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Genetically modified (GM) crop use in Colombia: farm level economic and environmental contributions

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ABSTRACT

This study assesses the economic and environmental impacts that have arisen from the adoption and use of genetically modified (GM) cotton and maize in Colombia in the fifteen years since GM cotton was first planted in Colombia in 2003. A total of 1.07 million hectares have been planted to cotton and maize containing GM traits since 2003, with farmers benefiting from an increase in income of US $301.7 million. For every extra US $1 spent on this seed relative to conventional seed, farmers have gained an additional US $3.09 in extra income from growing GM cotton and an extra US $5.25 in extra income from growing GM maize. These income gains have mostly arisen from higher yields (+30.2% from using stacked (herbicide tolerant and insect resistant cotton and +17.4% from using stacked maize). The cotton and maize seed technology have reduced insecticide and herbicide spraying by 779,400 kg of active ingredient (−19%) and, as a result, decreased the environmental impact associated with herbicide and insecticide use on these crops (as measured by the indicator, the Environmental Impact Quotient (EIQ)) by 26%. The technology has also facilitated cuts in fuel use, resulting in a reduction in the release of greenhouse gas emissions from the GM cotton and maize cropping area and contributed to saving scarce land resources.

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GM crops; Colombia; maize; cotton; insect resistance; herbicide tolerance

Introduction

GM crop technology has been widely used in cotton and maize in many parts of the world for more than 20 years and GM technology in these crops was first used in the USA in 1996. Since then, its use has been extended to 55.5 million ha (2018) of maize planted in thirteen countries and 23.8 million ha of cotton also planted in thirteen countries. In Colombia, GM cotton was first grown commercially in 2003 on a restricted basis, with unrestricted planting from 2004. In the first years of commercial growing, varieties containing the insect resistance trait (Mon 531 'Bollgard I): resistant to the following pests; budworms (*Heliothis virescens*), earworms (*Helicoverpa zeae*), pink bollworm (*Pectinophora gossypiella*), false pink bollworm (*Sacadodes pyralis*), cotton worm (*Alabama argillacea)* and cotton leafworm (*Spodoptera sp*) were planted. 'Stacked' seed containing both this IR trait and the herbicide tolerance trait Mon 1445 (tolerance to glyphosate) became available from 2006. These were then followed up with second generation GM traits such as Mon 15985 (IR: Bollgard II that extended control to include the Fall Armyworm (*Spodoptera*)) and Mon 88913 (HT: tolerant to glyphosate 'RoundupFlex' that allowed 'over the top' spraying of gylyphosate for weed control later in the growing season) from 2009/10. Liberty Link cotton (tolerant to the herbicide glufosinate) became available in 2011 and other 'second-generation' traits such as 'Twinlink' (IR) and 'Glytol (HT tolerant to glyphosate and glufosinate) became available to farmers from 2014. Cotton seed varieties containing the stacking of these two latter traits (Twinlink and Glytol) have been rapidly adopted and accounted for 75% of GM cotton plantings in 2018 (Data source: Instituto Colombiano Agropecuario (ICA)). In 2018, GM cotton was planted on 12,103 ha (of which 98% contained both IR and HT traits: Table 1).

GM maize was first grown commercially in 2006, initially on a restricted basis and post 2007, on an unrestricted basis. The first traits available (eg, 'Yieldgard' varieties containing the trait Mon 810) conveyed resistance to common maize pests like Corn borer (*Diatraea*) and corn earworm (*Helicoverpa*), with 'Herculex I' varieties containing the DAS 1507 trait conveying resistance to these two

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Table 1. GM crop plantings in Colombia 2013–2018 (ha).

Crop	2013	2014	2015	2016	2017	2018
Corn	75,094	89,048	85,251	100,109	86,030	76,014
Cotton	26,913	29,838	15,868	9,814	9,075	12,103
Total	102,007	118,886	101,119	109,923	95,105	88,117

Data source: ICA – Colombian Agricultural Institute

[a]The GM crop areas in Colombia in 2018 were equivalent to about 90% and 18% respectively of the total cotton and maize crops

[b]Th recent decrease in the areas planted to GM crops (in particular cotton) reflects the decrease in the total area planted to these crops. Overall planting areas are largely influenced by the price received and profitability for the crops relative to alternative crops and farming activities. This has fallen, especially for cotton because of decreasing international market prices for cotton and a reduction in the level of domestic support for growers. In terms of the share of total crop plantings accounted for by GM-traited seed, these have remained at over 80% of the total cotton crop since 2012 and been between 40% and 45% of the total 'non subsistence' maize crop (or about 20%-22% of the total maize crop) since 2013

pests plus the Fall Armyworm (*Spodoptera*) pest. Varieties conveying HT traits (tolerance to glyphosate and glufosinate) were also approved in 2007/08, with 'stacked' seeds containing both IR and HT traits available from 2009. In subsequent years, second generation traits have become available from several companies, offering farmers more effective control of pests and reduced chance of pest resistance developing to the technology via the inclusion of more traits with additional modes of control action. In 2018, GM maize was planted on 76,014 ha, of which 92.5% contained both IR and HT traits: Table 1).

