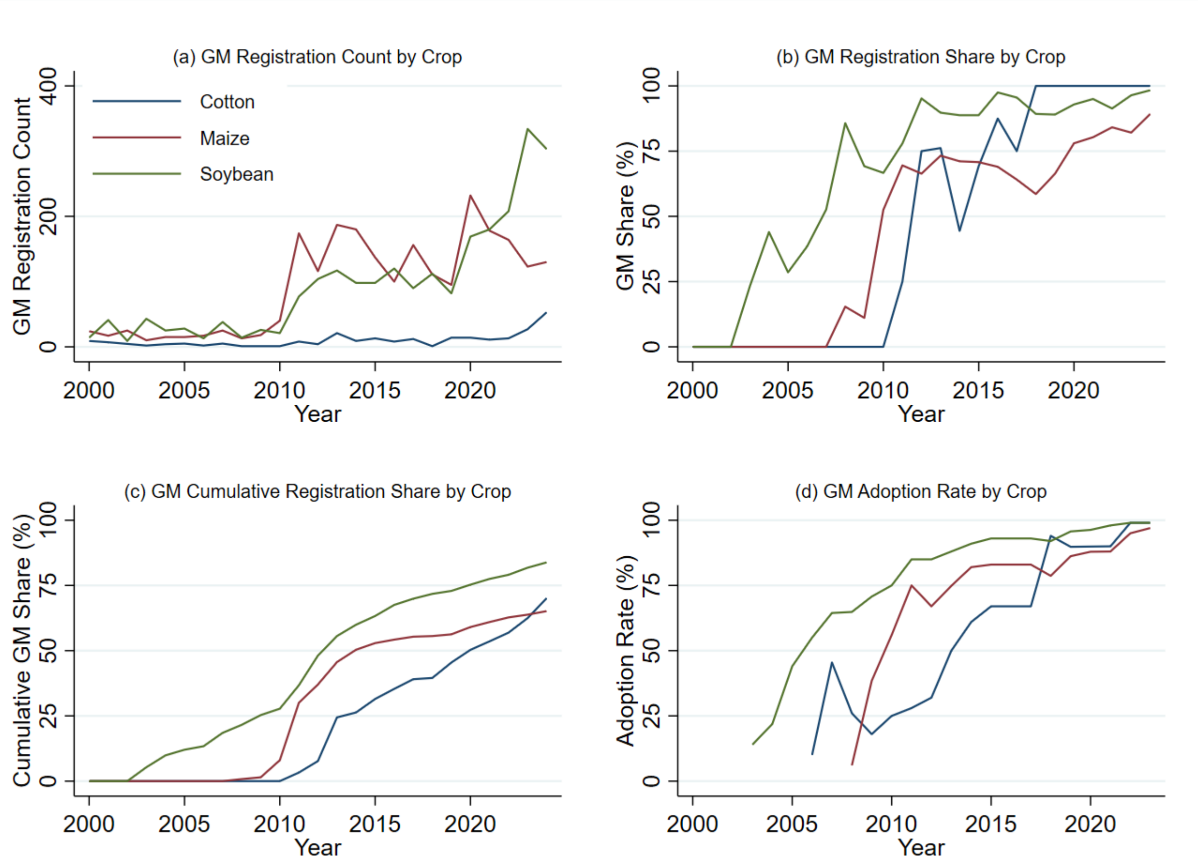
4.3 GM adoption and the introduction of new varieties in Brazil

Expanding within-country GM crop technology diffusion over time requires long-term commitment to spending on agricultural research that produces a constant stream of innovations available for farm adaptation and adoption (Wang et al. 2023). Hall (2004) shows that adoption S-curves for electric services, washing machines, telephones, and video cassette recorders (VCRs) in the United States over the 20th century are comprised of innovative activities that improve the related product or service offerings throughout the diffusion process. For example, telephony and other information and communication technologies were vastly different today than in the late 20th century or compared to the era of Alexander Graham Bell. This same stream of innovations applies to GM crop technologies, where product offerings and quality also evolve over time. For example, the introduction of new GM crop varieties to a country involves varieties with new or stacked traits or other improvements to the technology.

Here we investigate whether the introduction of new GM crop varieties in Brazil is propelling the expansion of GM crop production. To that end, we compare the introduction of new GM crop varieties for cotton, maize, and soybean cultivars registered in Brazil from 2000 to 2024 with the country's GM adoption rate for each crop, measured as the harvested area planted with each GM crop divided by the total harvested area for that crop. For new crop introductions, we use data from Brazil's *Registro Nacional de Cultivares* (National Registry of Cultivars), which contains authorizations for the production and marketing of new cultivars in Brazil.[18] Figure 9 below depicts these unique GM registration counts, shares, and adoption rates in Brazil.

In recent years, the annual total of new cultivars registered in Brazil are generally higher for soybean cultivars than maize cultivars, consistent with the relative agricultural production totals for each crop in Brazil during this period (an average of 151 million metric tons of soybeans compared to an average of 118 million metric tons of maize calculated between 2020 and 2024).[19] Annual shares of new, registered cotton and soybean cultivars that are genetically modified have converged to nearly 100% in recent years. In other words, nearly all the recently registered cultivars for soybeans and cotton in Brazil are GM.

Figure 9. Comparing Brazil's GM crop adoption rates with registration rates of new GM varieties of cotton, maize, and soybeans, 2000-2024.



Notes: We calculate the GM share in (b) as the annual count of newly registered GM cultivars divided by the total annual count of newly registered cultivars. We calculate the cumulative GM share in (c) as the cumulative count of newly registered GM cultivars divided by the cumulative count of newly

[18] Please see https://www.gov.br/agricultura/pt-br/acesso-a-informacao/acoes-e-programas/cartas-de-servico/defesa-agropecuaria-sementes-e-mudas/registro-nacional-de-cultivares-rnc?utm_source=chatgpt.com (accessed 31 July 2025).

[19] Please see https://ipad.fas.usda.gov/countrysummary/default.aspx?id=BR (accessed 5 August 2025) for more information.

registered cultivars. The adoption rates in (d) reflect the harvested area planted with each GM crop divided by the total harvested area for that crop.
Sources: Brazil's Registro Nacional de Cultivares (Subfigures 9(a), 9(b), and 9(c)); AgbioInvestor GM Monitor (Subfigure 9(d)).

The GM share of maize cultivars follows a slightly different trajectory. The share of GM maize cultivar registrations climbed to 73% in 2013, oscillated between 59 and 71% until 2019, and then increased to 89% by 2024, indicating that roughly 9 of 10 new maize cultivars registered at the *Registro Nacional de Cultivares* are genetically modified.

The high share of new GM registrations for each respective crop, along with corresponding high GM adoption rates (Figure 9(d)), indicates that the future expansion of GM crop production in Brazil is underpinned by the introduction of new GM crop varieties, consistent with the provision of a stream of new technologies for farmers over the long-term as argued by Wang et al. (2023).

5 Trademark filings and registrations as an indicator of GM crop technology diffusion?

In general, detailed data on technology usage and commercialization across countries can often be difficult to collate, while common data sources used to track technology diffusion have notable limitations. Patent citations, for example, have been used to track knowledge diffusion between entities engaged in inventive activity but do not track commercialization nor commercial intent. Recent advancements in the diffusion literature suggest that another form of intellectual property — trademarks — are better suited to study diffusion (von Graevenitz et al. 2022). A trademark "is a word, phrase, symbol, design, color, smell, sound, or combination thereof that identifies and distinguishes the goods and services of one party from those of others," (Graham et al. 2013, pg. 5). Trademarks, according to the prior literature, are a commonly used form of intellectual property that protect brand names from imitation (Fink et al., 2022).

These source identifiers are granted by intellectual property offices at the national level (e.g., the U.S. Patent and Trademark Office) or the regional level (e.g., the European Union Intellectual Property Office). However, registration requirements vary by jurisdiction. For example, some countries, such as the United States, require that a trademark be used in commerce at the time of registration, whereas others allow a grace period. Trademark registrations should, in principle, be closely aligned with commercial activities, including the introduction of new products and services to the market (Mendonça et al., 2004). The analysis by von Graevenitz et al. (2022) leverages this relationship and legal requirements that mandate use of the trademark in commerce to analyze regional technology diffusion within the United States from 1981 to 2012. Beyond the U.S. context, less is known about the use of trademarks as a measure of diffusion, particularly as a measure of international knowledge and technology flows.

Our purpose in the first case study below is to assess the strengths (weaknesses) of trademark data for tracking commercialization and thus technology diffusion across countries. Specifically, we assess the use of trademark registrations as an alternative indicator of global technology diffusion for *branded* innovations, focusing on a selected set of branded genetically-modified (GM) crop technologies with a global footprint such as *Roundup Ready*.[20] We benchmark our trademark data against the GM event regulatory approval data described above — an established proxy for brand-level market entry across countries and thus diffusion. Comparing the geographic distribution of these two data sources to jurisdiction-specific use requirements for trademarks, we find that trademarks serve as a meaningful measure of commercial intent in most jurisdictions across the globe. However, we argue that trademarks can only be extended to a measure of commercialization and therefore diffusion under certain assumptions. The use of trademark data in this manner is therefore most appropriate in countries with stronger trademark use requirements (e.g., Mexico, the Philippines, and the United States).

Our second case study in this section explores the potential of trademark data to track future or expected diffusion of newer genome-edited (GE) crops, as opposed to the previous technology of genetically modified (GM) crops. In the domain of genetically modified crops, heterogeneous shifts in regulatory standards across countries for technological advancements have led to the exclusion of non-regulated *GE* crops from the regulatory approval data, reducing their reliability to track commercial intent or future diffusion. For example, some users of CRISPR (Clustered Regularly Interspaced Short Palindromic Repeats) does not introduce *foreign* DNA into crops and is therefore subject to less stringent regulatory requirements than prior generations of GM crop technology (Tuncel et al. 2023). Therefore, we first evaluate whether commercialized crops developed using GE technologies are captured by either regulatory approval databases or trademark data. Although the number of commercially available GE crops is limited, we find that those that are commercialized do not generally appear in the regulatory approval data, with some exceptions. Trademark data, on the other hand, appear to capture the global commercial intent of focal firms but not their non-branded technologies. We argue that researchers may therefore benefit from using trademark data to track the prospective market expansion of nascent technologies at the firm level, especially if the product or service offerings of the firm are limited to the focal technology.[21]

5.1 Case Study 1: Evaluating trademark registrations as a measure of diffusion using well-known GM brands

U.S. trademark registrations are closely linked to commercial activities and market entry because U.S. trademark law requires use in commerce as a prerequisite for registration (Castaldi 2024; 15 U.S.C. § 1051). A recent study leveraged this characteristic to track the geographic diffusion of specific innovations within the United States using novel tokens[22] from trademark goods and services statements (von Graevenitz et al. 2022). A natural extension of this analysis would leverage trademark data to study diffusion in a *global* context. Castaldi et al. (2020) note that many countries allow for a grace period before the 'use in commerce' requirement comes into effect, but there is insufficient specificity to assess the applicability of a trademark-based diffusion measure on a country-by-country basis. It thus remains unclear in which jurisdictions trademark registrations exhibit a similar strength

[20] Trademarks may be registered to protect brands, provided they meet the statutory requirements of the focal jurisdiction. Accordingly, any branded component of a GM crop that meets these requirements may be trademarked. This includes not only GM traits (e.g., *Roundup Ready*) but also branded cultivars (e.g., Arctic Golden and Arctic Granny apples).

[21] We caveat these findings by acknowledging that most GE crops are not branded, limiting the applicability of these data to track future diffusion at the (non-branded) crop level.

[22] According to IBM (2025), "A token is a collection of characters that has semantic meaning for a model. Tokenization is the process of converting the words in your prompt into tokens."

of relationship with commercial activities as those approved in the United States. Clarifying that will lend insight into whether trademark registrations might be used to capture technology diffusion.

Our analysis unfolds in a two-step process. First, we compare the global footprint of trademark registrations associated with each brand at the jurisdictional level to the set of countries that have approved these focal technologies for import or cultivation. Then, second, we assess the viability of trademark registrations as a measure of technology diffusion on a country-by-country basis and comment on their applicability as a technology diffusion indicator more broadly.

We explore the applicability of trademark data as a measure of international technology diffusion across countries at the brand level[23] by focusing on a selected set of well-known GM crop brands: *Roundup Ready* (originally developed by Monsanto, now Bayer), *LibertyLink* (originally developed by Bayer, sold to BASF), *Bollgard* (Monsanto), and *WideStrike* (originally Dow, now Corteva). We compare the global footprint of trademark registrations associated with each brand at the jurisdictional level to the set of countries that have approved these focal technologies for import or cultivation. We expect substantial overlap as both trademark registrations and regulatory approvals are steps companies pursue prior to entering a new market (Seip et al. 2018).

We construct our sample for *Case Study 1* by linking the selected GM crop technologies (e.g., *Roundup Ready*) directly to trademarks via the protected brands themselves.[24] As described in Section 2, we match the four focal brands to global trademark data by querying WIPO's Global Brand Database for trademark registrations protecting these brands across jurisdictions. Regulatory approvals for GM events, which require significant financial investment (AgbioInvestor 2022), are a key proxy for production or import of GM crops and associated brands (ISAAA 2017; Parisi et al. 2016),[25] and thus serve as a benchmark for our comparison. Note, we limit our assessment of the global reach of these focal brands to first-generation technology, which simplifies our analysis and avoids complications from including follow-on innovations (e.g., *Bollgard* v. *Bollgard II*).

Once we compare the trademark and regulatory approval data for country coverage, it is then critical to evaluate the link between trademark registrations and commercialization as reflected in each jurisdiction's trademark law to assess whether those registered trademarks may proxy for product commercialization in that country. Registered trademarks in countries with weak or no use requirements break the direct link between having a trademark registration and using it to proxy for commercialization, thereby potentially impeding trademarks as a measure of technology diffusion. We thus evaluate the strength of this link by investigating and analyzing trademark use requirements — including declarations of use — for each jurisdiction in our matched trademark-regulatory approval data sample.

5.1.1 Coverage overlap

Since Monsanto first commercialized *Roundup Ready* seeds for cotton, maize, and soybeans in 1996 (Argimón-Cartaya 2023), *Roundup Ready* events for these three crops have obtained regulatory approval in 31 countries and regional regulatory bodies for either cultivation or import. Table 2 below

[23] While the token-based approach of von Graevenitz et al. (2020) identifies technologies through the goods and services statement, our analysis identifies well-known brands associated with our focal technology: GM crops. In Appendix D, we investigate whether the von Graevenitz et al. (2022) approach would be appropriate in our setting, finding that a token-based methodology may omit critical information. We note, however, our results and subsequent recommendations are not reliant on the method of technology identification.

