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The unintended environmental effect of a climate change adaptation strategy: evidence from the Colombian coffee sector

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Climate change is a major threat to agricultural productivity in developing countries. In this paper, we explore the unintended environmental effects of an adaptation policy that conditioned credit programs for the renewal of coffee crops on the use of pest-resistant varieties. We use the case of the Colombian coffee sector, which was severely affected by extreme rainfall events and pest proliferation from 2010–2011. In response, the National Federation of Coffee Growers (NFCG) changed its policy to protect farmers from future weather shocks by conditioning renewal credits to the use of pest-resistant seeds. We exploit the timing of the policy and a novel data set that includes coffee farms' productive characteristics matched with satellite tree cover data to analyze its environmental effect. We find that conditioning renewal credits on a seed change decrease tree cover in treated coffee growers by 390 m^2. If we extend this result to all treated farms in our sample, the total loss increases to 1,031 (10.31 million m^2). We calculate that this average loss in tree coverage on treated farms translates into a release of 61,912 tons of carbon.

KEYWORDS
Coffee production, climate change, adaptation, trees on farm, deforestation.

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Los efectos ambientales no intencionados de una política de adaptación al cambio climático: evidencia del sector cafetero en Colombia

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El cambio climático es una amenaza importante para la productividad agrícola en países en vía de desarrollo. En este trabajo, se estudian los efectos no intencionados de una política de adaptación que condicionó créditos para la renovación de cafetales a la adopción de variedades de semillas resistentes a pestes. Se utiliza el caso del sector cafetero en Colombia, el cual estuvo severamente afectado por las lluvias extremas y la proliferación de pestes entre 2010–2011. En respuesta a ello, la Federación Nacional de Cafeteros cambió sus políticas para proteger a los caficultores de futuros choques climáticos, condicionando los créditos para la renovación de cultivos al uso de semillas resistentes a las pestes. Para analizar el efecto ambiental de este cambio, se emplea el momento de cambio de la política y una base de datos novedosa que combina características de las fincas cafeteras con datos satelitales de cobertura arbórea. Se encuentra que condicionar la renovación de créditos a la adopción de las nuevas semillas disminuye la cobertura arbórea de los caficultores tratados en 390 m^2. Si se extiende este resultado a todas las fincas tratadas en la muestra, la pérdida total aumenta a 1.031 ha (10.31 millones m^2). Se calcula que la pérdida promedio de bosque para las fincas tratadas se traduce en la emisión de 61.912 toneladas de carbono.

KEYWORDS

Producción de café, cambio climático, adaptación, árboles en finca, deforestación.

1 | INTRODUCTION

Climate change threatens food security and the livelihoods of many, especially in the developing world (Mbow et al., 2019; Mendelsohn, 2008; Quiroga et al., 2020). Agriculture is one of the most susceptible sectors to the effects of climate change, given its vulnerability to increasing temperatures, the frequency of extreme weather events, and changing seasons (D'Agostino and Schlenker, 2016; Nelson et al., 2009). Reduced yields and the proliferation of weeds/pests are expected in many crops in any scenario of climate change (Lobell et al., 2011; Schlenker and Roberts, 2009; Ignaciuk, 2015; Mbow et al., 2019). Several programs and policies have incentivized farmers to adopt adaptation strategies to deal with this threat. They include but are not limited to, the development of technologies and practices to improve crop resilience and efficiency, the diffusion of information on agricultural best practices, insurance, climate-smart agriculture, and weather forecasting (Ignaciuk, 2015). However, short-term adaptation strategies or policies can deviate from their objectives and their long-term effects on the environment are unknown. Furthermore, negative unintended environmental consequences can undermine the effectiveness of such policies, leaving farmers more vulnerable to future climate threats.

In this paper, we explore the environmental consequences of an adaptation policy designed to protect farmers from extreme rainfall events, using the case of the Colombian coffee sector. In 2010-2011, the sector was severely affected by excessive rainfall due to the climatic event ENSO-La Niña (Jaramillo and Arcila, 2009). This event also triggered pest outbreaks, such as coffee rust, which decreased coffee crop productivity by nearly 30 % (Jaramillo and Arcila, 2009; NFCG, 2012; Rivillas et al., 2011).In response, the National Federation of Coffee Growers of Colombia (NFCG), which represents coffee growers, encouraged farmers to protect themselves against future shocks by conditioning credit programs to renew coffee crops with the use of pest-resistant seed varieties (NFCG, 2010). However, these new seeds require higher sun exposure to maximize their productive cycle (Arcila et al., 2007). Consequently, productive or unproductive trees in and out of farms were removed. Although policy protected against the risk of pests triggered by rainfall, loss of vegetable cover has the potential to diminish future returns, as it is important to protect crops against soil erosion, temperature increases, or excessive rainfall. That is, farmers could be more vulnerable to weather shocks, which are expected to become more frequent in the future (Bernal, 2016; Silva, 2012). Furthermore, tree cover contributes to carbon sequestration, and removing it produces a negative externality and a feedback loop to climate change.