This paper presents an assessment of some of the key economic and environmental impacts associated with the adoption of GM cotton and maize from 2003 and 2007 respectively in Colombia. The analysis focuses on:

- *Gross farm income effects* on costs of production, yield/production and farm income;
- *Changes in the amount of insecticides and herbicides applied to the GM crops relative to conventionally grown alternatives and;*
- *The contribution of the technology toward reducing global greenhouse gas (GHG) emissions*

Methodology

The approach used to estimate the impacts of the GM maize and cotton draws on the farm level and aggregate impacts identified in the global impact studies of Brookes and Barfoot.[1,2] These examined farm level economic impacts on crop yield and production gains and environmental impacts associated with changes in insecticide use and carbon emission savings associated with better pest and weed control with the GM HT and IR traits in the two crops. The material presented in this paper combines data presented in the Brookes and Barfoot papers referred to above that covers the period 2002/03-2016/17 but extends the analysis to include impacts in the years 2017/18 and 2018/19. Thus, the methodology used in the global impact of biotech crops covering the 2002/03-2016/17 period has also been applied to the latest two years. This analysis is, itself based on a combination of papers, data and analysis of the impact of the technology in Colombia by other authors plus the author's own analysis. Additional information about the assumptions can be found in Appendix 1 (together with examples of calculations of impacts for the year 2018/19).

The methodology used for assessing the environmental impact associated with pesticide use changes with GM crops in Colombia examines changes in the volume (quantity) of pesticide applied and the use of the Environmental Impact Quotient (EIQ) indicator.[3] The EIQ indicator provides an improved assessment of the impact of GM crops on the environment when compared to only examining changes in volume of active ingredient applied, because it draws on some of the key toxicity and environmental exposure data related to individual products, as applicable to impacts on farm workers, consumers and ecology. The author acknowledges that the EIQ is only a hazard indicator and has important weaknesses (see for example, Peterson R and Schleier J[4] and Kniss A and Coburn C[5]). Nevertheless, since assessing the full environmental impact of pesticide use changes with different production systems is complex and requires substantial collection of (site-specific) data (eg, on ground water levels, soil structure), it is not surprising that no such depth of data is available to provide a full impact assessment associated with pesticide use change with GM crops in Colombia. Therefore, despite the acknowledged weaknesses of the EIQ, it has been used in this paper because it is a superior indicator to only using amount of pesticide active ingredient applied.

Readers requiring further details relating the methodology should refer to the two Brookes and Barfoot[1,2] references cited above.

The Baseline – Nature of Production, Pests And Conventional Methods Of Control

Cotton

Cotton is grown in two distinct regions. The coastal (Caribbean) region accounts for 55%-60% of total plantings, of which the department of Córdoba accounts for the majority of production. Here the cotton is predominately rainfed. The other main growing region is the interior region, where the department of Tolima dominates production. The majority of cotton production in this region is irrigated.

At the time of the introduction of the technology, the average area planted to cotton was 7–9 ha per producer, with average crop size being higher in the interior growing region. The total number of farms growing cotton in the early years of adoption was between 6,000 and 7,000. In 2018, the average size of cotton crop was about 30 hectares per grower, with a total of about 500–600 growers (source: Conalgodon).

There are many cotton pests. The main pests targeted by the technology are budworms (*Heliothis virescens*), earworms (*Helicoverpa zeae*), pink bollworm (*Pectinophora gossypiella*), pink false pink bollworm (*Sacadodes pyralis*), cotton worm (*Alabama argillacea*) and cotton leafworm (*Spodoptera sp*). Other pests, not controlled by the IR technology are boll weevil *(Picudo Antonhomus grandis*) and white fly (*Bemisia tabaci)*. It should also be noted that the original Bollgard I technology did not control cotton leafworm.

Traditionally, in conventional cotton, the primary form of pest control was through the use of insecticides, with an average of about 11 applications being made during a growing season (sources: AgroBio personal communications, Céleres,[6] Brookes and Barfoot,[1,2] Zambrano et al,[7] Kleffmann (various years). Within this, six of the applications were typically made against the pests controlled by GM IR technology. The remaining 4–6 insecticide applications were/are mostly for the control of the boll weevil pest which has been, and remains, the main problem-pest for cotton. Quarantine measures such as requiring crops to be planted in different seasons by region are also important for the control of boll weevil. In the interior region: Cundinamarca, Huila, Tolima, Vichada and Valle del Cauca (which accounted for about 48% of total production in 2018) cotton planting is restricted to the first season (planted in February or March and harvested July-September) and in the Caribbean/Costa region – Cesar, Guajira, Sucre, Córdoba, Bolivar and Antioquia (which accounted for 52% of total production in 2018), it is restricted to the second season (planted in July-October and harvested January-March). Other quarantine measures include mandatory destruction of harvest residues and the use of pheromone traps both pre and during the crop growing season (Sources: as above plus Salazar J et al[8]).

In relation to weed control in conventional cotton this has traditionally been a combination of herbicide use (commonly a pre-emergent application of glyphosate plus two applications of diuron) and two manual/mechanical weeding cycles (source: AgroBio members personal communications and Kleffmann).

Maize

In 2018, the total maize crop in Colombia was about 400,000 ha, of which 65% was yellow maize, mostly used for animal feed use and 36% was white maize, for human consumption (Source: Federación Nacional Cultivadores de Cereales, Leguminosas y Soya – Fenalce). Fenalce statistics classify production into two distinct types of production, with 'tecnificado' production, where farmers use hybrid seed and the crop is sold commercially, accounted for 54% of the area planted, with the balance of 46% 'tradicional' production, where subsistence farming for own-household /domestic consumption is practiced and farmers typically do not use hybrid seed. The crop is grown in most regions of Colombia, although the main departments where commercial maize is grown are Meta Altillanura, Córdoba, Tolima and Valle which accounted for 18%, 16%, 13% and 7% respectively of total plantings in 2018. The GM maize is grown by 'tecnificado' (commercial) growers only and hence the approximate share of this crop using GM technology in recent years has been within the range of 36% to 48% of the total (commercial) crop (36% in 2018).