[24] Results for the three other brands are presented in Appendix C.

[25] While regulatory approval does not necessarily indicate import or production of a GM crop, it is often a pre-condition of these commercial activities.

shows considerable overlap between countries where Monsanto obtained regulatory approval (observed in the AgbioInvestor data) and where the *Roundup Ready* trademark is registered via the Global Brand Database. Of the jurisdictions presented in Table 2, 42% have information provided by both sources, 50% have trademark information only, and 8% have regulatory approval information only. The significant overlap between trademark registrations and regulatory approvals across jurisdictions exhibited in Table 2's columns two and three, and the dominant share reporting only trademark information, suggests that global trademark data *can* be a useful proxy for tracking the international commercial diffusion of branded technology. Findings in Appendix C for *Bollgard*, *LibertyLink*, and *Widestrike* show similar patterns across countries, underlining the importance of accounting for trademark registration in any diffusion analysis. Only *WideStrike* shows greater country coverage from regulatory approvals than trademark registrations, but we note that this GM crop has the smallest sample of countries among the four GM products assessed.

Table 2. International coverage of regulatory approvals and trademark registrations for *Roundup Ready*

Country	Trademark Filing / Registration	Regulatory Approval	Use Required at Registration	Eligible for Cancellation after	Declaration/Statement of Use Required during lifecycle of TM
Australia	1	1	No*	3 years of continuous non-use	
Belize	1	0	No (Trade Marks Act, Chapter 257 - Revised 2020)	5 years of continuous non-use	
Brazil	1	1	No^	5 years of continuous non-use	
Bulgaria	1	0	No*	5 years of continuous non-use	
Canada	1	1	No, use requirements were removed effective 2019^	3 years of continuous non-use	
Chile	1	0	No*	2 years of continuous non-use	
Costa Rica	1	1	No^	5 years of continuous non-use	
Denmark	1	0	No*	5 years of continuous non-use	
Egypt	1	0	No*	5 years of continuous non-use	
European Union	1	1	No (Regulation (EU) 2017/1001 - Article 58 1(a))	5 years of continuous non-use	
France	1	0	No^	5 years of continuous non-use	
Germany	1	0	No^	5 years of continuous non-use	
Ghana	0	1	No*	5 years of continuous non-use	
India	1	1	No^	5 years of continuous non-use	
Indonesia	1	1	No*	3 years of continuous non-use	Yes, statement of use required at renewal*
Israel	1	0	No*	2 years of continuous non-use	
Italy	1	0	No*	5 years of continuous non-use	
Japan	1	1	No^	3 years of continuous non-use	No, checks on use were abolished after a 1996 law change.*
Kenya	1	0	No*	5 years of continuous non-use	
Malaysia	0	1	No*	3 years of continuous non-use	
Mexico	1	1	No*	3 years of continuous non-use	Effective 2018, declarations of use must be submitted three years following registration and at renewal.*
Moldova (Republic of)	1	0	No*	5 years of continuous non-use	
Montenegro	1	0	No*	5 years of continuous non-use	
Morocco	1	0	No*	5 years of continuous non-use	
New Zealand	1	1	No*	3 years of continuous non-use	
Norway	1	0	No^	5 years of continuous non-use	
Philippines	1	1	Declaration of Actual Use (DAU) must be filed at three years of filing (source: ipophil.gov.ph)	5 years of continuous non-use	Declaration of Actual Use (DAU) must be filed at various points after registration, including at renewal (source: ipophil.gov.ph)
Republic of North Macedonia	1	0	No*	5 years of continuous non-use	
Serbia	1	0	No*	5 years of continuous non-use	
Singapore	0	1	No*	5 years of continuous non-use	
South Korea	1	1	No*	3 years of continuous non-use	No, proof of use requirements were abolished effective 1994*
Spain	1	0	No*	5 years of continuous non-use	No, current law does not require an affadvit declaring use*
Switzerland	1	1	No^	5 years of continuous non-use	
Thailand	1	0	No*	3 years of continuous non-use	
UK	1	1	No*	5 years of continuous non-use	
USA	1	1	Yes, appliant must demonstrate use in commerce prior to registration*	3 years of continuous non-use	
Ukraine	1	0	No^	3 years of continuous non-use	
Uruguay	1	1	No*	5 years of continuous non-use	
Viet Nam	1	1	No*	2 years of continuous non-use	
Zimbabwe	1	0	No*	5 years of continuous non-use	

Note: TM refers to trademark. A '1' indicates the country had a trademark filing or registration for *Roundup Ready* or had regulatory approval per the AgbioInvestor database, whereas a '0' indicates they did not.
Sources: WIPO's Global Brand Database (Col.: TM Filing/Registration); AgbioInvestor GM Approval Database (Col.: Regulatory approval); * Horwitz on World Trademark Law (2025); ^ Chambers and Partners (2023)

5.1.2 Linking trademark registrations to commercialization

While Table 2 suggests potential for trademarks as an indicator of technology diffusion, their applicability depends on the strength of the link between trademark registrations and commercial activity of the focal brands. Most countries in Table 2 do not require an explicit declaration or statement of use but allow for a period of continued non-use (typically 3 to 5 years) post-registration. Only in the U.S., in the Philippines, and in Mexico do authorities require a statement or declaration of use during the trademark's lifecycle, other jurisdictions allow some years of grace period before use requirements come into effect. Thus, the link between commercialization and trademark registrations is tenuous while the grace period is in effect, and even weaker under policy regimes with no use requirements as evidenced by trademark squatters (Fink et al. 2018).[26]

Indeed, the applicability of trademark registrations as a valid proxy for commercialization depends on the jurisdiction-specific use requirements, and that the measure must be tailored to each country, even in the United States. For example, Fikkema et al. (2014) and Seip et al. (2018) find that the timing of trademark filings may occur at various points in the innovation process, including before, around, or even after market introduction. von Graevenitz et al. (2022) exploited requirements at the USPTO that mandate use prior to obtaining a trademark registration. Yet even in the U.S. trademark use requirements are not always satisfied. To wit, any USPTO trademark registered via the World Intellectual Property Organization's (WIPO's) Madrid System or Paris Convention do not follow U.S. national law requiring evidence of a trademark's use at the time of registration. The Madrid system allows applications to register a trademark to multiple countries at the same time, delaying evidence of use for up to 6 years.[27,28] The Paris Convention[29] ensures equal treatment between two national intellectual property offices, thus requirements in another jurisdiction must be upheld in the U.S., including use requirements.[30] As such, applicants seeking trademark protection in the U.S. via international pathways are not required to use the mark in commerce as a prerequisite for trademark registration (WIPO 2016). Notably, in 2024, about 14% of all new trademark applications in the U.S. came through these pathways.[31] In other words, even in the U.S. one cannot assume that a trademark registration represents an intent to commercialize or actual use in commerce. One may more comfortably assume that a trademark registration signals an intent to commercialize, unless further refinements of the trademark data are undertaken.

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[26] Trademark squatting "describes a situation in which a company or individual registers a trademark that protects a good, service, or trading name of another company," (Fink et al. 2018, pg. 341).

[27] The Madrid System is a centralized international trademark system that allows applicants to file for trademark protection in multiple jurisdictions with a single application. Each designated IP office then individually determines if the application meets the required standard for trademark registration (WIPO 2021). See also https://www.wipo.int/en/web/madrid-system.

[28] Declarations of use or excusable nonuse must be filed between the fifth and sixth year after the registration date of your extension protection with the USPTO, between the ninth and tenth years, and every subsequent ten years thereafter. A six-month grace period after each deadline is available with an additional fee. See https://www.uspto.gov/ip-policy/international-protection/madrid-protocol/inbound-post-registration.

[29] See https://www.wipo.int/wipolex/en/text/288514.

[30] See https://www.uspto.gov/ip-policy/trademark-policy/well-known-marks.

[31] See Trademarks Dashboard | USPTO; accessed on 08/15/2025.

5.2 Case study 2: Trademark applications, regulatory approvals, and genetically edited technologies

Recent advancements in the field of gene editing have led to the emergence of new genomic techniques, which include Clustered Regularly Interspaced Short Palindromic Repeats (CRISPR) technologies --- the predominant technology for gene editing (Tuncel et al. 2023; Polidoros et al. 2024). These techniques empower scientists “to insert, delete, modify, or replace specific sequences within an organism’s genome, offering unprecedented control over the genetic code” (Polidoros et al. 2024, p. 2). Genetically edited (GE) crops do not involve the insertion of foreign DNA to achieve the desired traits (e.g., drought resistance), precipitating a debate among governmental entities and other stakeholders over how GE crops should be regulated. Several countries, including member states of the European Union, South Africa, Peru, and New Zealand, regulate GE crops in the same manner as GM crops. Other countries, including the United States and Argentina, have less stringent commercialization restrictions on crops developed through gene editing (Tuncel et al. 2023). Like the regulatory debate on GM crops, the policy landscape of GE crops is uncertain and evolving. For example, after the European Court of Justice (ECJ) ruled in 2018 that GE crops are subject to the same EU regulatory framework as GM crops, the EU started a multi-year process to create new, less stringent regulations for GE crops --- particularly if the edited crop is essentially equivalent to a conventional variant (Polidoros et al. 2024).

As governments and supranational organizations loosen restrictions on GE crops, new GE crop innovations may be less likely to appear in the regulatory approval data than GM crops that are developed through the introduction of foreign genes (e.g., glyphosate-tolerant seeds). Our objective is therefore to understand the degree to which GE crops are captured by regulatory approval data, and to analyze how frontier firms in the GE crop product space use trademark registrations to protect their brands.

We construct our sample by identifying firms using frontier genome-editing technologies that have commercialized or are commercializing a GE crop. There are several candidate startups and small firms that meet these criteria, as identified in the prior literature (Tuncel et al.,2023; Polidoros et al., 2024), including Calyxt, Cibus, CoverCress, GreenVenus, Pairwise Plant Services, Sanatech Seed, Tropic Biosciences, and Yield10 Biosciences. Interestingly, most of the GE crops commercialized by the firms listed above are not branded. We therefore analyze the spread of these nascent technologies by tracking the use of trademarks at the firm level rather than product level.

The sample links these eight small firms to three datasets: (1) WIPO’s Global Brand Database, (2) AgbioInvestor GM Monitor’s regulatory approval data, and (3) the ‘Am I regulated?’ (AIR) data from the U.S. Department of Agriculture’s (USDA’s) Animal and Plant Health Inspection Service (APHIS).[32] The AIR data contains requests from firms who wish to commercialize GM crops in the United States, inquiring whether their GM crop is a regulated article under U.S. law or exempt from such regulation by the USDA. These inquiries and corresponding decisions are publicly released by the USDA and represent another potential resource to track commercial intent of GE firms. We present a summary of our sample in Table 3. Of the 8 firms, 7 have commercialized at least one GE crop in at least one country: soybeans (Calyxt), canola, and rice (Cibus), lettuce (GreenVenus), mustard greens (Pairwise Plant Services), pennycress (CoverCress), tomatoes (Sanatech Seed), and bananas (Tropic Biosciences).

[32] For more information, please see https://www.aphis.usda.gov/am-i-regulated.

The APHIS "Am I Regulated?" column in Table 3 shows that each firm has received at least one regulatory exemption or confirmation of non-regulation for its focal GE crops in the United States. Note that the exemptions/confirmations offer a less strict regulatory threshold for assessing GE crop regulations. Moreover, while certain GE crops may not be regulated by the USDA under 7 CFR 340 or may seek an exemption from such regulation under the same statute,[33] additional health and biosafety regulations may still apply. For example, as shown in Table 3, Calyxt's GE soybean appears in the regulatory approval data as regulated by the U.S. Food and Drug Administration (FDA), rather than the USDA's APHIS. Additionally, CoverCress's GE pennycress appears in the regulatory approval data as being regulated by APHIS, despite receiving an exemption from APHIS for its GE pennycress under 340.1(b)(1); please see Table 3 for more information.

Although the APHIS "Am I Regulated?" data apply exclusively to regulation in the United States, we expect commercialized crops developed using new genomic techniques to appear less frequently in global regulatory data provided by AgbioInvestor (or other databases such as ISAAA). Except for a GE banana approval in Honduras for Tropic Biosciences, the remaining commercialized and pre-commercial GE crops in our selected sample do not appear in the regulatory approval data in any country, confirming expectations that regulatory data capture GE developments less comprehensively as GM technologies.[34]

We next turn to the trademark registration data to determine whether firms developing GE crops protect their brands with trademarks. In doing so, we evaluate how trademark registrations of GE crops might complement regulatory approval data to anticipate the future spread of this technology. We find that while some of these GE crops are branded, most are not --- even if commercialized. For example, Sanatech Seed, a Japanese company, commercialized its "Sicilian Rouge High GABA" tomato without a trademark in its home market in 2021 (Waltz 2022; Tuncel et al. 2023). SanaTech Seed has filed firm-level trademarks in several countries, including Australia, Brazil, Canada, Indonesia, Japan, Malaysia, the Philippines, Singapore, Thailand, the United Kingdom, and the United States. These trademark filings, combined with non-regulation or exemption requests in the USA (see Table 3) and in the Philippines[35] point to either commercial intent or evidence of commercialization in these jurisdictions.

However, given findings from our first case study, one must exercise caution when interpreting trademark filings as evidence of commercialization. Sanatech Seed's registered trademark in the United States, registration number 6060967, was filed through the Madrid System (filed 6 February 2019 and registered 26 May 2020) and thus does not have to present proof of use until 6 years after the registration date. Using the USPTO's online Trademark Status & Document Retrieval interface (accessed 31 July 2025), we find that Sanatech Seed has not submitted the required use declarations that were due 6 years post-registration --- despite being sent a courtesy reminder e-mail on 26 May 2025. This evidence suggests that USPTO trademark registration is not unconditional evidence of commercial use in the United States, although there is evidence of intent to commercialize the GE tomato based on Sanatech Seed's non-regulation/exemption inquiry to APHIS. Consistent with the

[33] 7 CFR 340 defines the scope of genetically modified organisms regulated by the USDA but also provides several exemptions. 7 CFR 340.6 specifically describes the process by which an interested party may petition for the determination of non-regulated status.
[34] Dionglay (2024) notes other instances of non-regulation internationally, including the non-regulation of a GE banana (Tropic Biosciences) in the Philippines.
[35] Please see https://sanatech-seed.com/en/240524-2/ (accessed 6 August 2025).

literature on the timing of trademark filings (Fikkema et al. 2014; Seip et al. 2018), the Sanatech Seed example highlights that certain trademark filings, like regulatory approvals, and particularly in the case of Madrid System or Paris Convention filings, appear to *precede* commercialization.