To analyze environmental effects, we assemble a new panel data set at the farm level that combines (i) detailed production data and characteristics at the farm level, (ii) information from NFCG credit counseling visits, and (iii) satellite data on tree cover. The coffee production data set provides georeferenced information between 2005 and 2014 on all coffee growers affiliated with NFCG (approximately 80 % of all coffee farmers). The credit counseling visits dataset contains the number of yearly visits made to each farm by NFCG to advise on different programs, such as credit programs. Finally, we constructed tree cover as our environmental measure at the farm level using satellite images from Global Forest Change (GFC), which provides a yearly measure of tree cover from 2001 until 2019 at a $30m^2$ resolution (Hansen et al., 2013). Thus, we can calculate tree cover changes in each coffee farm in our sample for 2001–2019.

Our empirical strategy exploits the timing of the policy with a difference-in-differences approach to identify the environmental effect of the conditioning characteristic in the credit program. We define 2010 as our treatment year, since this was when NFCG introduced the condition of credit renewal programs on the use of pest-resistant seeds. Our time frame comprises the years between 2005 and 2014, with a treatment period between 2010 and 2014. We compare small coffee farms (< 5 ha) with vulnerable coffee seeds before 2010 that received (or did not) credit counseling visits from the NFCG between 2010–2013. Our treated farms are those that received credit counseling visits, and our control farms are those that did not receive any credit visits at all. We estimate multiple robustness checks using new difference-in-difference techniques (Callaway and Sant'Anna, 2020), as well as alternative definitions for treatment and time.

We find that those coffee growers who received credit counseling visits are more likely to adopt pest-resistant seeds than those in the control group. Furthermore, conditioning renewal credits on a change in seeds diminish tree cover on treated coffee farms. We show that farms with low vulnerability to climate change lost relatively more tree cover than farms located in highly vulnerable areas. Using our more conservative estimates and back-of-the-envelope calculations, we estimate that removing tree cover from treated farms translates to a release of 61,912 tons of carbon into the atmosphere, equivalent to the emissions of approximately 12,500 cars per year. If we consider the carbon tax in Colombia, the cost of emissions add up to 15.6 % of the country's GDP in 2014. Extending these estimates to the total number of credits issued by NFCG for renewal purposes, the loss of tree cover meant an additional 161,200 tons of carbon, thus contributing to soil degradation and climate change (Olsson et al., 2019).

Our study contributes to several bodies of literature. First, this article is related to the empirical literature investigating the effects of productivity-oriented interventions on the modernization of the agricultural sector (Syrquin, 1988; Kuznets, 1973; Barrett et al., 2017; McArthur and McCord, 2017). We add to this literature by studying the environmental effects of the change in land use in farms led by the implementation of new practices. Although some previous studies have shown the effect of agricultural modernization on the degradation of soil and water sources (FAO, 2008; Rudel et al., 2009; Valdivia et al., 2017), few have focused on tree cover. We show how implementing new productive practices (such as pest-resistant seed) could reduce agroforestry practices within the farm, which will impose direct and indirect costs on the farm's livelihood, especially in a climate change scenario. Therefore, our findings point out the need to include short- and long-term environmental costs to fully characterize a cost-benefit analysis and design policies that improve productivity in an environmentally conscious manner.

This paper also contributes to the literature on the role of trees on farms on climate change. There is extensive literature showing how agroforestry practices provide critical ecological services such as shade, nitrogen fixation, pollination, or soil erosion prevention, and they play an essential role in the well-being of rural households (Place et al., 2016; Miller et al., 2017). These benefits become critical in the context of climate change, as they could reduce exposure and sensitivity to external shocks such as climate change and variability, food scarcity, market volatility, and financial liquidity constraints, among others (Place et al., 2016). Furthermore, it can be an essential contribution to reducing climate change due to its importance for carbon sequestration (Zomer et al., 2016). Finally, our results allow us to emphasize the need to uncover the hidden cost of reducing trees on farms in developing countries.