The main pests of maize in Colombia are Fall Armyworm (*Spodoptera*), Corn borer (*Diatraea*), corn earworm (*Helicoverpa*) and sucking pests

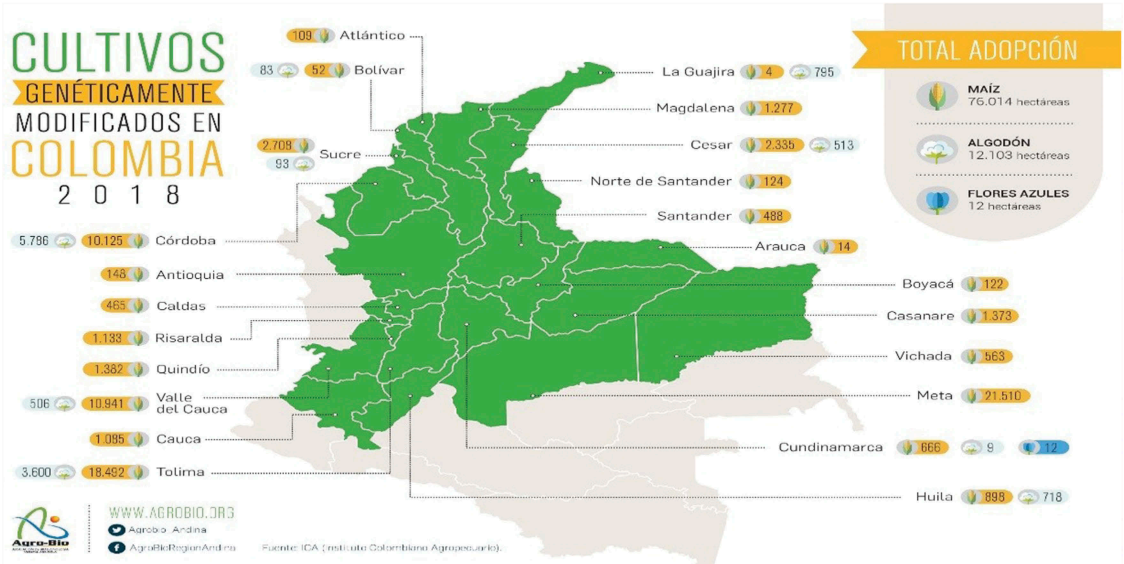

Figure 1. GM crop area in Colombia 2018: by region (hectares).
Source: AgroBio Colombia.

(*Dalbulus maidis*). GM IR technology in maize targets the first three of these pests. Corn borers have traditionally been the main insect pest with widest incidence, with lower levels of incidence of Fall Armyworm and cutworms (source: AgroBio members personal communications). As indicated in Brookes G,[9] with all pests, the pest pressure incidence and levels of infestation typically vary by region and year, being influenced by local climatic conditions, the extent to which conventional forms of control (notably the application of insecticides) are used and planting times (early planted crops are usually better able to withstand attacks compared to crops planted later in year). This means that the negative impact on crop yields can vary widely from zero in years or seasons of no pest pressure to in excess of 50%, when pest pressures are high and insecticides are not used (see for example, Brookes,[9] and Brookes G and Barfoot P.[1]

The traditional method of control of maize pests in commercial crops has been the use of insecticides, with crops typically subject to 1–2 applications for the control of corn boring, armyworm and cutworm pests, and 1–2 applications for the control of sucking pests (plus seed treatments). Given the widespread and regular incidence of pest pressure across all growing regions, almost all (commercial) growers traditionally used insecticides for control of the main maize pests (sources: AgroBio member personal communications and Kleffmann pesticide usage statistics).

Since GM IR maize technology became available to farmers, the highest concentrations of adopters have, not surprisingly, been in the regions of Tolima, Valle del Cauca, Córdoba and Meta regions (Fig. 1), which are also the main maize-growing regions (see above).

Weed control in conventional maize has been mostly based on the use of herbicides; the use of active ingredients like pendimethalin, acetochlor, atrazine and glyphosate/glufosinate pre-emergence, possibly followed by hand weeding (Source: AgroBio member personal communications).

Results

Yield Impacts

In assessing the performance of the GM technology in the two crops of cotton and maize in Colombia, it is important to recognize that there are a number of factors that have/do impact on its performance:

- *Pest pressure*: The level of crop and yield damage caused by pests (both those that the GM IR technology targets and other pests) varies by location, year, climatic factors, timing of planting, whether insecticides are used or not and the timing of application. This means that any potential positive impact on yields derived from the GM IR technology may vary by region, year and farm;