Market estimates suggest annual sales of GE crops will increase from approximately $8.9 billion to $13.7 billion between 2025 and 2030 (Research and Markets 2025). In addition to understanding the scale of expansion, geographic scope of GE market expansion is a key dimension of *future* global diffusion. Firms in the nascent market for GE crops, including those highlighted above, can reasonably be classified as innovative startups. Previous studies (Block et al. 2014; Lyalkov et al. 2021; Castaldi et al. 2020) suggest that innovative firms file for trademark protection prior to market entry, using trademarks to attract resources and as a signaling device. The specific timing of the trademark filing depends on the intended signal recipient (e.g., venture capital firms, other investors, or consumers). Consistent with these studies, GE firms (including Sanatech Seeds discussed above) have filed for trademark protection in several jurisdictions without an explicit commercial footprint. These pre-market trademark registrations therefore reflect commercial intent by the focal firm in the chosen jurisdiction.

To what extent then do brands associated with pre-market registrations become commercialized? While data limitations in many jurisdictions prevent us from directly observing this relationship, an analysis of “intent-to-use” (ITU) filings at the USPTO and their registration rate provides some guidance on the issue. The USPTO introduced “intent-to-use” filings in 1989, allowing applicants to file trademark applications with a good faith intent to use the trademark in commerce at the time of filing rather than requiring explicit use. However, ITU-based trademark filings cannot become registered trademarks without satisfying the USPTO’s use requirements. The registration rate for ITU applications, conditional on filing a trademark application using an ITU legal basis, therefore approximates the rate at which commercial intent through filing a trademark leads to its use in commerce, or commercialization.

After identifying roughly 4.3 million ITU trademark filings between 1989 and 2019 from the USPTO’s Trademark Case Files database, we track the annual registration rate over time by application filing year, shown in Figure 10. The registration rate for the roughly seven thousand initial ITU applications filed in 1989 was 38.7%, hitting a low of 32.8% by year 2000 in the lead-up to the dot-com bubble bursting, and reaching a high of 47.1% in 2012. The average registration rate over the entire period is 38.3%, indicating that a significant percentage of ITU applications — representing commercial intent — ultimately achieve use in commerce. Although the conversion rate is unlikely to be constant across jurisdictions or product categories, the calculation does provide some evidence in favor of our ‘future commercialization and diffusion’ interpretation. We also note that our registration rate is estimated at the application level and not the registration level, likely acting as a lower bound for the conversion rate for registered trademarks (i.e., approved but not yet registered ITU applications). Future research may exploit these administrative data further, looking at the registration rate, conditional on approval, for these applications.[36]

The use of trademarks as an indicator of future GE diffusion relies on the relatively weak assumption that trademark registrations reflect firm-level evidence of commercial intent of genome-editing

[36] ITU applications may be approved by the USPTO prior to use in commerce but cannot be registered until the use requirements are met. Under some assumptions, one could theoretically estimate the conversion rate for approved “intent-to-use” applications by estimating the probability of registration (i.e., use in commerce) conditional on approval.

technologies by small agricultural biotechnology firms with limited product offerings (indicated by the lack of branded GE crops). This assumption becomes less reliable if and as such firms diversify beyond GE products. Ideally, a well-defined set of branded GE crops would simplify the matching process and allow researchers to track the technologies at the brand level, but branded technologies in this product space are limited. This empirical approach risks adding analytical noise by tracking diffusion at the firm-level as opposed to the branded technology level.

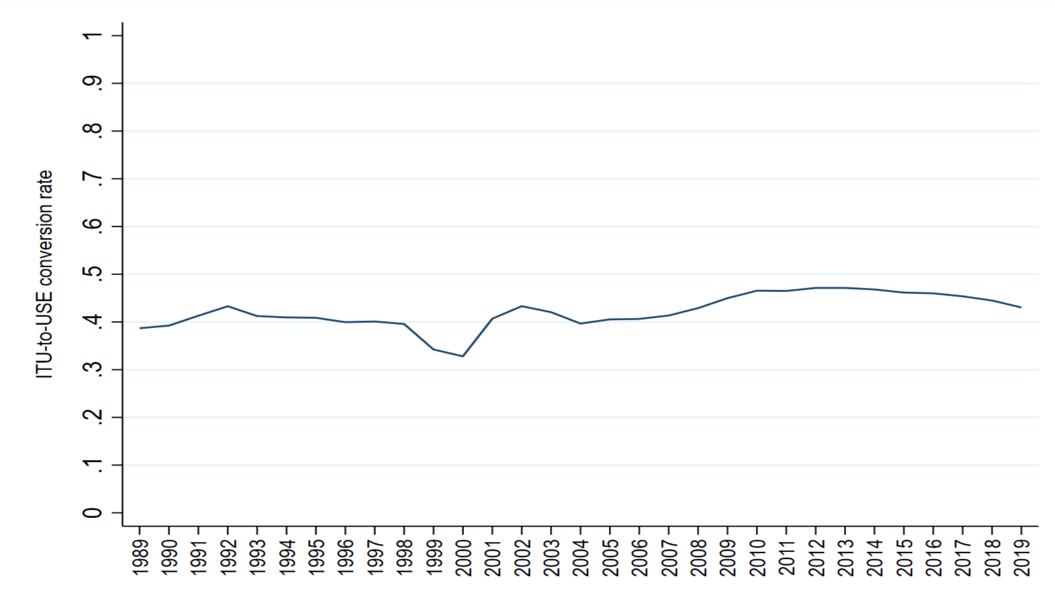
In conclusion, crops developed using frontier techniques, including CRISPR, will not be fully captured by regulatory approval data as regulatory frameworks for GE crops continue to evolve, necessitating alternative sources of information. Despite evidence that small startups developing GE crops protect their brands using trademarks, our analysis shows the geographic distribution of firm-level GE trademark registrations does not fully represent actual commercialization of these GE technologies in the filing jurisdictions but signals commercial intent — consistent with the findings of Case Study 1.

Table 3. Regulatory approvals and trademark registrations for new genomic technologies

Brand	Trademark countries	Approval Countries	Commercialized Crop	Am I Regulated? (AIR) - USDA's APHIS Data
Calyxt	Australia, Brazil, Canada, UK, USA	USA (FDA) - Soybean	Soybean	Exemption 1 of §340.1(b)(1) - Genome Edited High Oleic Low Linolenic Soybean; Nutritionally-Enhanced Wheat Developed by TALEN Technology; Alfalfa with Improved Nutritional Quality Developed with TALEN Technology; TALEN PPO_KO Potato; MLO_KO Wheat
Cibus, Inc.	Australia, Canada, UK, USA	N/A	Canola, Rice	Not regulated under 7 CFR part 340 - Genome Edited Canola for Disease Resistance, Herbicide Resistance, and Fungal Resistance
CoverCress	USA	USA (AHPIS) - Pennycress	Pennycress	Exemption 1 of §340.1(b)(1) - Pennycress (altered plant maturation time; altered flowering window; altered seed composition; altered podcomposition)
GreenVenus	USA	N/A	Lettuce	Not regulated under 7 CFR part 340 - Genome Edited Lettuce for Increased Biomass; Genome Edited Lettuce for Reduced Browning; Genome Edited Wine Grapes for Reduced PPO; Genome Edited Avocado
Pairwise Plant Services	USA	N/A	Mustard greens	Exemption 1 of §340.1(b)(1) - Blackberry/Black raspberry (altered growth habit; CBI; reduced pungency; seedless; thornless)
Sanatech	Australia, Brazil, Canada, Indonesia, Malaysia, Philippines, Singapore, Thailand, UK, USA	N/A	Tomato	Not regulated under 7 CFR part 340 - Genome Edited Tomato with Increased - Aminobutyric Acid (GABA)
Tropic Biosciences	European Union, UK, USA	Honduras - Banana	Banana	Requested: Exemption from regulations under 7 CFR part 340 pursuant to 340.1(b1) - Banana; Exemption from regulations under 7 CFR part 340 pursuant to § 340.1(c) - Potato
Yield10 Biosciences	N/A	N/A	N/A	Not regulated under 7 CFR part 340 - Genome Edited Canola with Altered Oil Content; Genome Edited Camelina Lines Developed with CRISPR/Cas Technology; Genome Edited Camelina Lines Developed with CRISPR/Cas technology; Genome Edited Camelina Developed by CRISPR/Cas Technology

Sources: WIPO's Global Brand Database (Column: Trademark countries); AgbioInvestor GM Monitor's regulatory approval data (Column: Approval Countries); 'Am I regulated?' (AIR) data from the U.S. Department of Agriculture's (USDA's) Animal and Plant Health Inspection Service (Column: Am I regulated?)

Figure 10. Registration rate for "intent-to-use" trademark filings at the USPTO filed between 1989 and 2019



Source: Authors' calculations from the USPTO's Trademark Casefiles Dataset (https://www.uspto.gov/ip-policy/economic-research/research-datasets/trademark-case-files-dataset)

6 Conclusion

In the above, we analyzed the spatial and temporal diffusion of genetically modified (GM) and genome-edited (GE) crop technologies, beginning with the regulatory approval and market introduction of the first commercialized GM crop: *Flavr Savr*, a delayed-ripening tomato. The diffusion speed of these controversial technologies exhibits considerable heterogeneity both within and across countries. Within-country adoption periods (i.e. slopes) for three focal GM crops --- cotton, maize, and soybeans --- range from 3 to 22 years from initial market availability at 10% GM share of harvested area to market saturation at 90% adoption of total cultivated area. Notable instances include Argentina (GM soybeans – 3 years; GM cotton – 3 years), India (GM cotton – 6 years), South Africa (GM cotton – 7 years), and Uruguay (GM maize – 7 years). These within-country diffusion rates underline the time needed for technologies to fully disseminate across users and become widely adopted in systems or processes. Studies investigating how innovation inputs such as research and development expenditures affect economic performance such as total factor productivity should therefore account for such long diffusion processes in their models, as argued by Alston et al. (2023) and originally by Griliches (1957). Differences in the rate of international GM crop diffusion is driven by several supply- and demand-side factors, including affordability, regulatory and institutional environment (including intellectual property regimes), observability and awareness, infrastructure, among others (Falck-Zepeda 2026).

We further analyzed an underused form of intellectual property (IP)---trademarks---to assess its applicability as a new measure of international technology diffusion. We compare trademark data with an established proxy for commercialization intent (regulatory approvals), and thus diffusion, in two contexts: established branded technologies and nascent technologies. In the former, we find a significant overlap between the geographic distribution of *Roundup Ready* trademark registrations ---

an established branded GM technology originally developed by Monsanto --- and jurisdiction-level regulatory approvals for *Roundup Ready* GM events. Although use in commerce is required for trademark registration in the United States (except for Madrid System and Paris Convention filings there), most countries allow a grace period before use is required or permit certain durations of continuous non-use. Although an appropriate measure for commercial intent, trademark registrations from jurisdictions with weaker use requirements are likely to be a noisy measure of diffusion --- unless further refinements of the trademark data are undertaken. But most importantly, the TM data offer insight into where the agricultural GM databases, such as ISAAA and AgbioInvestor, should expect to expand operations, as TM registrations are best interpreted in countries with weak requirements as intent to commercialize. We identified half of our sample as countries where these agricultural GM databases will likely need to expand coverage.

Last, we assessed trademark registration data as a measure of diffusion for a nascent technology: genome-edited (GE) crops. Evidence for the applicability of trademark data in this context is mixed. First, most commercialized GE crops are not branded, necessitating the use of firm-level rather than product-level trademarks. Second, because our analysis is contemporaneous, the statutory grace period has not elapsed in many jurisdictions where related trademarks have been registered, making it difficult to distinguish commercial intent from actual commercialization. We argue that trademark registrations are less useful for nascent technologies than for established, branded technologies. Overall, our findings suggest that the key assumption underlying the use of trademarks as a measure of diffusion --- the link between trademark registration and commercialization --- is most reliable in jurisdictions with explicit declarations or statements of use. A stronger assumption is needed for countries with weaker use requirements: namely, that a trademark registration reflects use in commerce after the statutory grace period has elapsed, which will not always hold.

Future research could track the dynamics of trademark filings as they relate to follow-on innovations. For example, researchers could study the extent to which branded follow-on innovations appear in the global trademark data. Researchers might also assess whether additional requirements or data generated through the trademark registration process may assist in pinpointing the existence and timing of commercial activities related to specified brands or tokens across jurisdictions.

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Appendix A. Comparing GM adoption rates from ISAAA and AgbioInvestor databases

The AgbioInvestor Approval database provides bulk downloads from their website of, among other data, maize, soybean, and cotton total cultivated area, total cultivated area of genetically modified (GM) crop technology, and the proportion of total cultivated area planted to GM. We use these data to construct and analyze crop-specific adoption S-curves of GM maize, soybeans, and cotton in countries that are top global producers of each crop and in relevant other smaller countries.

The AgbioInvestor database relies on secondary data sources. For instance, United States estimates of harvested area relies on information from the Economic Research Service (ERS) of the U.S. Department of Agriculture (USDA).[37] Notably, the ERS data rely on data collected by the USDA's National Agricultural Statistics Service (NASS). The AgbioInvestor uses national cultivation data when available, although we find that of the 38 jurisdictions with information in the AgbioInvestor database, 21 of them (55%) rely, at least in part, on agricultural statistics provided by the USDA, either through GAIN Reports[38] or via the Production, Supply, and Distribution database.[39]

We compare the AgbioInvestor adoption curves to those generated using data from annual reports from the International Service for the Acquisition of Agri-biotech Applications (ISAAA). These data are not provided in bulk to the public; we therefore relied on data compiled from ISAAA annual reports by Keith Fuglie (personal communication). The ISAAA data include total hectares planted to GM crop technology as well as that specific to maize, soybeans, and cotton. These data are divided by crop- and year-specific Food and Agricultural Organization (FAO) data on total hectares planted to create adoption curves. As we show below, the adoption curves of GM crop technology provided by AgbioInvestor and ISAAA largely align, although some differences are observed.

In general, we find the AgbioInvestor data as providing more timely, more accessible information, and more manicured. Moreover, using the ISAAA data to create adoption curves requires FAO data that may introduce minor error.

A.1 GM Maize Adoption

Our first assessment is specific to maize, in which we compare GM adoption curves from seven countries: the USA, Brazil, Argentina, South Africa, Canada, Colombia, and Uruguay. In 2023, three of those countries ranked in the global top-10 of total maize harvested area: The USA ranked 2nd, Brazil ranked 3rd, and Argentina 5th (FAOSTAT 2025).[40] South Africa, Canada, Colombia, and Uruguay do not rank in the top-10 among countries in terms of maize harvested area, but we include them to provide more insight than achieved by focusing only on 'large' countries.