Finally, we add to the growing literature on climate-smart agriculture (CSA) in developing countries. Our findings support the need to create interventions that combine agricultural productivity, climate change resilience, and carbon mitigation. To our knowledge, studies have focused on the benefits of adaptation and mitigation strategies, but not on their potential environmental consequences (Harvey et al., 2014).

The paper continues as follows. Section 2 describes the institutional background of the coffee sector in Colombia and the policies used to inform the empirical strategy. The data and empirical strategy are presented in Sections 3 and 4. Section 5 discusses the main results and the heterogeneous findings. Section 6 presents the discussions and 7 concludes.

2 | CONTEXT

Developing countries are the top coffee producers in the world. Colombia is among the leading producers, along with Brazil and Vietnam; together, they account for 70 % of the world's production. Coffee is one of the key agricultural sectors of the Colombian economy. In 2019, Colombia contributed approximately 9 % of global production, representing 10,46 % of total exports, and 11,3 % of national agricultural production (ICO, 2020b,a).

There are two types of coffee production systems: traditional and technified. The former relies on a non-intensive production system that requires shade trees as a climate regulation method (Beer et al., 1997; Arcila et al., 2007); it is vulnerable to pests and suffers from low productivity. In contrast, the latter uses highly productive genetically modified seeds that result in pest-resistant coffee trees (Perfecto et al., 1996; Farfán and Jaramillo, 2009).[1] Figure 1 shows the difference in the distribution of tree cover between traditional and technified crops.

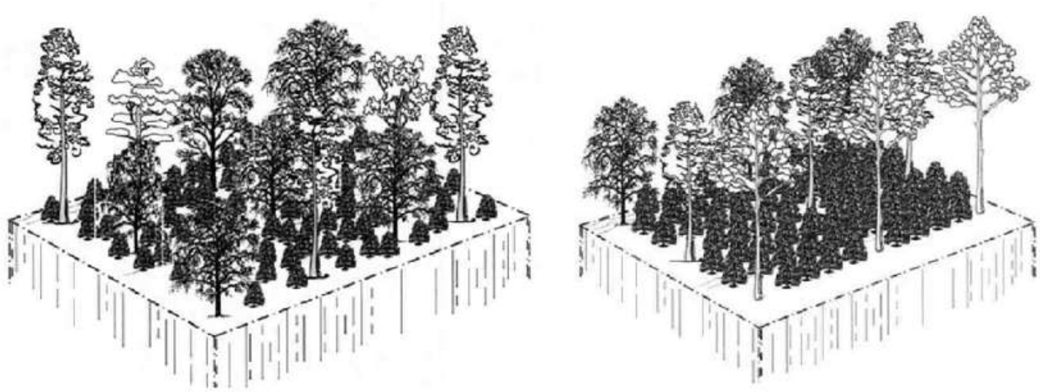

FIGURA 1 Shade management in coffee crops. *Notes:* This graph shows the differences in the use of shade trees between traditional coffee crops (left) and technified coffee (right). *Source:* Arcila et al. (2007).

Regardless of seed variety and type of production, coffee trees have a productive cycle that loses productivity as they age. To maintain crop productivity and profitability, trees must be renewed every 6 to 8 years (Arcila et al., 2007). When trees reach such an age, farmers have two options: (i) renew coffee crops without changing the seed variety, or (ii) renew with pest-resistant or improved seed varieties.[2] When changing seeds, farmers remove part of their shade trees that, in addition to providing climate regulation, also promote forest-like biodiversity, help maintain soil fertility, and control soil erosion (Beer et al., 1997; Guhl, 2008; Elder et al., 2014). By removing shade trees, farmers also lose the opportunity to obtain certifications for shade-grown coffee, which could provide economic benefits such as price

[1]Traditional crops use the Tipica seed variety, while the technified use improved seeds like Caturra, Colombia, Castillo and Tabi.

[2]A major characteristic of pest-resistant seed systems is higher sun exposure as compared to the traditional system. Technified uses a maximum of 50 % shade in crops

premiums (Hernandez-Aguilera et al., 2018; Arcila et al., 2007). Furthermore, differentiated products also provide less volatile prices to the coffee grower, protecting them from market fluctuations (Rueda and Lambin, 2013).