- *Impact of pests not targeted by the GM IR technology*. In the cotton crop, this is of particular importance because boll weevil, which is not controlled by GM IR technology is the main pest in Colombia, especially in the coastal region. Similarly, in the maize crop, whilst the pests targeted by the GM IR technology represent the main pests of maize, other pests such as *Dalbulus maidis* (sucking insects) are widespread and can cause significant crop damage (as vectors of virus diseases). Therefore, conventional forms of control (use of insecticides) are still required for control of these pests;
- *Availability of the GM traits in the leading seed varieties* adapted to growing in each region of the country. If the technology is not available in leading varieties then the performance of seed (notably relating to yield) varieties containing GM technology may perform relatively poorly when/if compared to the yield performance of leading varieties that do not contain the GM technology. Sometimes in the early years of adoption of a new technology when the technology is launched in a limited number of varieties, some of these may not be the best performing varieties and early comparison of varieties containing the GM traits perform relatively poorly when compared to the leading varieties containing no GM traits;
- *The changing nature of seed technology available*. The GM technology available in seed in 2019 is not the same as the GM technology available when first adopted by farmers (2003 for GM IR cotton, 2006 for GM HT cotton, 2006 for GM IR maize, 2007/08 for GM HT maize), as highlighted in the introduction. This means that performance identified in the early years of adoption may not necessarily be representative of performance in later years. For example, the second generation of GM insect resistance genes in (Bollgard II) cotton provided control of more pests than the first generation of GM (Bollgard I) cotton. Also, the underlying performance of seed varieties containing GM traits is subject to change as new, better performing seed varieties are developed.

The influence of these factors can be seen in the findings of some of early studies into impact of using GM technology in Colombia (summarized in Table 2):

- *Zambrano et al.*[7] This study examined the early adoption of IR cotton. It was undertaken in 2007–08, interviewed 364 farmers, mostly in the two most important cotton producing departments of Córdoba and Tolima plus Sucre, which has a relatively small cotton growing area but a significant number of small-scale producers. The survey found that farmers using the IR cotton had higher yields than those using conventional varieties but higher costs of production per hectare. In terms of costs per tonne of cotton fiber, these were, however, lower for the IR cotton growers. The main benefit came from higher yields via enhanced protection against pest attack rather than (expected) reductions in the use of insecticides. The study found that IR cotton growers in two out of the three departments surveyed spent more on insecticides that farmers using conventional varieties. The continued significant expenditure on insecticides reflected the need to control pests that the IR cotton technology did (does) not control (notably boll weevil) and because most IR cotton adopters at that time were larger farms with more resources and access to inputs and machinery than their conventional counterparts (eg, Tolima was the most economically advanced cotton growing region, where the vast majority of farmers had access to irrigation and machinery). The highest levels of adoption were also found in Tolima which was the region which had experienced the highest incidence of pest pressure for the pests controlled by the IR technology. This contrasted with the coastal region of Córdoba and Sucre, where production was mostly rain-fed, farmers had less access to machinery and pests not controlled by the IR technology were

Table 2. Yield impacts from using GM maize and cotton in Colombia.

Crop	Yield of GM relative to conventional % difference	Range of yield impacts (where identified)	Source	Comments
Cotton (IR)	+35% 2007/08	+9.2% to +75%	Zambrano et al[7]	Reported growers in the interior region made significant yield gains whilst those in Caribbean region had mixed results and lower average levels of yield gain. See section for additional discussion
Cotton (IR)	None estimated	+29% to +48%	Fonseca L and Zambrano P[10]	Yield comparisons from Cordoba (Coastal) region in 2009, comparisons by variety (containing only IR traits)
Cotton (HT and stack)	None estimated	−27% to −42%	Fonseca L and Zambrano P[10]	Yield comparisons from Cordoba (Coastal) region in 2009, comparisons by variety (containing both HT and IR traits)
Cotton (stack)	None estimated	−23% to +21%	Zambrano[14]	Small scale survey conducted in early 2010 with farms in El Espinal (Tolima) and Cerete (Cordoba)
Maize	+22% (stacked: IR and HT (tolerance to glufosinate)	None estimated/ provided	Ávila Méndez K et al[11]	Small scale survey in San Juan Valley (Tolima region) undertaken in 2009
Cotton	+24.7% cotton stack	+3% to +39%	Céleres[6]	Survey of farmers in main growing regions plus advisors, industry and public sector researchers
Maize	+16% maize stack	Zero to +31%	Céleres[6]	Survey of farmers in main growing regions plus advisors, industry and public sector researchers
Cotton	+72% cotton stack	Not provided	Céleres[15]	Small scale survey of farmers in main growing regions plus advisors, industry and public sector researchers
Maize	+8% maize stack	Not provided	Céleres[15]	Small scale survey of farmers in main growing regions plus advisors, industry and public sector researchers

the primary pests (especially boll weevil and white fly but also, at that time armyworm, a pest that was latterly controlled by the second generation of IR cotton available in varieties in later years). The yield differences between farmers using IR and conventional cotton varied considerably (higher yields for IR cotton of +9.2% in Córdoba, +17.6% Sucre and +75% in Tolima). It is important to recognize that only some of these yield differences were attributable to the IR technology alone – other important factors being access to adequate resources and inputs, quality of land, access to irrigation and incidence of pests not controlled by the IR technology and efficacy of conventional control methods of these pests and the underlying performance of the seed variety used. When the authors adjusted their yield analysis to take account of some of these factors, essentially by comparing the performance of IR cotton and conventional cotton grown on the same farm (in Tolima), where farmers were essentially using varieties of similar underlying yield performance, the difference in yield performance in favor of GM IR cotton was +35%. Weather also influenced the results in the coastal region, with, for example, drought during the growing season, followed by unusually heavy rains in Sucre affecting yields. At the time, the authors concluded that overall adoption of IR cotton was showing clear yield and income benefits in Tolima but was less economically advantageous to farmers in the Coastal region (Córdoba and Sucre) because of a combination of lower levels of pest pressure for the pests controlled by the IR technology and factors unrelated to the technology such as less access to inputs, credit and machinery and weather extremes during the season the study was undertaken;