Below we find the adoption curves are nearly identical for Colombia and the United States, with very similar trends observed in all other countries except Uruguay. In some instances, the ISAAA adoption rates exceed 100% for a given year and the adoption curves appear less smooth than the AgbioInvestor data suggest. As noted above, the AgbioInvestor-based adoption curves are internally consistent in that the data provide information about total and GM harvested area for a given country, crop, and year. Comparison of the ratio of GM harvested area to total harvested area shows minor differences with the proportion of GM harvested area data they provide, suggesting some smoothing of the data array.

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[37] See Methodology - AgbioInvestor-GM, which points to Adoption of Genetically Engineered Crops in the United States | Economic Research Service.

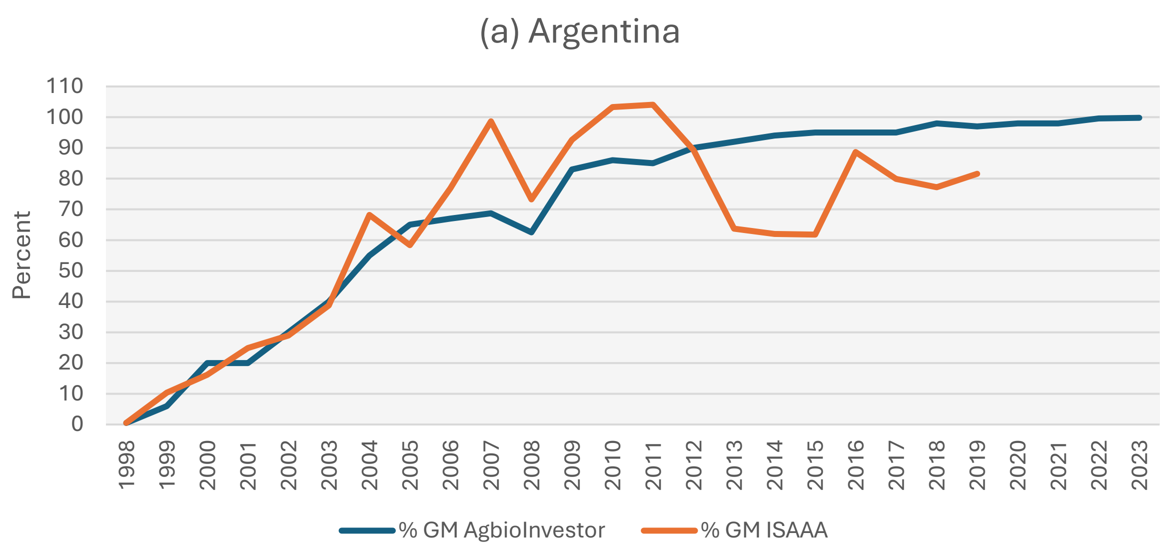
[38] See Home | Global Agricultural Information Network.

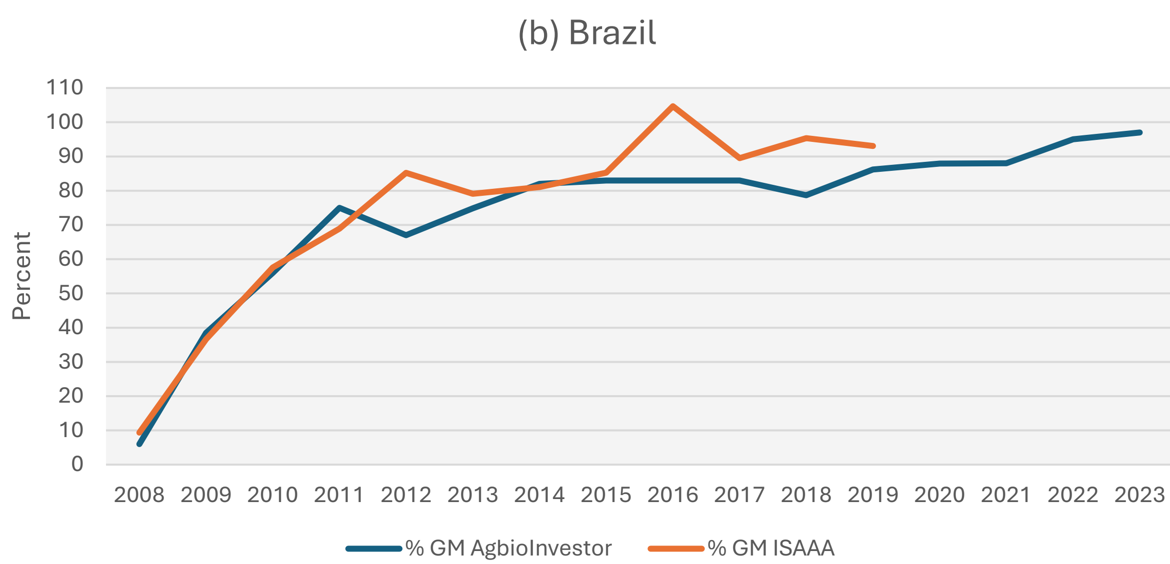
[39] See PSD Online.

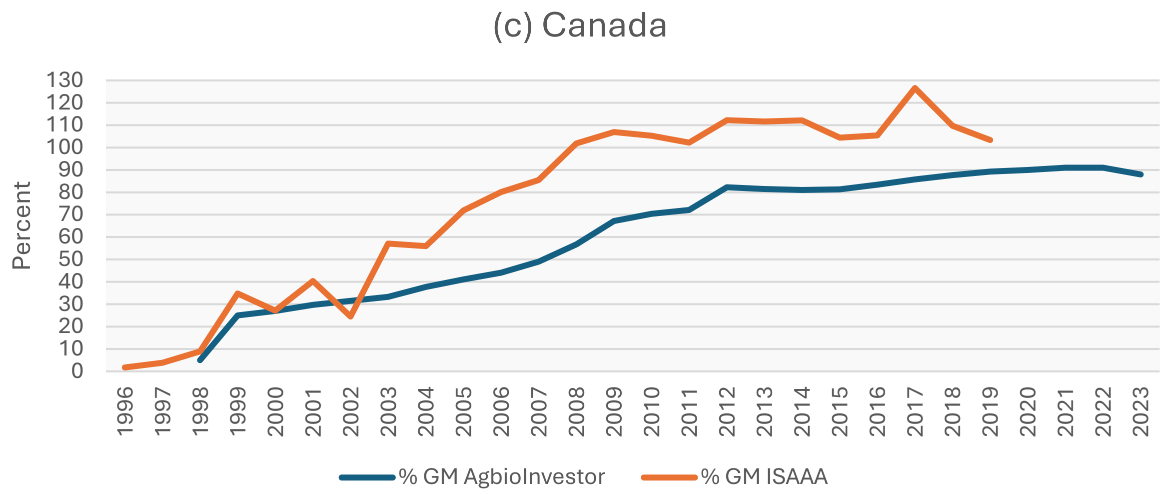
[40] The AgbioInvestor data does not include: China (ranked 1st globally), India (4th), and Mexico, Nigeria, Tanzania, Ukraine, and the Congo (which respectively ranked 6th-10th).

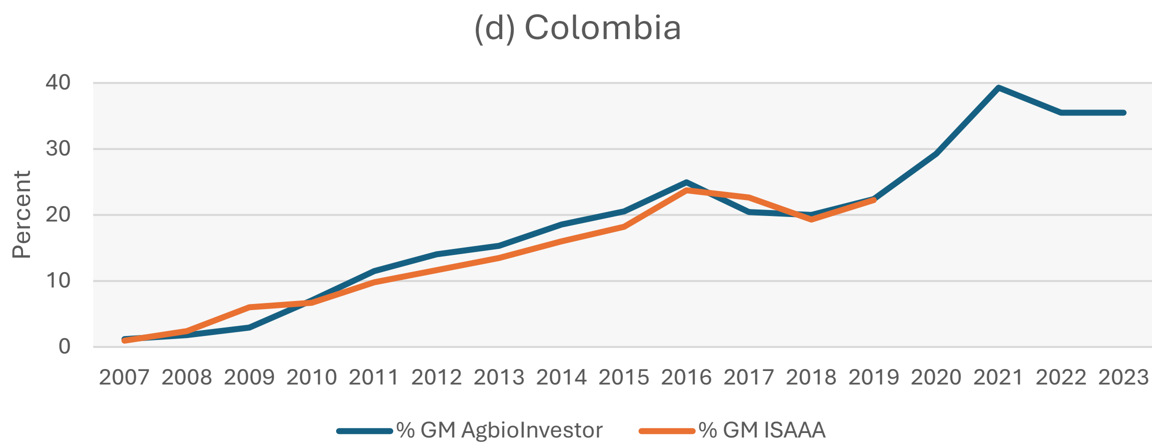
In the case of Uruguay's adoption of GM maize, ISAAA data start in 2010, seven years after data are first recorded in the AgbioInvestor database. While the hectares of area planted to GM maize are somewhat similar, once we account for total area planted to maize from FAO data, thus enabling adoption curves, we find the ISAAA adoption curve to exaggerate differences in GM-harvested area between the two databases. Uruguay is not the only country to exhibit differing years of initial GM crop technology adoption. We also see differing start years in Canada and South Africa. In the cases of Uruguay and South Africa, the AgbioInvestor data has more early information, while in the case of Canada the ISAAA data that show more historical information.

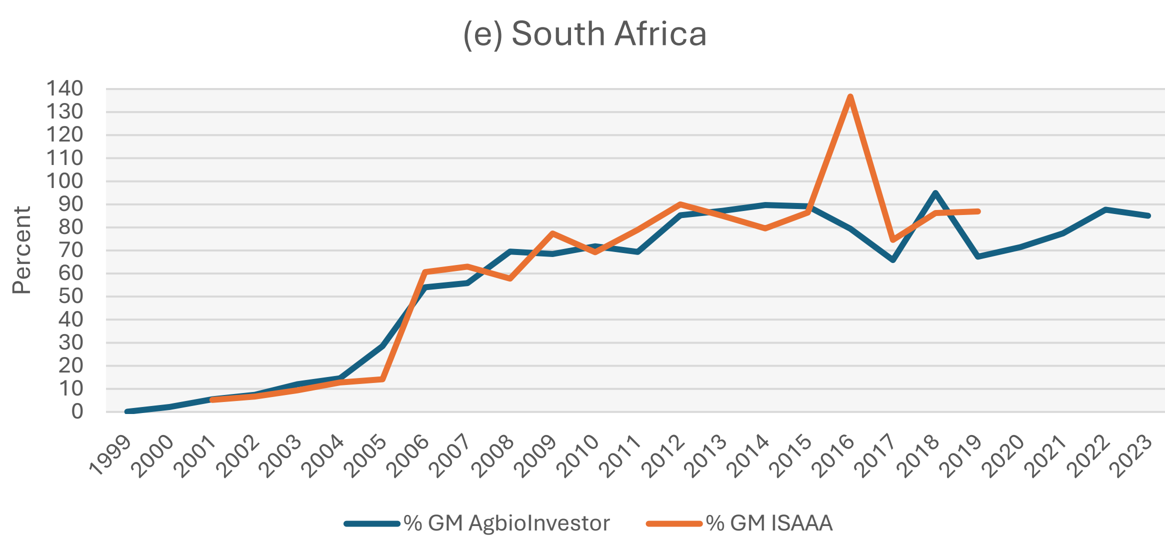
Figure A1 (a) – (g). Comparing AgbioInvestor and ISAAA GM Maize Adoption Curves, selected countries, 1996-2023