Since the 1970s, the National Federation of Coffee Growers of Colombia (NFCG) has promoted the adoption of improved technology (that is, high-yielding and pest-resistant seed varieties, fertilizers, pesticides and irrigation) to increase productivity and protect farmers against weather shocks and pests (Guhl, 2008). NFCG is the Nongovernmental Organization (NGO) that represents Colombian coffee growers at the national and international levels. It is responsible for protecting the economic interests of coffee growers, improving their quality of life, and generating research and technological advances to increase the productivity and competitiveness of the sector. NFCG promotes productivity, among others, through the research and development of new seeds and technology, through access to credit, fertilizer transfers, and extension programs to train coffee growers in good farming practices (NFCG, 2018, 2009; Bernal, 2016).

There have been three major attempts to transform and boost productivity in the Colombian coffee sector since the 1970s. An initial program was launched in 1970 and lasted until 1998. During this time, almost 60 % of the country's traditional crops adopted the pest-resistant seed developed at the time: *Caturra* (Farfán and Jaramillo, 2009; Perfecto et al., 1996; Guhl, 2008; Perfecto et al., 1996). Between 1998 and 2011, the NFCG ran the Competitiveness Program to promote the renewal of coffee crops and help reduce their susceptibility to pests (NFCG, 2002; DNP, 2001). Producers could participate regardless of their farm size, whether large or small. This program was co-financed by the Colombian government and the NFCG (NFCG, 2010, 2002).

The results of the Competitiveness Program were limited. One of its objectives was to promote the adoption of pest-resistant seeds, but 70 % of the sown area remained vulnerable to pests (Bernal, 2016). The renewal was concentrated on medium and large producers with more than 5 hectares, who accounted for 16 % of the total area grown but received 53 % of the program's resources (Bernal, 2016; Silva, 2012). Meanwhile, the conditions of small farmers deteriorated, with 46 % of their area planted with traditional or old crops, with unproductive trees of more than 18 years, and their crop density too low for modern standards (<4,000 trees/ha) (Bernal, 2016).

One of the main reasons for the poor results in implementing the Competitiveness Program was the weak institutional support. The instability of international coffee markets and the high cost of maintaining public goods provision and institutional support from NFCG led to institutional bankruptcy. Between 1992 and 2002 the NFCG lost 80 % of its assets (Ramirez et al., 2002). To recover the economic viability of the sector, in 2001 the Colombian government defined a support strategy and created a special commission to reform institutional coffee support (DNP, 2001; Ramirez et al., 2002).[3]

In 2008 NFCG implemented the *Permanence, Sustainability, and Future program (PSF)* to promote the renewal of old and traditional crops. This program included several lines of credit, as well as educational activities aimed at raising awareness of the importance of crop renewal, assisting farmers in loan application processes, and technical support

[3]One of the main changes was relieving the NFCG from the provision of the public goods on the coffee-growing region, a key element of its financial deterioration (Ramirez et al., 2002). The government's economic support was also essential for the sector's recovery. In 2002 the government agreed to support the internal price of coffee, to fund technical assistance and research programs, and to refinance NFCG'S debts (NFCG, 2002). This collective effort helped improve the financial outlook of the NFCG. Between 2003 and 2006 the NFCG was able to reduce its debts and gradually increase the value of its assets (NFCG, 2006).

(NFCG, 2010). The credit program for the renewal of coffee crops targets small farmers ($\leqslant 50,000\text{m}^2 = 5\text{Ha}$) willing to renew between 0.2 and 5 hectares of coffee crops (NFCG, 2009). Participation is voluntary, but eligibility requires that farmers be registered in the Colombian Coffee Information System (SICA) and be affiliated with NFCG. They must also have 75 % of their capital invested in agriculture, 66 % of their income must come from agricultural activities, and their assets cannot exceed a value of $ 36.000 (Silva, 2012; Echavarría et al., 2018). If farmers meet all the requirements, they receive a loan to cover renovation costs and secure their income for more than 2 years while the new crop produces its first harvest (NFCG, 2010).

In 2010, after a breakdown of a coffee rust plague triggered by excessive rainfall linked to ENSO-La Niña, farmers were also required to renew their crops with pest-resistant varieties (NFCG, 2010). NFCG conditioned credit disbursement on fulfilling and proving the change in seed requirement. Farmers are required to repay in seven years in equal installments after the second year. This timing of the program and the condition imposed by the NFCG after 2010 is of particular interest.