- *Fonseca L and Zambrano P*[10] extended some of the earlier impact analysis of IR cotton by examining the yield impact, specific to some of the new (in 2008–09) varieties containing both IR and HT technology, based on data from the national cotton association Conalgodon. At this time, two of the varieties containing both IR and HT (tolerance to glyphosate), DP455BRR and Deltaopal RR performed poorly; yield performance of between −27% to −42% relative to leading conventional varieties A third variety, Nuopal RR containing both IR and HT (tolerance to glyphosate) traits, however yielded 29% higher than leading conventional varieties. In addition, the yield performance of the main varieties containing only the IR trait (DP164B2F and Nuopal) recorded yields between +44% and +48% higher than the leading conventional varieties. These yield comparisons related to crops grown in the Córdoba region;

- *Ávila Méndez K et al*[11] examined the impact of using stacked maize in the Valley of San Juan (Tolima) in the first growing season of 2009. This small scale, localized study interviewed 20 farmers (10 growing GM maize and 10 conventional growers) and found the yield difference in favor of the GM maize to be +22%, with overall costs of production also being lower by 14% for GM maize growers (higher cost of the GM seed, more than offset by reduced expenditure on insecticides and herbicides). It also found that the GM maize production system had a lower (beneficial) environmental impact on the environment, as measured by the Environmental Impact Quotient (EIQ) than the conventional maize production system mainly because of the elimination of use of insecticides and a change in the profile of herbicides used (use of five herbicides being replaced by one, glufosinate, for weed control). As the authors acknowledged, this study related to one small growing region in the first growing season of 2009. It also related to GM seed technology that was tolerant to one herbicide, glufosinate, whereas most of the latterly adopted stacked GM maize was tolerant to glyphosate only, or to both glyphosate and glufosinate;
- *Ávila Méndez K et al*[12] and *Reyes G et al*[13] examined the environmental impact of using both GM cotton and maize. The analysis relating to GM maize essentially summarized the finding of the 2009 analysis referred to above, whilst the cotton analysis was based on interviewing 20 cotton farmers (15 growing some of the then first varieties of stacked GM cotton – the stacked traits of Bollgard 1 and glyphosate tolerance) and 5 growing conventional varieties) in the municipality of El Espinal, in the department of Tolima in the first half of 2009. The paper concluded that the GM varieties delivered higher yields of about +14%. In relation to the environmental impact of insecticide use, as measured by the EIQ indicator, these were worse for GM cotton than the environmental impact associated with insecticide use on conventional cotton. The environmental impact of herbicide use, as measured by the EIQ indicator on GM cotton was however, better than the environmental impact associated with herbicide use on conventional cotton. The study was, however very small scale and localized, and hence not representative of cotton production across all regions. It is also likely that differences in the nature of farming practices used by the early GM technology adopters compared to conventional growers [as identified as important by Zambrano et al,[7] – such as adopters tending to be larger farms with greater access to inputs and machinery] probably had an important influence on the amount of insecticides used. In addition, the early stacked varieties of GM cotton introduced in the first season of 2009 experienced poor performance (eg, poor boll formation) resulting in inferior yields (see for example, Fonseca L and Zambrano P.[10] The 2008 season in this region was also very wet, with little sunshine and this also affected performance of these new varieties;
- *Zambrano P et al*[14] undertook analysis of experience in using GM cotton in 2010 through interviews with 34 farmers in El Espinal (Tolima) and 45 farmers in Cereté (Córdoba). Whilst the study focused on the role of women in cotton production, it collected some data relating to the relative performance of the two types of cotton production. The analysis found a range of yield impacts from −23% to +21% across the two localities for the performance of the GM cotton growers compared to conventional growers.

Later studies are limited to a 2017 study (based on data collected in 2013–2015) by Céleres for AgroBio and an update, in 2019 (based on data collected in 2018).[6,15] Both studies were based on interviews with a combination of farmers growing conventional and GM crops plus interviews with extension advisors, industry (seed company) advisors, representatives of farmer associations and public sector researchers. The 2017 Céleres data identified average yield gains for stacked-traited maize and cotton of +16% and +24.7% respectively.[6] The 2019 update found the average yield gains to be +8% for stacked-traited maize and +72% for stacked-traited cotton. The 2019 study was, however based on very small samples of farms and was much less representative of production systems across the crops in different regions of the country than the earlier study.[15]

It should be noted that these latter studies were made against a background of different (second generation) GM crop technology availability and significantly higher adoption levels than at the time of the early studies. The performance of second-generation GM IR traits in both cotton and maize has been better and more consistent than the first generation of GM IR traited seed. Thus, the levels of pest control of 'Bollgard II' cotton technology which has two or more modes of action for pest control relative to the single mode of action in the early 'Bollgard I' technology were better (eg, improved control of pests later in the growing season and control of the Fall Armyworm). Pests such as pink bollworm and false pink bollworm (commonly known as Colombian and India pink bollworms) and *Trichoplusia sp* have an almost zero incidence in crops with GM IR traits, while *Spodoptera* and *Heliothis* occur at levels that usually, either do not require or, only require one or (possibly) two insecticide applications for control throughout the production cycle. In contrast, in conventional cotton crops between four and six insecticide applications is commonly required for the control of these pests. On the other hand, due to the decrease in the number of insecticide applications, some secondary pests have assumed greater relative importance, especially sucking pests. For example, the white fly pest is now considered to be the second most significant pest after boll weevil.