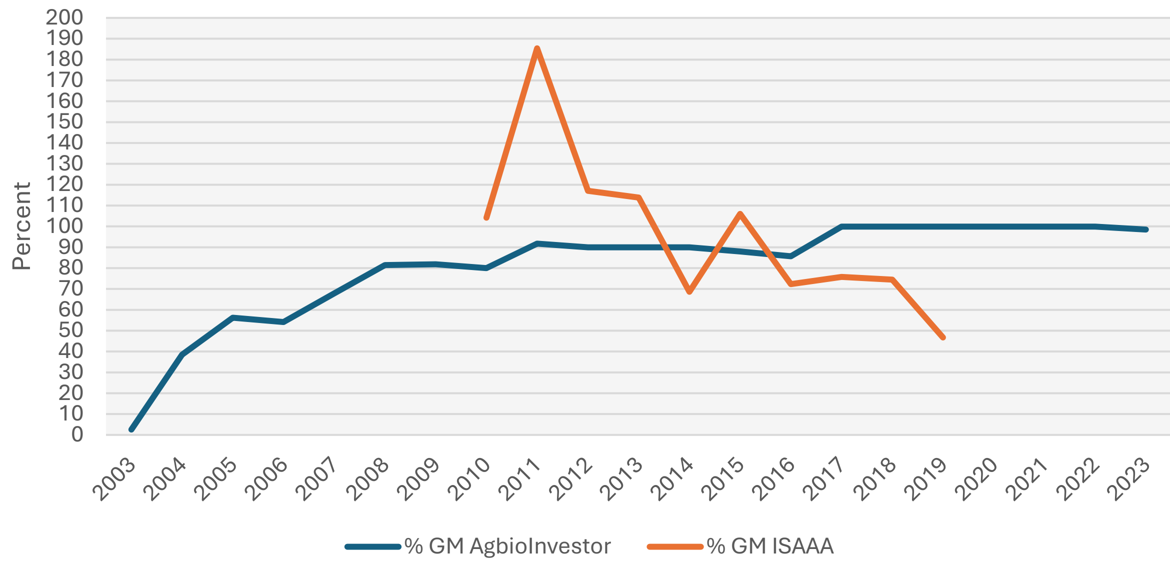



(c) Canada
Percent
% GM AgbioInvestor
% GM ISAAA

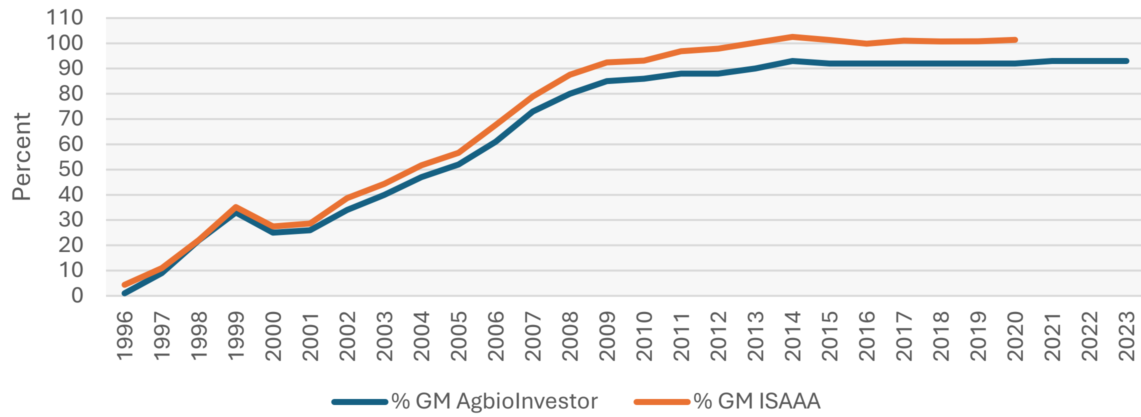

(d) Colombia
Percent
% GM AgbioInvestor
% GM ISAAA


(e) South Africa
Percent
% GM AgbioInvestor
% GM ISAAA

(f) Uruguay



(g) USA



A.2 GM Soybean Adoption

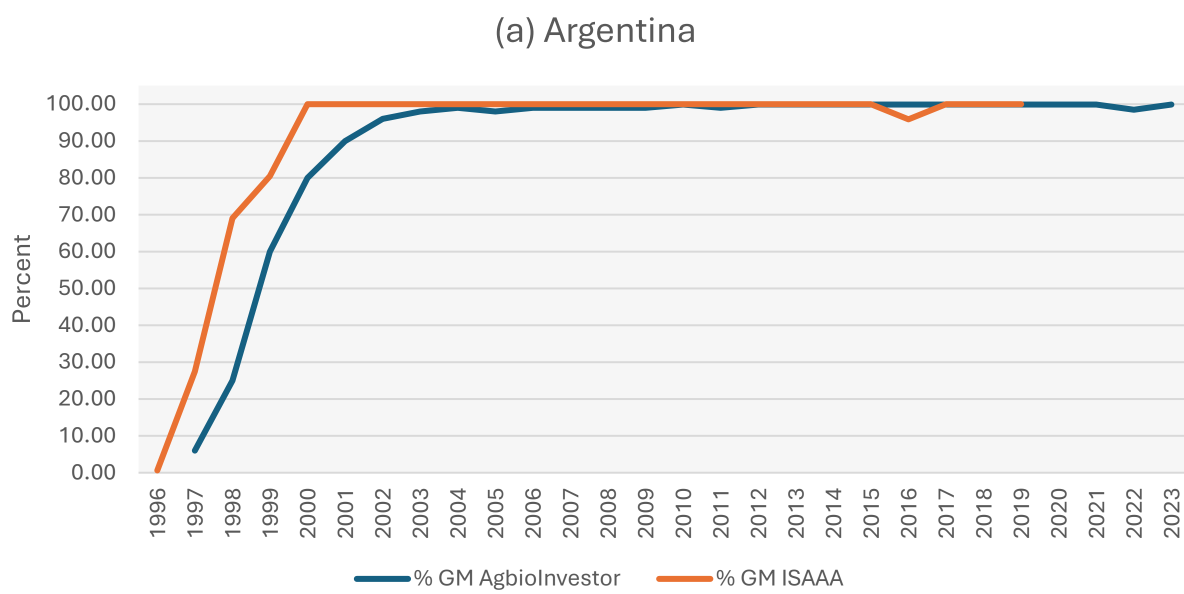
We also assess the 2023 top-10 countries worldwide in terms of soybean harvested area using FAO data. AgbioInvestor provides soybean harvested area for Brazil (ranked 1st), USA (2nd), Argentina (3rd), Paraguay (6th), Canada (8th), and Bolivia (10th).[41] We also include South Africa, which ranked 12th in 2023 among worldwide countries of soybean harvested area.

The soybean adoption curves are well aligned for the USA, Brazil, Argentina, and to some extent even Paraguay. Bolivia's and South Africa's GM area matches sufficiently well to the ISAAA data but the adoption curves differ, again pointing to the application of FAO data as likely introducing some error. We observe Canada's adoption curves differ as do the data reflecting GM harvested area. Since the year 2000, the ISAAA has consistently reported higher rates of GM soy adoption. By 2019, the ISAAA suggests Canada had 2.39 million hectares in GM soybeans while AgbioInvestor reports

[41] Remaining top-10 countries include: India (ranked 4th), China (5th), Russia (7th), and Ukraine (9th).

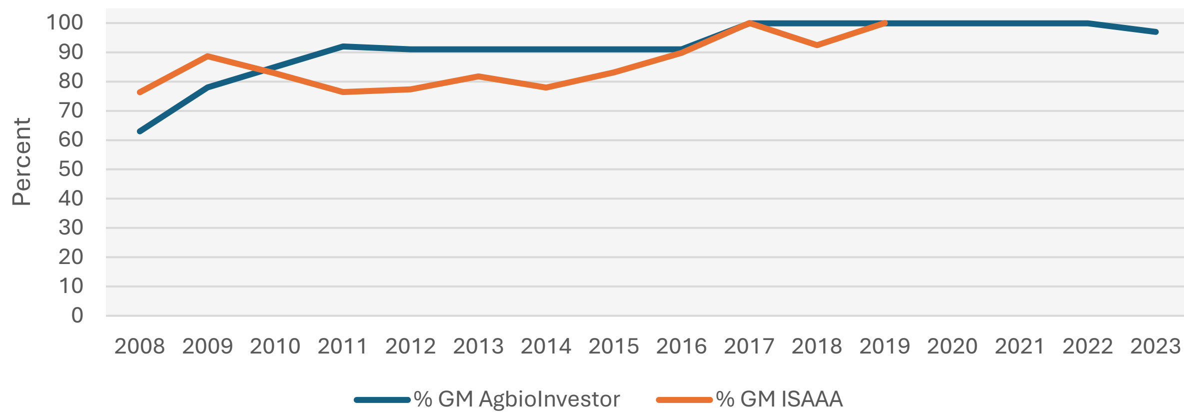
1.83 million hectares in GM soybeans. Statistics Canada data suggest 1.74 million hectares of GM soybean were harvested in 2019, close to the AgbioInvestor data estimate.[42]

Figure A2 (a) – (g). Comparing AgbioInvestor and ISAAA GM Soybean Adoption Curves, selected countries, 1996-2023

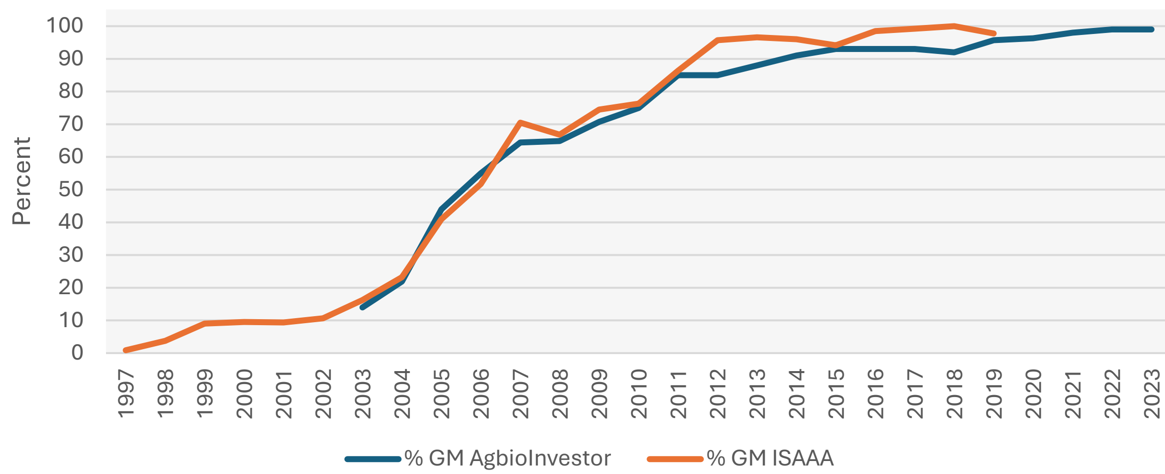


[42] See: https://www150.statcan.gc.ca/t1/tbl1/en/cv.action?pid=3210004201

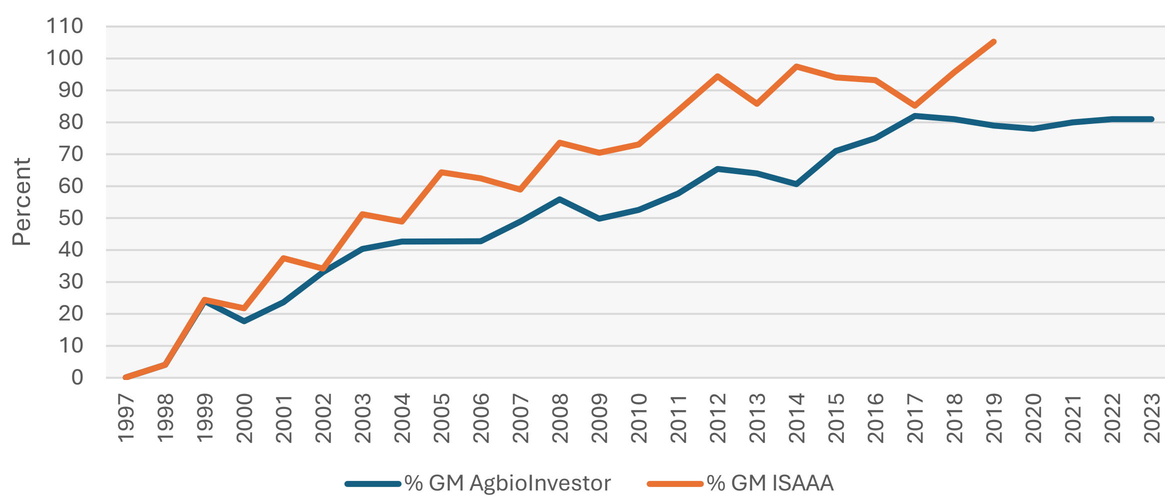
(b) Bolivia

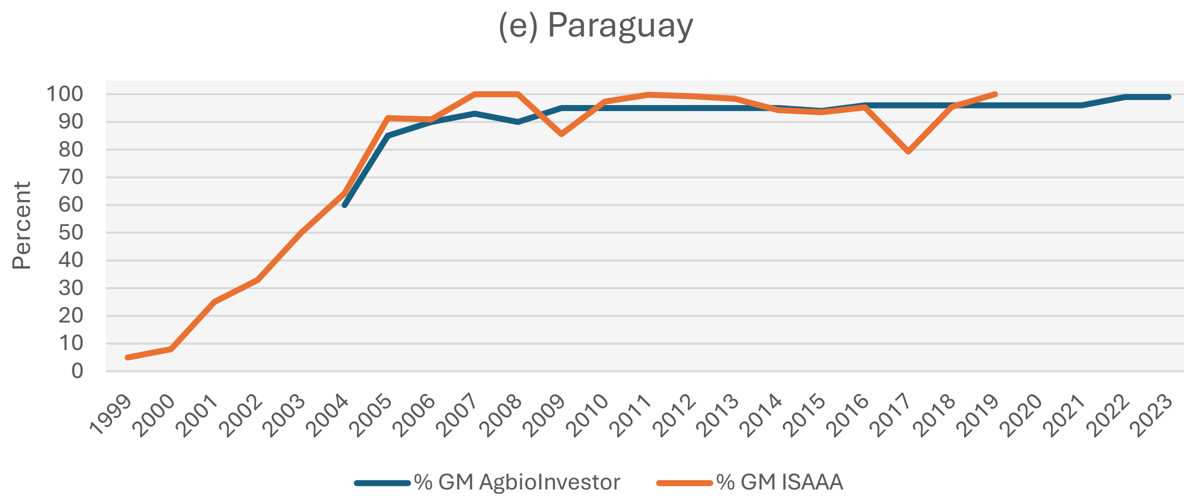


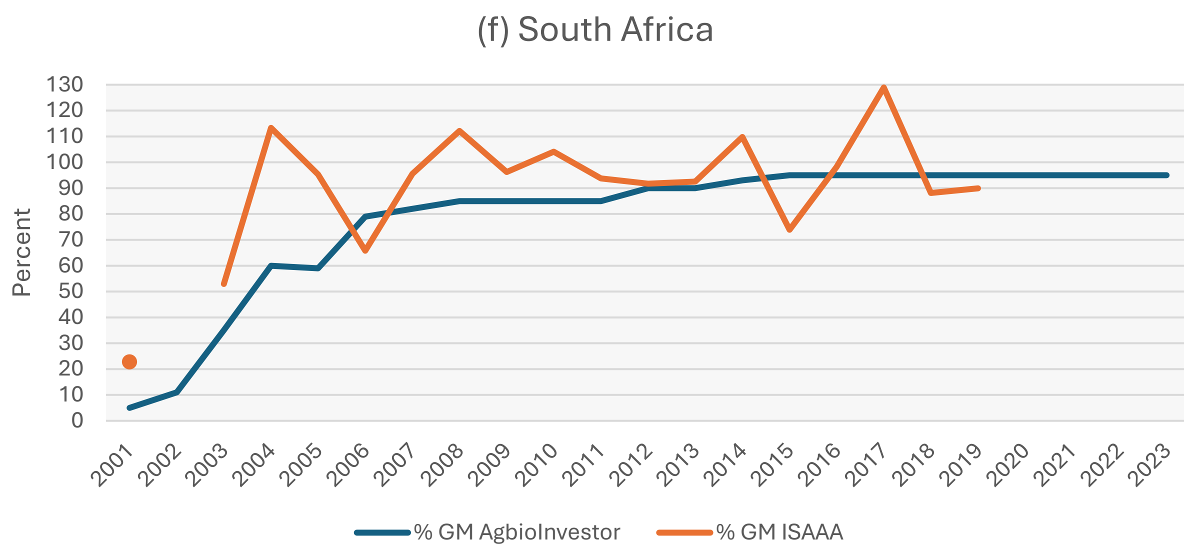
(c) Brazil

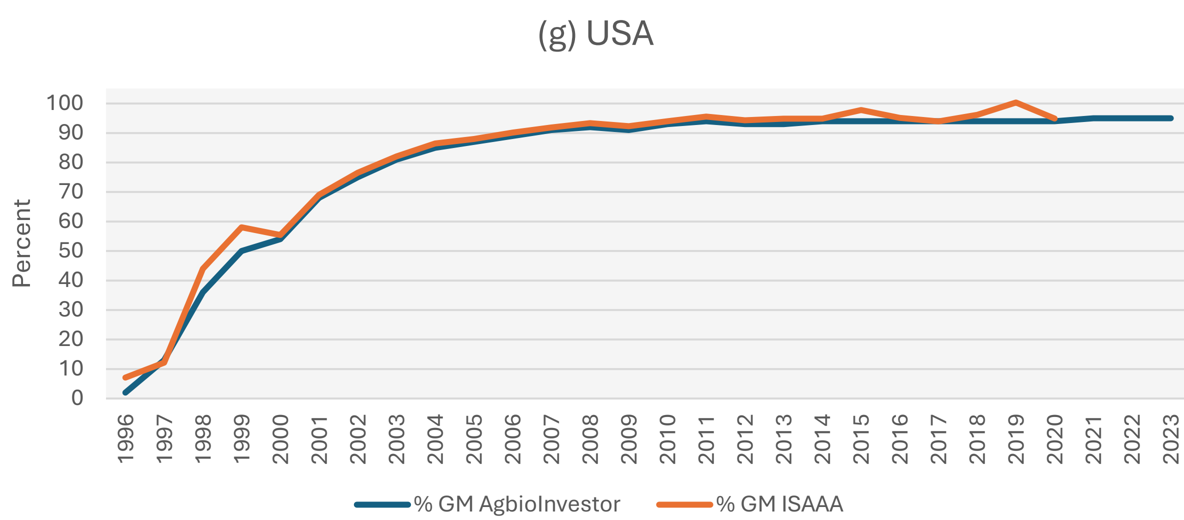


(d) Canada




(e) Paraguay
Percent
100
90
80
70
60
50
40
30
20
10
0
1999
2000
2001
2002
2003
2004
2005
2006
2007
2008
2009
2010
2011
2012
2013
2014
2015
2016
2017
2018
2019
2020
2021
2022
2023
% GM AgbioInvestor
% GM ISAAA