There were 98,762 loans granted since the launch of the PSF program until 2014, with almost 50 % disbursed between 2010 and 2011 (20,623 and 28,271 respectively). Farmers receive COP$6,000,000 (≈ USD$3,000 exchange rate December 2010) per renewed hectare, and the average value of the PSF credits was COP $4,430,399 (≈ USD$2,200) (Echavarría et al., 2018). Credits for the renewal of coffee crops account for most public loans to the coffee sector, which amount to 45 % of total loans between 2010 and 2011 and around 32 % between 2004 and 2014 (Echavarría et al., 2018).

Unlike previous programs, the renewal program between 2009 and 2014 had positive results. 82 % of coffee crops now use a technified system with young trees (also known as young-technified crops), compared to 62 % in 1997 (Bernal, 2016). The crop density increased by 23 % and the average age of the trees decreased to 7.2 years. All of this contributed to an increase in productivity of 50 % between 2009 and 2014. The outlook for the coffee sector has continued to improve. By 2019, 82.4 % of coffee crops are seeded with improved seeds, and tree age has continued to fall to 6.7 years on average (NFCG, 2019a). Together, this contributed to an increase of 80 % in coffee crop productivity when comparing 2010 and 2019 production (NFCG, 2019a). The renewal of all types of crops, old and young, reached its peak in 2012 with the intervention of 118,000 hectares (Echavarría et al., 2018).

Rural extension services are one of the main mechanisms through which coffee growers receive information on credit programs (NFCG, 2005). NFCG Extensionists visit farms and coffee-growing communities at least once a year by NFCG extensionists to receive information through talks, field trips, and demonstration activities (NFCG, 2019b). Visits focus on the different programs offered by the NFCG, e.g. credit counseling visits to inform farmers about how to access funding to improve the productive conditions of their crops (NFCG, 2019b). In addition to promoting credit, extensionists also assist farmers during the application process, helping them with administrative tasks (such as filling out the paperwork) and verifying that their farm meets the minimum application requirements.

Other types of extension visits include: (i) Business management visits, aimed at training farmers in the management of their farms and administrative skills; (ii) Social development visits, focused on building links between coffee growing communities and promoting better living conditions in their households; (iii) Technology transfer visits, which support the coffee grower in matters related to good farming practices (NFCG, 2000; Ministerio de Agricultura y Desarrollo Rural, 2014).

3 | DATA

This article aims to quantify the unintended environmental effects of the adaptation policy that conditioned credit programs on the use of pest-resistant varieties using the cases of Colombia's coffee sector. We exploit the spatial and temporal variation led by the coffee crop renewal program *the Permanence, Sustainability, and Future program (PSF)*, which provides flexible loans to farmers conditioned on the conversion of crops to an intensive production system using pest-resistant seeds. We used a newly assembled and detailed data set that combines geo-referenced information from coffee growers and satellite data on tree cover.

3.1 | Data

3.1.1 | Coffee growers data

We use data from the Colombian Coffee Information System (SICA) from 2006 to 2014, compiled and provided by NFCG. SICA is intended to monitor the coffee production of all NFCG members, almost 80 % of coffee growers in the country, by combining information on production and agroecological information obtained from aerial and satellite pictures. As a requirement for having any interaction with NFCG, coffee growers are obliged to update their information on SICA, which is physically verified by NFCG technicians. It constitutes a reliable source of information given the frequent interaction between coffee growers and NFCG through affiliated local cooperatives, social services, and technical support provided by *extension* workers.

Information in SICA is collected at the coffee plot level (that is, the sub-farm level). Each farm has at least one plot. Coffee growers usually combine different seeds, trees of different ages, and production systems on the same farm by dividing their land into smaller parcels or plots. For each coffee plot, SICA provides information on the plot and farm size, seed variety, hectares allocated to coffee trees, number of trees, average tree age, crop density (i.e., trees per hectare), and longitude and latitude of the plot's centroid. Furthermore, information on the exact year of sowing or renewal is also available. Despite the detailed information on SICA, NFCG does not collect information on productivity or yields. Furthermore, SICA includes the georeferenced location of each plot's centroid, but it does not provide the polygons with plot shapes.