In relation to maize, all of the second generation of GM IR maize provided better levels of control of three of main pests of the crop (Fall Armyworm, Corn Borer and Corn Earworm) compared to some of the first-generation GM IR seed that targeted control only of Corn Borer pests. As a result, the average number of insecticide applications has fallen from 4–5 with conventional varieties to 1–2 for varieties containing second generation IR traits.

In both crops, weed control systems have changed from a combination of mostly pre-emergent herbicides and hand/mechanical weeding (typically 3–4 applications/weeding cycles) to the use of single pre-emergent application of herbicide followed by a post-emergent 'over the top' application of glyphosate or glufosinate.

In relation to adoption levels, in 2008–09, GM IR cotton adoption was 40%–50% of the total crop, with GM HT cotton in its first year of adoption. In 2018, GM (stacked) cotton seed accounts for about 90% of the total crop. GM maize was also in its early years of availability in 2008–09 (about 20,000 ha using the technology). By 2018, the area of maize planted to seed containing GM technology had increased to annually between 70,000 ha and 90,000 ha, equal to about 35%–40% of the commercial 'tecnificado' crop.

The analysis presented in the section below on farm income and production draws on the various research referred to above and summarized in Table 2. Additional information is provided in Appendix 1. In terms of average yield gains over the respective periods of adoption for GM cotton and maize, these were +30.2% for (IR/stacked) cotton and +17.4% for IR/stacked maize.

Impacts on Farm Income and Crop Production

At the farm level, GM cotton and maize seed technology has provided Colombian farmers with higher yields mostly from better pest control (relative to pest control obtained from conventional insecticide technology). In some cases, the technology has also provided for higher yields via improved weed control.

The technology has also provided savings in expenditure on insecticides and weed control for many farmers. In cotton, the farm level studies identified average reductions in annual expenditure on insecticides of between US $41/ha and US $63/ha (annual average saving of about US $55/ha) and in maize, insecticide use decreased by between US $42/ha and US $55/ha (annual average saving US $45/ha: see Appendix 1: sources as Table 2). For weed control, the studies identified average reductions in annual cotton weed control costs of between US $34/ha and US $105/ha (annual average saving US $92/ha) and in maize annual weed control costs fell by between US $32/ha and US $44/ha (annual average saving of US $37/ha: sources: as Table 2).

The combination of these impacts has increased the incomes of farmers using the technology by US $301.7 million over the fifteen-year period 2003–2018. This is the equivalent of an average farm income gain of US $294/ha per year for stacked maize and US $358/ha for stacked cotton. In 2018, the income gain was US $19 million (Table 3). The largest share of the farm income benefits has been maize US $188.1 million (62%), with US $113.6 million in cotton.

Examining the cost farmers pay for accessing GM seed technology, the average additional cost of seed (seed premium) relative to conventional seed, over the period of adoption were US $79/ha (2007–2018) for maize (US $65/ha in 2018 for stacked maize) and US $171/ha (2003–2018) for cotton (US $107/ha in 2018 for stacked cotton). These cost of technology values are equal to 19% (maize) and 32% (cotton) of the total (gross) technology gains (before deduction of the additional cost of the technology payable to the seed supply chain – the cost of the technology accrues to the seed supply chain including sellers of seed to farmers, seed multipliers, plant breeders, distributors and the GM technology providers). In terms of investment, over the 15 years of adoption, this means that for each extra dollar invested in GM cotton crop seeds in Colombia, farmers gained an average US $3.09 and over the 12 years of adoption of GM maize, for each extra dollar invested in GM maize crop seeds in Colombia, farmers gained an average US $5.25.

Based on the yield gains referred to in Table 2, the GM IR technology has added 0.63 million tonnes of maize and cotton lint to production since 2002 (Table 4). This extra production contributes to reducing pressure on farmers to use additional land for crop production. To illustrate, if GM maize technology had not been available to farmers in 2018, maintaining production levels for this year using conventional technology would have required the planting of an additional 11,240 hectares of agricultural land to maize. This equates to about 5.2% of the total commercial area planted to maize in 2018.

Impacts on the Environment Associated with Insecticide and Herbicide Use and Greenhouse Gas Emissions

GM IR maize and cotton traits have contributed to a reduction in the environmental impact associated with insecticide use on a significant proportion of the areas devoted to these crops. Since 2003, the use of insecticides on the GM IR cotton area was reduced by 176,500 kg of active ingredient (−25% reduction), and the environmental impact associated with insecticide use on these crops, as measured by the EIQ indicator, fell by 27% (Table 5). The use of herbicides on cotton has fallen by about 45,000 kg (−5%), with the associated environmental impact, as measured by the EIQ indicator also falling by 5% since this technology was first used in 2007.

The use of insecticides on the GM IR maize area has decreased by 279,400 kg of active ingredient (−66% reduction), and the environmental impact associated with insecticide use on these crops, as

Table 3. Farm income gains derived from GM cotton and maize ('US million $).