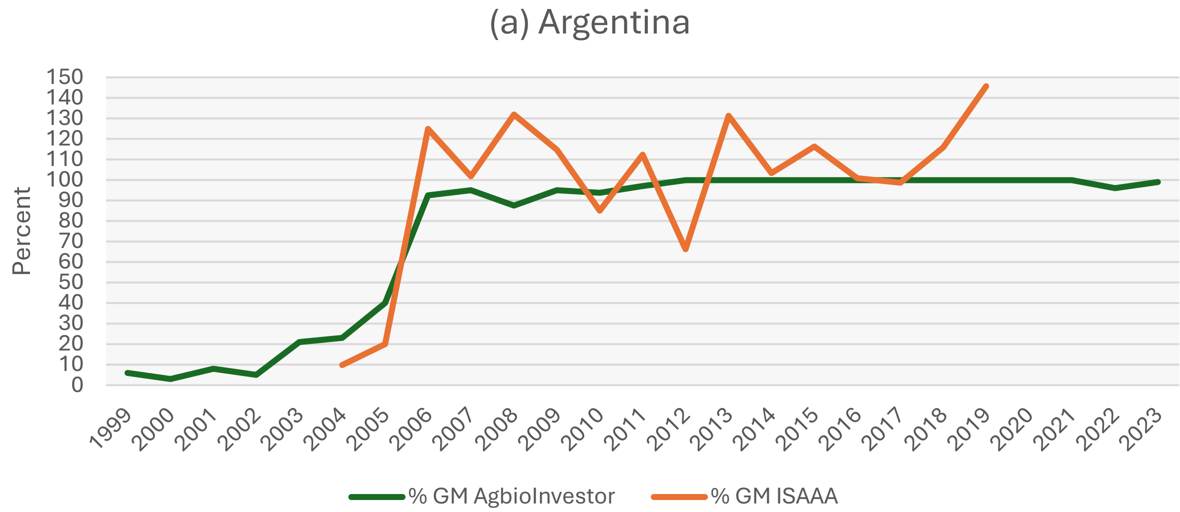

(f) South Africa
Percent
130
120
110
100
90
80
70
60
50
40
30
20
10
0
2001
2002
2003
2004
2005
2006
2007
2008
2009
2010
2011
2012
2013
2014
2015
2016
2017
2018
2019
2020
2021
2022
2023
% GM AgbioInvestor
% GM ISAAA

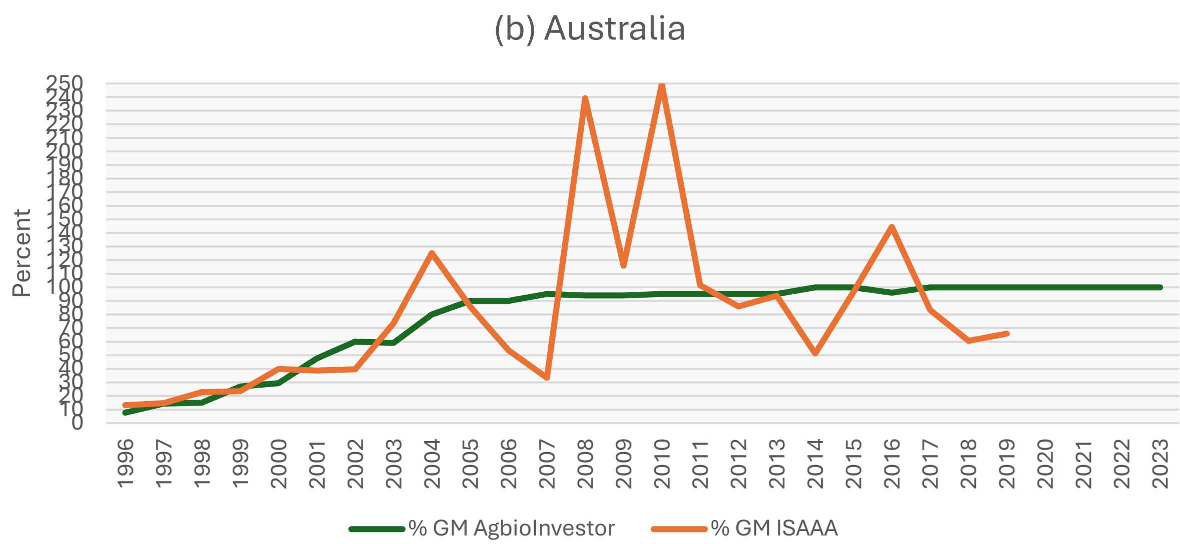

(g) USA
Percent
100
90
80
70
60
50
40
30
20
10
0
1996
1997
1998
1999
2000
2001
2002
2003
2004
2005
2006
2007
2008
2009
2010
2011
2012
2013
2014
2015
2016
2017
2018
2019
2020
2021
2022
2023
% GM AgbioInvestor
% GM ISAAA

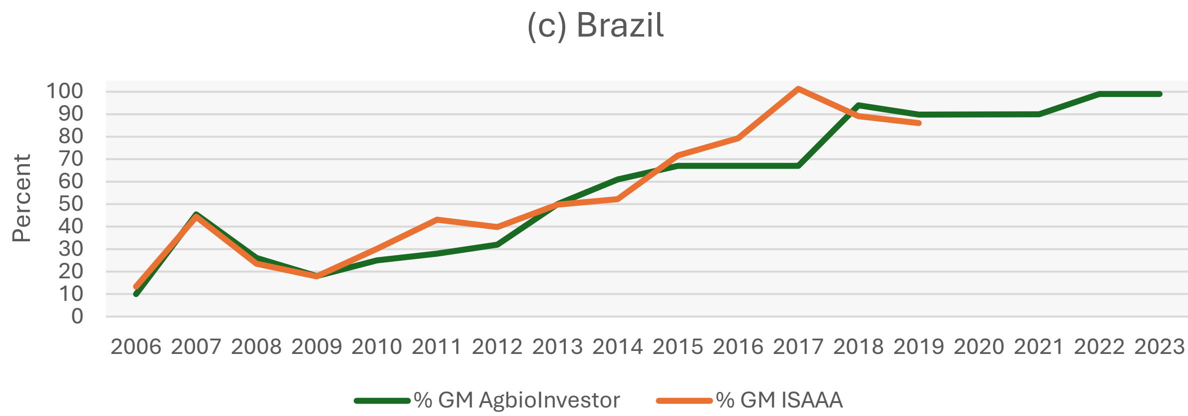
A.3 Cotton harvested area

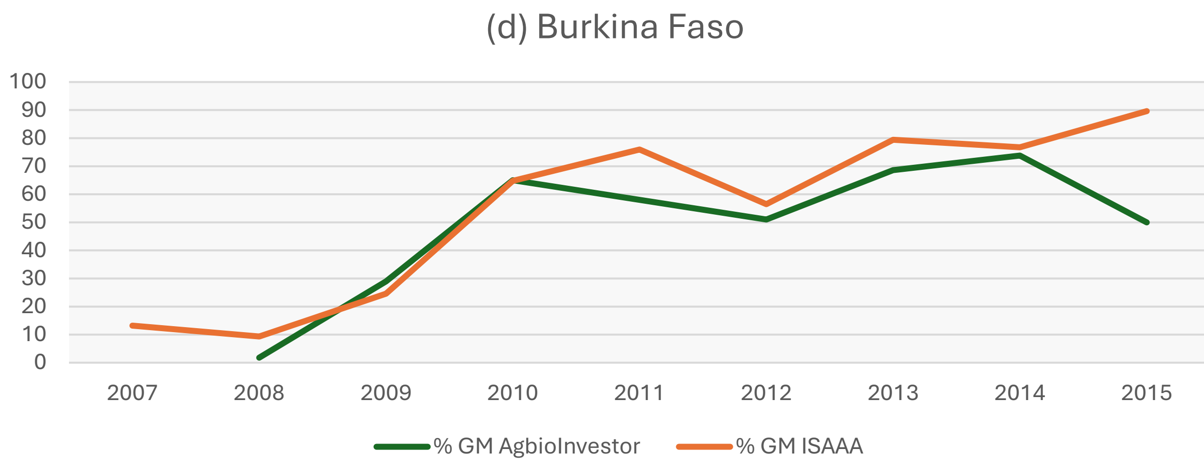
Among GM adoption curves exhibited below, only India, Burkina Faso, and China match well. Brazil and Pakistan also compare although there are some modest differences. Argentina, Australia, and South Africa show wide differences in adoption curves that again appear to originate from differences in estimates of GM area that become exacerbated once compared to FAO data. In terms of temporal coverage, as with the other crops, we identify differing starts years of GM area between the two sources for countries, such as Argentina, Burkina Faso, China, and South Africa. Notably, the AgbioInvestor data are more recent.

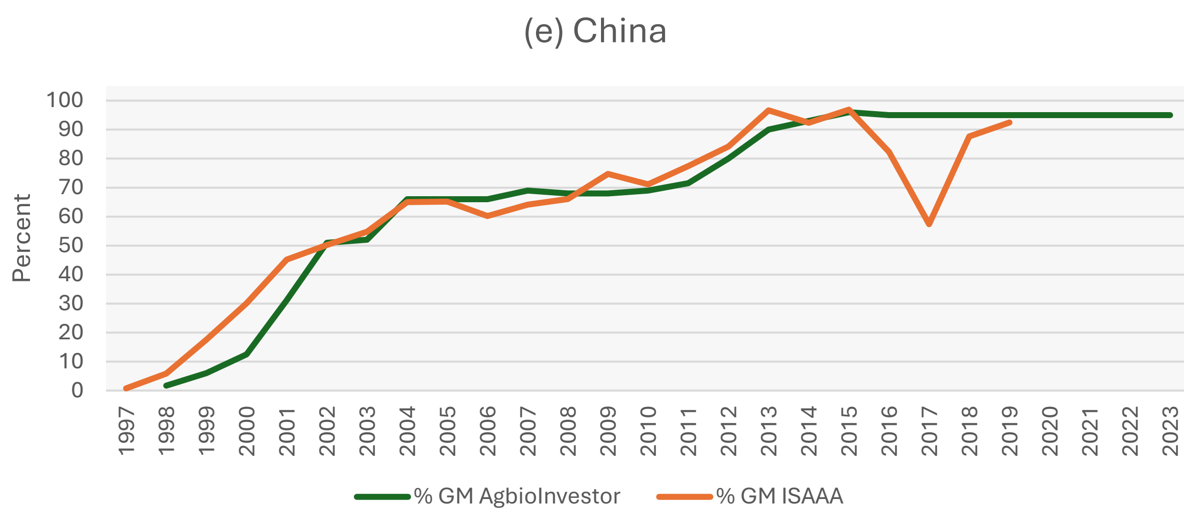
Figure A3 (a) – (h). Comparing FAOSTAT and AgbioInvestor databases for selected countries, cotton harvested area, 1996-2023

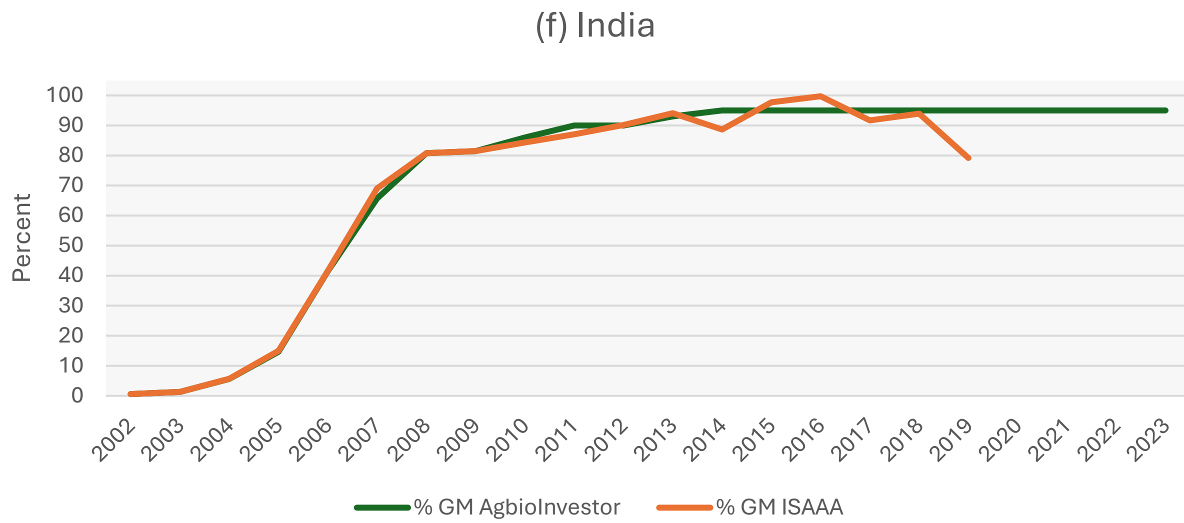


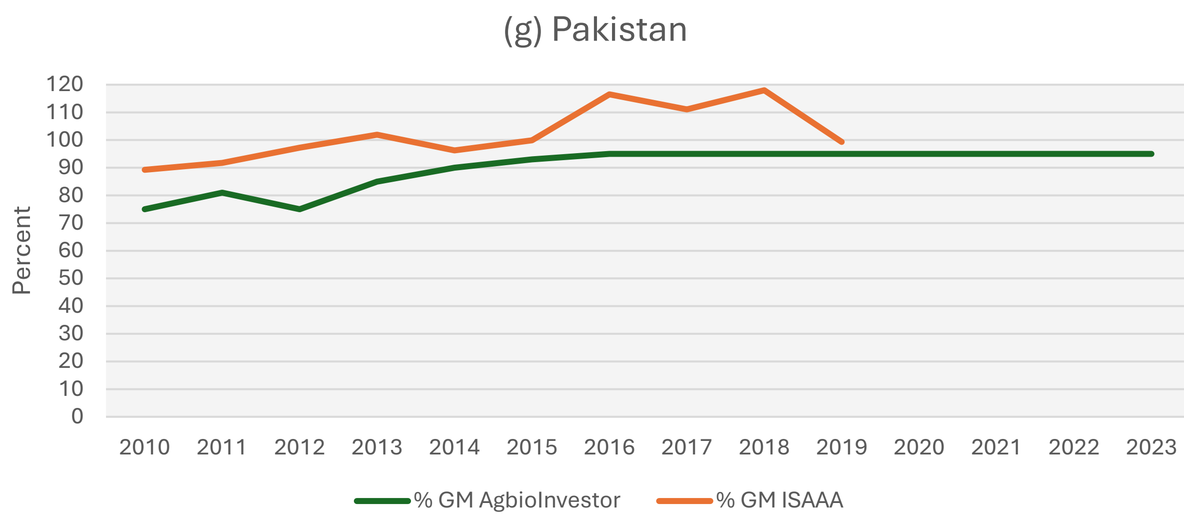


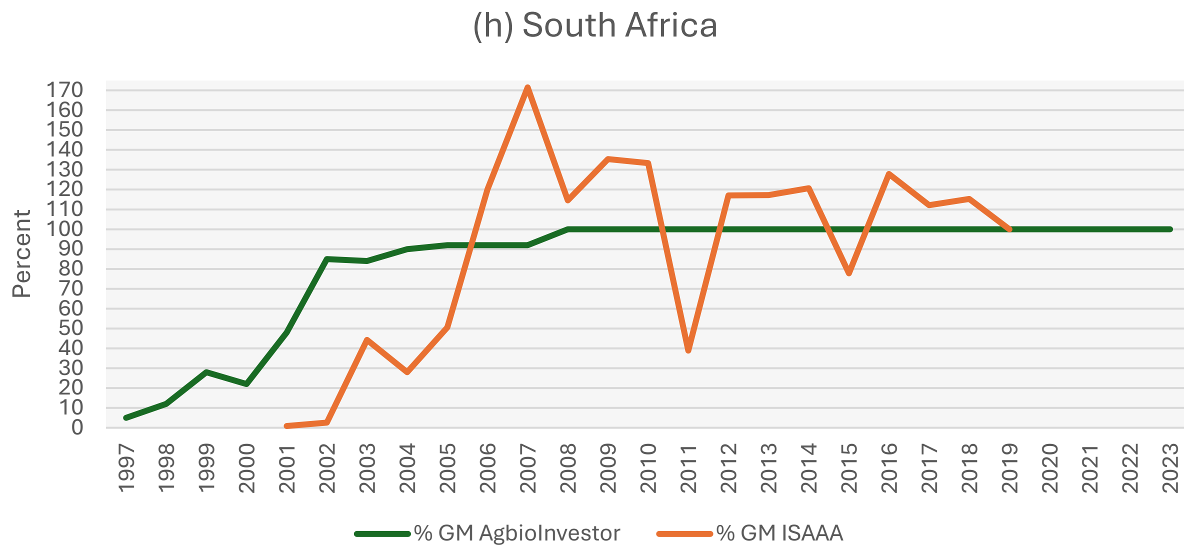

(c) Brazil
Percent
100
90
80
70
60
50
40
30
20
10
0
2006 2007 2008 2009 2010 2011 2012 2013 2014 2015 2016 2017 2018 2019 2020 2021 2022 2023
% GM AgbioInvestor
% GM ISAAA


(d) Burkina Faso
100
90
80
70
60
50
40
30
20
10
0
2007 2008 2009 2010 2011 2012 2013 2014 2015
% GM AgbioInvestor
% GM ISAAA


(e) China
Percent
100
90
80
70
60
50
40
30
20
10
0
1997 1998 1999 2000 2001 2002 2003 2004 2005 2006 2007 2008 2009 2010 2011 2012 2013 2014 2015 2016 2017 2018 2019 2020 2021 2022 2023
% GM AgbioInvestor
% GM ISAAA


(f) India
Percent
100
90
80
70
60
50
40
30
20
10
0
2002 2003 2004 2005 2006 2007 2008 2009 2010 2011 2012 2013 2014 2015 2016 2017 2018 2019 2020 2021 2022 2023
% GM AgbioInvestor
% GM ISAAA


(g) Pakistan
Percent
120
110
100
90
80
70
60
50
40
30
20
10
0
2010 2011 2012 2013 2014 2015 2016 2017 2018 2019 2020 2021 2022 2023
% GM AgbioInvestor
% GM ISAAA


(h) South Africa
Percent
170
160
150
140
130
120
110
100
90
80
70
60
50
40
30
20
10
0
1997
1998
1999
2000
2001
2002
2003
2004
2005
2006
2007
2008
2009
2010
2011
2012
2013
2014
2015
2016
2017
2018
2019
2020
2021
2022
2023
% GM AgbioInvestor
% GM ISAAA

Appendix B. Comparison of regulatory approval databases

As discussed in Appendix A, the AgbioInvestor Approval database provides bulk downloads of regulatory approval records for genetically modified events, covering GM cotton, maize, soybean, and other GM crops. These regulatory approvals constitute a suitable empirical benchmark for assessing the accuracy of trademark data as a measure of diffusion across jurisdictions. In our study, we exploit this relationship to construct and analyze GM crop–specific diffusion trends over time and across countries. In addition, we use these data in our case studies as a baseline comparator against which we benchmark trademark registrations for our focal GM crop brands.

According to the AgbioInvestor website, the regulatory approval information used to compile the AgbioInvestor GM Monitor database has "principally been sourced from government websites for each country," (see https://gm.agbioinvestor.com/methodology for more information). Each observation in the AgbioInvestor GM Monitor database includes a website link to its primary source (variable: *URL*). We note that a small number of observations are drawn from non-governmental sources, including press releases issued by firms seeking regulatory approval (variable: *ReportOnly*). Although these data are derived directly from official sources, the database itself may be incomplete. Prior research (Mallah et al. 2017) finds that no single regulatory database fully captures all GM regulatory approvals. In Mallah et al. (2017), the authors standardize and compare three GM regulatory approval databases from the following sources: (1) ISAAA; (2) the Biosafety Clearing House (BCH); and (3) the Center for Environmental Risk Assessment (CERA). Leveraging these standardized regulatory approval data and the AgbioInvestor GM Monitor data, we evaluate the relative coverage of the AgbioInvestor GM Monitor data by comparing it to the cumulative counts of GM approvals at the event–jurisdiction level through 2015 for each respective database contained in the Mallah et al. (2017) data, e.g. BCH, CERA, ISAAA.[43]

Our analysis relies on approval counts over time rather than a direct comparison of the specific approvals contained in each database, because GM event information in the AgbioInvestor GM Monitor database is not necessarily standardized in the same manner as in the Mallah et al. (2017) data matrix ---potentially introducing error into a databased matched at the GM event level. In addition, we calculate cumulative approval counts to mitigate differences in reporting years across databases, an issue highlighted by Mallah et al. (2017). We plot cumulative counts of GM regulatory approvals from each database for cotton (Figure B1), maize (Figure B2), and soybean (Figure B3) over the period 1994–2015. Focusing primarily on the relative performance of the AgbioInvestor and ISAAA databases, these figures show that the AgbioInvestor GM Monitor database slightly underperforms the ISAAA database in terms of cumulative regulatory approval counts across all three focal crops for most of the observed timeframe. However, by the end of the sample period, cumulative counts in the AgbioInvestor GM Monitor database converge toward and exceed the corresponding ISAAA totals. Cumulative totals for the CERA database are higher than those in the AgbioInvestor database through 2010; however, the CERA database appears to exhibit relatively weaker coverage of GM cotton and maize approvals beginning in 2010 and contains fewer additional regulatory approvals thereafter compared to the AgbioInvestor data. Finally, the BCH database shows relatively weaker coverage across all crops compared to the other three databases.

[43] We transformed this publicly-available data matrix into an event-level dataset for purposes of our analysis. Our sample is truncated at reporting year 2015 to avoid right-censoring of the data.

Figure B1. Cumulative counts of GM cotton regulatory approvals by database, 1994-2015

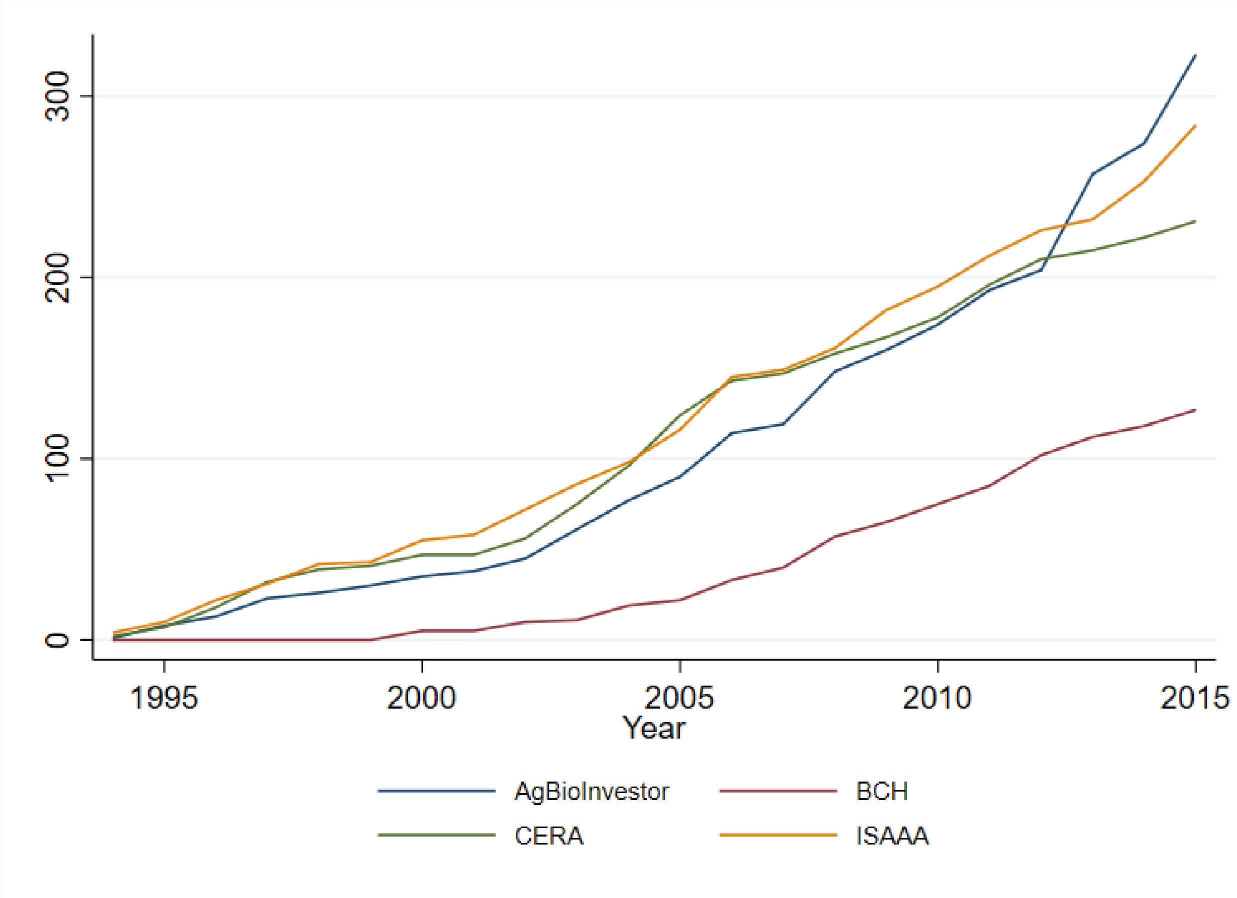


Figure B2. Cumulative counts of GM maize regulatory approvals by database, 1994-2015