Country	2018	Cumulative	Cumulative area planted to GM crops ('000 ha)
Maize	14.59	188.11	718,940
Cotton	4.37	113.55	354,460
Total	**18.96**	**301.66**	**1,073,400**

Sources: Brookes G and Barfoot P[1] [and updated]
Notes: GM maize from 2007, GM cotton from 2003

Table 4. Additional cotton and maize production from positive yield effects of GM technology (tonnes).

Country	2018	Cumulative
Maize	58,440	566,970
Cotton (lint)	2,405	67,810
Total	**60,845**	**634,780**

Sources: Brookes G and Barfoot P[1] [and updated]
Notes: GM maize from 2007, GM cotton from 2003

Table 5. Impact of using GM maize and cotton in Colombia: changes in insecticide use and associated environmental impact (as measured by EIQ indicator) 2003–2018.

Trait	Change in volume of active ingredient used ('000 kg)	Change in field EIQ impact (in terms of million field EIQ/ha units)	Percent change in active ingredient use on GM crops	Percent change in environmental impact associated with insecticide use on GM crops
IR maize	−279.4	−7.0	−66	−65
HT maize	−278.5	−10.4	−13	−22
IR cotton	−176.5	−7.1	−25	−27
HT cotton	−45.1	−0.7	−5	−5
Total	**−779.4**	**−25.2**	**19**	**26**

Source: Derived from Brookes G and Barfoot P[2] and updated

measured by the EIQ indicator, fell by 65% since this technology became available in 2007 (Table 5). The use of herbicides on maize (available since 2009) has decreased by 278,000 kg (−13%), with the associated environmental impact, as measured by the EIQ indicator also falling, by 22%.

The scope for impacts on greenhouse gas emissions associated with GM crops in Colombia has come from one principal source; fuel savings associated with less frequent insecticide and herbicide applications. The use of GM IR cotton and maize has resulted in total savings equal to 8,761 million kg of carbon dioxide not released into the atmosphere, arising from less fuel use of 3.28 million liters. This is equivalent to taking 5,410 cars off the road for a year. To provide context, this represents a very small, positive contribution to greenhouse gas reduction when compared to the 5.4 million cars registered in Colombia (2017: statistical source Ministry of Transportation).

Other Impacts

The various pests targeted by the IR traits in maize damage crops making them susceptible to fungal damage and the development/buildup of fumonisins (a group of cancer-causing mycotoxins produced by a number of fusarium mold species) in the grain. This increases the possibility of grain failing to meet the maximum permitted thresholds for the presence of these toxins, set by buyers in the food and animal feed sectors. A number of studies have identified that the use of GM IR maize has, through a significant reduction in pest damage and the levels of fumonisins found in grains, led to an improvement in grain quality (eg, Folcher L et al[16], Bakan et al[17]). This then is likely to result in less maize being rejected by users in both the food and feed using sectors in any country where this technology is used. The author is not aware of any publicly available data that has examined this issue in Colombia (or elsewhere).

The adoption of GM IR maize has also provided a number of other benefits, identified in analysis such as Brookes.[18] These include improved production risk management, with the seed technology being seen by many farmers as a form of insurance against corn boring pest damage. Farmers have also been able to reduce the amount of time monitoring levels of pest pressure and the technology has made harvesting easier because of fewer problems of fallen crops. Whilst, there is no data available on the time saving derived from these changes, the gains are likely to be limited (eg, savings associated with reduced insecticide application, where applicable have been typically only 2–4 treatments).

The evidence presented above in this paper has identified largely positive impacts associated with the use of GM technology in both crops over the cumulative periods of adoption for GM cotton and maize. However, it is important to recognize in the early years of adoption of both the IR technology and when stacked-traited seed became available, especially in cotton, difficulties and negative impacts arose for some farmers. These were due to a combination of factors such as the technology not being available in leading varieties suited to all local growing conditions, which resulted in poor performance relative to conventional varieties for some farmers. In addition, the knowledge transfer (advice provided to farmers) about management of the new varieties (eg, about the most appropriate pest and weed control practices) was considered to be poor/inadequate. The poor performance of some of the first stacked cotton varieties also resulted in legal cases being bought against the main technology provider at that time and this poor performance may have contributed to the adoption level of GM traited seed in the cotton sector subsequently falling as a proportion of the total crop in the next year (2008). The subsequent increase in adoption levels, especially in cotton, to a point where GM-traited seed now accounts for 90% of the crop suggests that lessons have been learned relating to farmer advice and ensuring that traits are available in leading varieties adapted to local conditions so that most farmers obtain consistent farm income benefits from using the technology relative to the conventional alternative. It is, nevertheless, interesting to note that whilst in recent years, the proportion of the cotton crop using GM technology has increased, the total cotton crop in Colombia has fallen significantly (eg, from 34,600 ha in 2014/15 to 13,500 in 2018/19). This decline in planting is likely to reflect the poor profitability from growing cotton for some farmers (even when using GM seed technology) relative to alternative agricultural enterprises (eg, maize, rice and livestock enterprises) and difficulties in competing with imported cotton.

Concluding Comments

GM cotton and maize technology has now been used by many farmers in Colombia for up to 15 years and, in 2018, about 88,000 hectares were planted to seeds containing this technology (equal to 90% and 36% respectively of the total cotton and (commercial) maize area in Colombia). The seed technology has helped farmers grow more food and feed (567,000 tonnes of additional maize 2007–2018 and 68,000 tonnes of cotton lint 2003–2018), using fewer resources and therefore contributed to reducing the pressure on scarce resources such as land. The extra production and reduced cost of pest and weed control have provided maize farmers with higher incomes equal to an average of US $294/ha and an average return on investment equal to +US $5.25 for each extra US $1 spent on GM maize seed relative to conventional seed. For cotton farmers, the average increase in income has been + US $358/ha, with an average return on investment equal to +US $3.09 for each extra US $1 spent on GM seed relative to conventional seed. This additional farm income from growing GM cotton and maize will have boosted farm household incomes and, assuming some of this additional income has been spent by the households, this additional expenditure will have provided a wider economic boost to the local (rural) and possibly national economy.