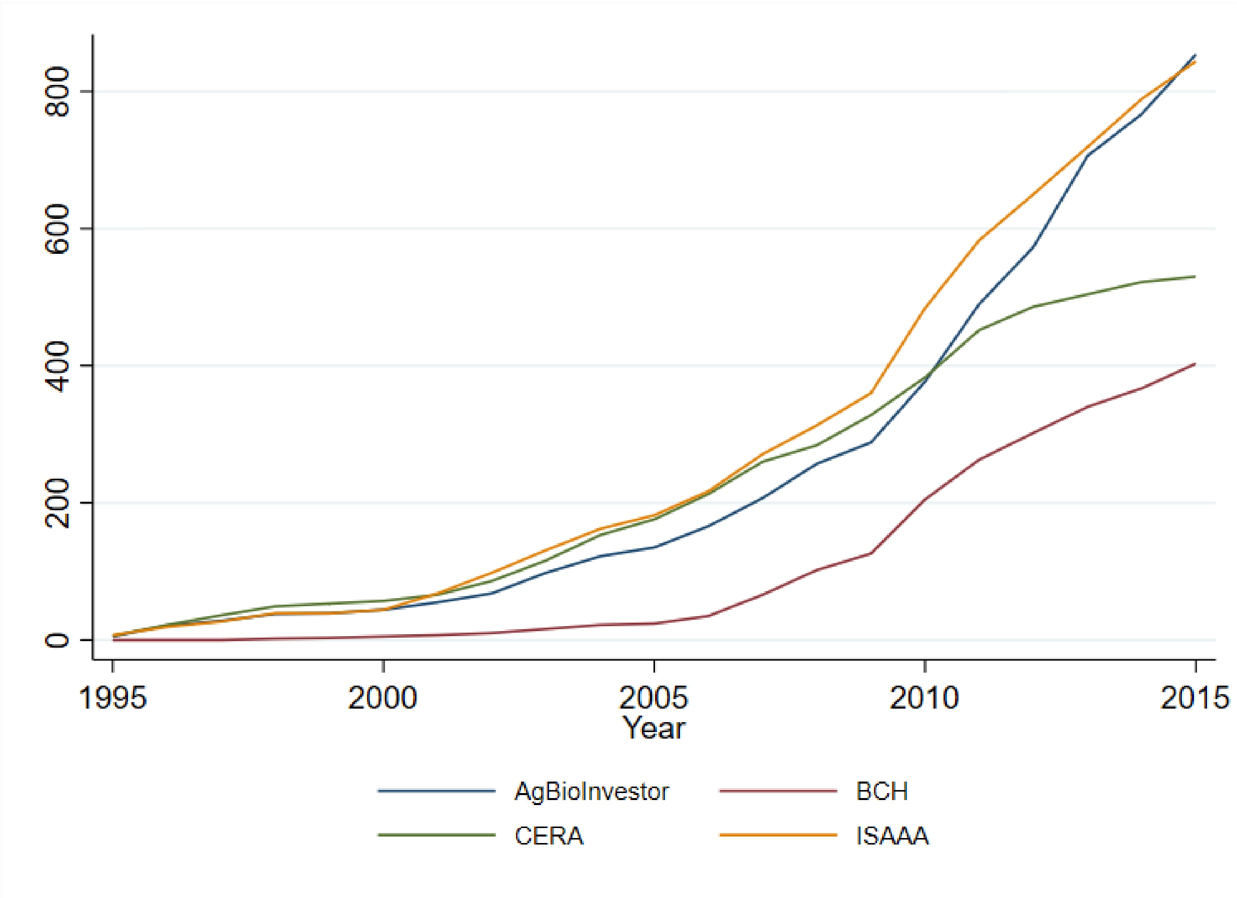
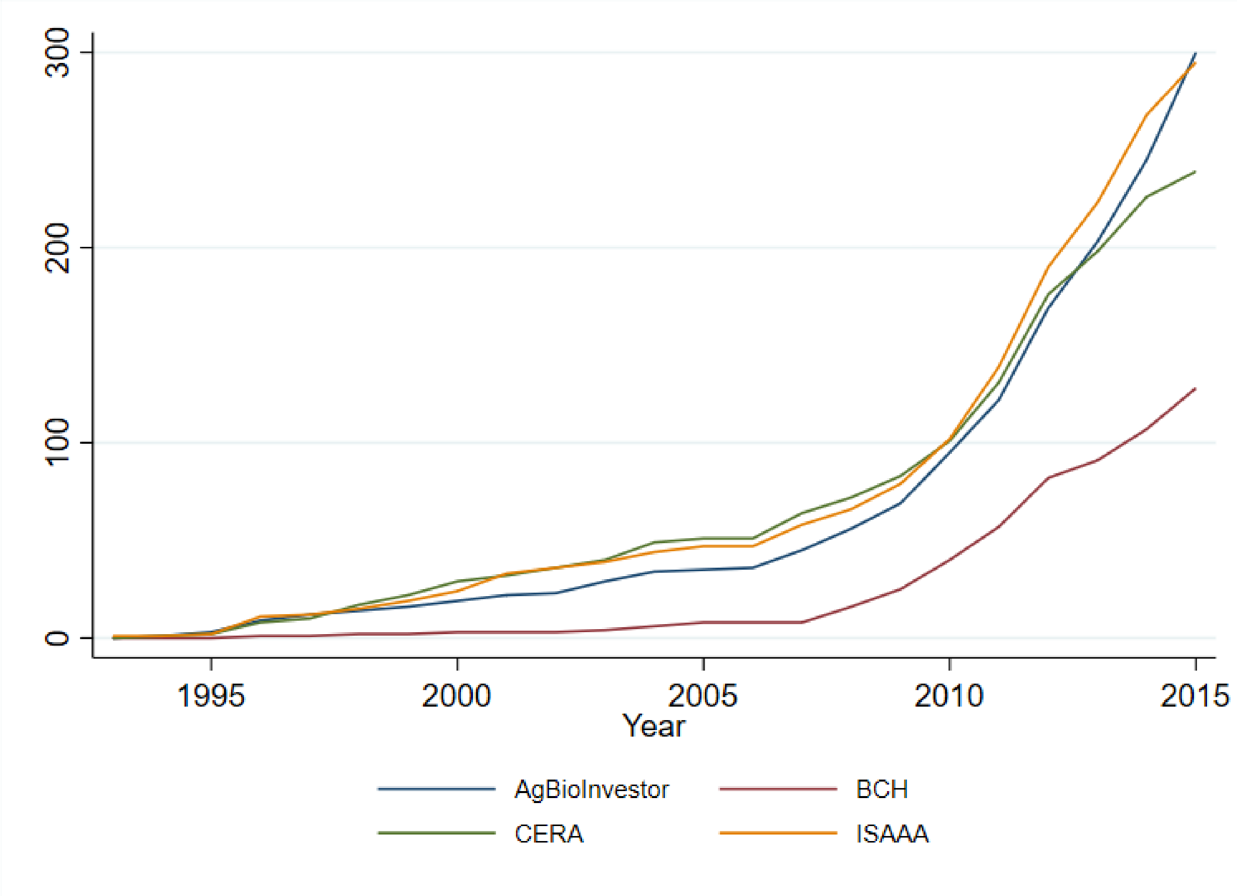


Figure B3. Cumulative counts of GM soybean regulatory approvals by database, 1994-2015



Appendix C. Regulatory approvals and trademark registrations for *Bollgard*, *LibertyLink*, and *Widestrike*

In this appendix, we compare the international coverage of regulatory approvals and trademark registrations for the three remaining brands, shown in Tables C.1, C.2, and C.3. We observe a similar pattern of overlap between these brands and the *Roundup Ready* technologies. For *Bollgard*, we identify 24 jurisdictions that have either trademark registrations or regulatory approval. Of those, 10 (42%) countries have both data indicators, 9 (37.5%) have only trademark registration as an indicator of technology diffusion, and 5 (21%) have only regulatory approval information. The coverage detailed in Table C.1 indicates that, similar to *Roundup Ready* shown in Table 2 above, the importance of accounting for trademark registrations in any technology diffusion study, given the more expansive country coverage afforded by those data.

Table C.1. International coverage of regulatory approvals and trademark registrations for *Bollgard*

Country	Trademark Filing / Registration	Regulatory Approval	Eligible for Cancellation after	Use Required at Registration	Declaration/Statement of Use Required during lifecycle of TM
Australia	1	1	3 years of continuous non-use	No*	
Belize	1	0	5 years of continuous non-use		
Brazil	1	1	5 years of continuous non-use	No^	
Canada	0	1	3 years of continuous non-use	No, use requirements were removed effective 2019^	
Costa Rica	1	1	5 years of continuous non-use	No^	
European Union	1	1	5 years of continuous non-use	No (Regulation (EU) 2017/1001 - Article 58 1(a))	
India	1	1	5 years of continuous non-use	No^	
Indonesia	1	1	3 years of continuous non-use	No*	Yes, statement of use required to maintain registration*
Israel	1	0	2 years of continuous non-use	No*	
Japan	0	1	3 years of continuous non-use	No^	No, checks on use were abolished after a 1996 law change.*
Kenya	1	0	5 years of continuous non-use	No*	
Mexico	1	1	3 years of continuous non-use	No*	Effective 2018, declarations of use must be submitted three years following registration and at renewal.*
Mozambique	1	0			
Namibia	1	0			
New Zealand	0	1	3 years of continuous non-use	No*	
Philippines	1	1	5 years of continuous non-use		Declaration of Actual Use (DAU) must be filed at three years of filing and at various points after registration (source: ipophil.gov.ph)
Singapore	0	1	5 years of continuous non-use	No*	
South Korea	0	1	3 years of continuous non-use	No*	No, proof of use requirements were abolished effective 1994*
Spain	1	0	5 years of continuous non-use	No*	No, current law does not require an affadvit declaring use*
Thailand	1	0	3 years of continuous non-use	No*	
UK	1	1	5 years of continuous non-use	No*	
USA	1	1	3 years of continuous non-use	Yes, appliant must demonstrate use in commerce prior to registration*	
Viet Nam	1	0	2 years of continuous non-use	No*	
Zimbabwe	1	0	5 years of continuous non-use	No*	

Sources: WIPO's Global Brand Database; AgbioInvestor GM Approval Database; * Horwitz on World Trademark Law (2025); ^ Chambers and Partners (2023)

For LibertyLink, we identify 27 jurisdictions in Table C.2 where either the product has a trademark registration or a regulatory approval. Of those, 14 (52%) countries have both diffusion indicators, 8 (30%) have only trademark registrations as an indicator of technology diffusion, and 5 (18%) have only regulatory approval information. A similar trend holds for *Widestrike* in Table C.3, where we identified 13 jurisdictions with either trademark registrations or regulatory approval. Surprisingly, only 3 (23%) have both sets of indicators, and only 4 (31%) have only trademark registrations recorded. In this case, the majority (6 countries or 46% of the sample shown in Table C.3) have only regulatory approvals. The international coverage of *Widestrike* thus differs from *Bollgard* or *Roundup Ready* in that the most coverage comes not from the trademark data but the regulatory approval data.

Table C.2. International coverage of regulatory approvals and trademark registrations for *LibertyLink*

Country	Trademark Filing / Registration	Regulatory Approval	Eligible for Cancellation after	Use Required at Registration	Declaration/Statement of Use Required during lifecycle of TM
Australia	1	1	3 years of continuous non-use	No*	
Brazil	1	1	5 years of continuous non-use	No^	
Canada	1	1	3 years of continuous non-use	No, use requirements were removed effective 2019^	
Chile	1	0	2 years of continuous non-use	No*	
Costa Rica	0	1	5 years of continuous non-use	No^	
Denmark	1	0	5 years of continuous non-use	No*	
Estonia	1	0	5 years of continuous non-use	No*	
European Union	1	1	5 years of continuous non-use	No (Regulation (EU) 2017/1001 - Article 58 1(a))	
Germany	1	0	5 years of continuous non-use	No, but serious use required to maintain registration^	
India	1	1	5 years of continuous non-use	No^	
Indonesia	1	1	3 years of continuous non-use	No*	Yes, statement of use required to maintain registration*
Japan	0	1	3 years of continuous non-use	No^	No, checks on use were abolished after a 1996 law change.*
Malaysia	1	1	3 years of continuous non-use	No*	
Mexico	1	1	3 years of continuous non-use	No*	Effective 2018, declarations of use must be submitted three years following registration and at renewal.
Mongolia	1	0	5 years of continuous non-use	No*	
New Zealand	1	1	3 years of continuous non-use	No*	
Norway	1	0	5 years of continuous non-use	No, but use required to maintain registration^	
Philippines	1	1	5 years of continuous non-use		Declaration of Actual Use (DAU) must be filed at three years of filing and at various points after registration (source: ipophil.gov.ph)
Singapore	0	1	5 years of continuous non-use	No*	
South Korea	1	1	3 years of continuous non-use	No*	No, proof of use requirements were abolished effective 1994*
Switzerland	0	1	5 years of continuous non-use	No^	
Thailand	1	0	3 years of continuous non-use	No*	
UK	1	1	5 years of continuous non-use	No*	
USA	1	1	3 years of continuous non-use	Yes, appliant must demonstrate use in commerce prior to registration*	
Uruguay	1	1	5 years of continuous non-use	No*	
Viet Nam	0	1	2 years of continuous non-use	No*	
Zimbabwe	1	0	5 years of continuous non-use	No*	

Sources: WIPO's Global Brand Database; AgbioInvestor GM Approval Database; * Horwitz on World Trademark Law (2025); ^ Chambers and Partners (2023)

Table C.3. International coverage of regulatory approvals and trademark registrations for *Widestrike*

Country	Trademark Filing / Registration	Regulatory Approval	Eligible for Cancellation after	Use Required at Registration	Declaration/Statement of Use Required during lifecycle of TM
Australia	1	1	3 years of continuous non-use	No*	
Brazil	1	1	5 years of continuous non-use	No^	
Costa Rica	0	1	5 years of continuous non-use	No^	
European Union	0	1	5 years of continuous non-use	No (Regulation (EU) 2017/1001 - Article 58 1(a))	
India	1	0	5 years of continuous non-use	No^	
Japan	0	1	3 years of continuous non-use	No^	No, checks on use were abolished after a 1996 law change.*
Mexico	1	1	3 years of continuous non-use	No*	Effective 2018, declarations of use must be submitted three years following registration and at renewal.*
New Zealand	0	1	3 years of continuous non-use	No*	
South Korea	0	1	3 years of continuous non-use	No*	No, proof of use requirements were abolished effective 1994*
Spain	1	0	5 years of continuous non-use	No*	No, current law does not require an affadvit declaring use*
UK	0	1	5 years of continuous non-use	No*	
USA	1	0	3 years of continuous non-use	Yes, appliant must demonstrate use in commerce prior to registration*	
Uruguay	1	0	5 years of continuous non-use	No*	

Sources: WIPO's Global Brand Database; AgbioInvestor GM Approval Database; * Horwitz on World Trademark Law (2025); ^ Chambers and Partners (2023)

Appendix D. Evaluation of von Graevenitz et al.'s (2022) Approach to GM Crop Brand Diffusion Analysis

In this appendix, we assess the applicability of the token-based approach from von Graevenitz et al. (2022) to analyze the diffusion of GM crop technologies, focusing on four well-known GM crop brands: *Roundup Ready* (originally developed by Monsanto, now Bayer), *LibertyLink* (originally developed by Bayer, sold to BASF), *Bollgard* (Monsanto), and *Widestrike* (originally Dow, now Corteva). To this end, we identify all trademark applications related to these focal brands using trademark filings and registrations from the U.S. Patent and Trademark Office --- the same focal country as von Graevenitz et al. (2022). The initial match yields 48 individual trademark applications associated with the four brands.

Next, we search each matched trademark's goods and services statement for identifiable markers that are consistent with GM crop terminology (e.g., gene, genetically-modified). After reviewing these statements, we find substantial variation in the presence of identifying language across trademarks. Only 15 of the 48 (31%) U.S. trademark applications contain language consistent with GM technology in their respective goods and services statements. For example, an early *Roundup Ready* trademark application (serial number 74,663,984) defined the scope of protection as "agricultural seed, namely, vegetable seeds" without explicitly mentioning any GM technology.

We further assess the timing of the first occurrence of identifying language in the trademark filings. For three of the four brands, at least one early trademark application contains language consistent with GM crop technology. For example, the goods and services statement for trademark application 74,395,853, filed on 28 May 1993, by Monsanto includes the following description: "herbicide-tolerant genes for use in the production of agricultural seed". *LibertyLink* was the only brand of the four that did not contain such language in its early trademark filings, where its first application containing language identifying the mark as GM-related was filed on 12 November 2012 (application number 85,776,886) --- nearly 20 years after the first such application was filed at the USPTO. Given this brand's significance in GM crop commercialization, the extended period between market entry (January 1997) and the first mention of GM-related language in the *LibertyLink* TM registration suggests that applying a token-based methodology may omit critical information.

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