The technology has also contributed to reducing the environmental impact associated with insecticide and herbicide use and made a small contribution to lowering fossil fuel use for crop spraying.

Overall, the impact evidence from the fifteen years of adoption of GM cotton and twelve years of GM maize points to a net positive contribution toward addressing the crop production and environmental challenges facing agriculture in Colombia.

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Statistical sources

- Data source for GM crop planting statistics: Instituto Colombiano Agropecuario (ICA).
- Kleffmann is a subscription-based data source (derived from farmer surveys) on pesticide use
- Number of cars in Colombia: Ministerio de Transporte. www.mintransporte.gov.co
- Confederación Colombiana del Algodón (Conalgódon). www.conalgodon.com
- Federación Nacional Cultivadores de Cereales, Leguminosas y Soya (Fenalce). www.fenalce.co/estadsticas

Appendix 1. Details of Application of Data and Methodology to Calculating 2018 Farm Income Gain and Insecticide Use Changes for GM Crops in Colombia and Key Assumptions

Farm income gains (values in US dollars)

Country	Area of trait (000′ ha)	Yield assumption % change	Base yield (tonnes/ha)	Farm level price: $/tonne)	Cost of tech (€/ha)	Impact on costs, net of cost of tech ($/ha)	Change in farm income ($/ha)	Change in farm income at national level ('000 $)	Production impact (tonnes)
Stacked-traited maize	70,347	+16	5.2	243.72	70.76	74.79	206.49	14,582	58,440
HT maize only	5,667	0	5.47	243.72	23.16	32.98	9.82	55.6	0
Staked traited cotton	11,849	20.66	0.82	1,730	107.30	123.87	366.43	4,342	2,007
HT cotton	254	4	0.82	1,730	34.20	63.94	86.49	22.0	397

Sources:
Areas planted: ICA – Colombian Agricultural Institute
Costs of technology: Brookes and Barfoot[1], AgroBio (personal communications), Céleres[6,15]
Cost changes for IR maize and cotton based on reduction in insecticide use and application. Cost changes for HT crops based on reductions in weed control: use of herbicides for maize and use of herbicides and hand weeding in cotton. Sources: Céleres,[6,15] Brookes and Barfoot.[1]

Notes:

(1) The cost of the technology represents the value paid by farmers to the seed supply chain including sellers of seed to farmers, seed multipliers, plant breeders, distributors and the GM technology providers. It does not represent the value accruing to the technology providers but to the whole seed supply chain. The cost of the most used form of the technology – seed containing stacked genes for IR and HT traits were $70.76/ha for maize and $107.3/ha for cotton.

(2) Yield gains derive from a reduction of pest damage (IR trait) in maize and a combination of improved pest and weed control in cotton

Insecticide and herbicide use change (2018)

Country	Area of trait (ha)	Average ai use GM crop (kg/ha)	Average ai use if conventional (kg/ha)	Average field EIQ/ha GM crop	Average field EIQ/ ha if conventional	Aggregate change in ai use ('000 kg)	Aggregate change in field EIQ/ha units ('000s)
Maize insecticides	70,347	0.07	0.281	1.9	9.25	14.7	517
Maize herbicides	76,014	2.07	2.514	43.98	59.05	34.0	1,146
Cotton insecticides	11,849	0.35	0.69	8.49	20.29	4.0	140
Cotton herbicides	12,103	1.79	2.305	28.03	38.21	6.2	123

Sources: Insecticide and herbicide use changes based on Brookes and Barfoot[2], Céleres[6,15] and personal communications with industry staff about more recent/current insecticides and herbicides that are/would need to be used to control pests or for weed control, if GM maize and cotton technologies were not used

Reduction in fuel and water use from less frequent insecticide applications

For insecticide and herbicide applications, the quantity of energy required to apply the insecticide is based on use of a 50-foot boom sprayer which consumes approximately 0.84 liters/ha.[19] In terms of carbon emissions, each liter of tractor diesel consumed contributes an estimated 2.67 kg of carbon dioxide into the atmosphere (so 1 less application reduces carbon dioxide emissions by 2.24 kg/ha).

Base yields used where GM technology delivers a positive yield gain

In order to avoid over-stating the positive yield effect of GM technology (where studies have identified such an impact) when applied at a national level, average (national level) yields used have been adjusted downwards (see example below). Production levels based on these adjusted levels were then cross checked with total production values based on reported average yields across the total crop.

Example: GM IR maize Colombia (2018)

Average yield all commercial crop (t/ha)	Total maize area ('000 ha)	Total production ('000 tonnes)	GM IR area ('000 ha)	Conventional area ('000 ha)	Assumed yield effect of GM IR technology	Adjusted base yield for conventional maize (t/ha)	GM IR production ('000 tonnes)	Conventional production ('000 tonnes)
5.47	216,327	1,183,309	70,347	145,980	6.03	5.20	424,245	759,096

Note: Figures subject to rounding