3.1.2 | Credit Counseling Visits

The NFCG provides information on visits to coffee growers to advise them on credit programs and other types of initiatives, such as social development and business management activities. This data set reports the number of visits received by each farm between 2007 and 2013, classified by each program. Although we are interested in identifying coffee farmers who participated (or did not) in the PSF program, we do not have information on their credit access. Given this limitation, our best option is to use the extensionists' credit counseling visits as a proxy for the farmers' interest/participation in the program. Furthermore, our identification strategy is based on studying only small producers (farms < 5ha), the main target of the PSF program (NFCG, 2010), since they are more likely to face liquidity restrictions and therefore would not be able to renew their crops without receiving financial support from NFCG.

To provide additional evidence to support our hypothesis that farmers who received a credit counseling visit participated in the program, we link the probability of changing the seed of a coffee crop to having received credit visits after the NFCG conditioned renewal programs to the use of pest-resistant seeds (i.e. after 2010). To do this, we analyze small farms with crops that were eligible to change their seeds, that is, those with plots in the traditional system or in the technified system planted with pest-susceptible varieties before 2010.[4] We then examine whether these farms received a credit counseling visit after the change in the NFCG discourse. The regression we fit is summarized by 1:

$$change\_seed_i = \beta Visit_i + Z'_{it}\delta + \gamma_{vt} + \varepsilon_{it} \quad (1)$$

Where $change\_seed_i$ is a dummy variable equal to one if farm i changed one of its crop seed types during 2010–2014. $Visit_i$ is a dummy variable that equals 1 if farm i received a credit counseling visit during 2010–2013. Z_{it} are farm-level controls such as the share of coffee farms planted, crop density, tree age, temperature, and rainfall shocks, all interacting with a pre-2010 time trend. γ_{vt} are rural division year fix effects. Standard errors are clustered at the rural division level (Veredas in Spanish).[5]

Table 1 shows that having received at least one credit counseling visit between 2010 and 2013 increases the probability that a farm renews its crops using pest-resistant seeds (columns 1 and 3). Furthermore, the more visits a farm receives, the more likely it is to change its seed variety (columns 2 and 4). This is true for farms with traditional crops (columns 1 and 2) and for farms with technified production systems (columns 3 and 4). These findings provide additional validity to our decision to use credit counseling visits as a proxy for farms that have received the PSF credit.

3.1.3 | Tree cover data

The Global Forest Change (GFC) data set provides information on tree cover for the year 2000 and year-by-year deforestation from 2001 to 2019 (Hansen et al., 2013). The time series covers the whole world and is available at $30m^2$ resolution. Using tree cover in 2000 and annual deforestation data, we can estimate tree cover for each year between 2001 and 2019.[6]. Hansen et al. (2013) defines tree cover as dense vegetation taller than $5m$ in height. In this sense, we are confident that our forest cover measure does not capture the mechanical effect on the renewal of old trees. Coffee trees in the last stage of their life reach at most 2.5 meters in height (Moreno Ruiz, 2002) so young or old coffee trees are not identified separately in the GFC.[7]

[4] The Castillo, Colombia, and Tabi seeds are pest-resistant seed varieties, while the Típica and Caturra seeds are susceptible to diseases such as the coffee rust (Arcila et al., 2007).

[5] Vereda is the smallest administrative division of rural areas in Colombia. There are approximately 34,000 veredas in the country, of which 15,703 have coffee production and are included in our sample.

[6] See Figure A.1 in the Appendix A.2 shows Colombia's tree cover in 2000 and deforestation from 2001 to 2019.

[7] A potential issue with using GFC is the possibility of miss-classifying oil palm crops as tree cover. The study of Fergusson et al. (2020) further explores this issue. However, this might not be an issue in this setting, as oil palm crops tend to be located in different areas than coffee crops.

CUADRO 1 The link between credit counseling visits and changes in coffee farms' seed variety. Extensive and intensive margin.

	Dependent variable:			
	Adoption of improved seeds			
	Traditional crops		Technified crops	
	(1)	(2)	(3)	(4)
$Credit\_visits$ (Extensive)	0.20***		0.17***	
	(0.02)		(0.003)	
$Credit\_visits$ (Intensive)		0.14***		0.11***
		(0.01)		(0.002)
Farm mean size	18.9	18.9	15.23	15.23
Time frame	2005-2014	2005-2014	2005-2014	2005-2014
Rural division and year-fixed effect	Yes	Yes	Yes	Yes
Controls on weather and production activity	Yes	Yes	Yes	Yes
Observations	83,692	83,692	3,035,344	3,035,344

Notes – This table reports the relationship between receiving credit counseling visits and changing coffee crops' seeds to pest-resistant types. $^{*}p<0.1$; $^{**}p<0.05$; $^{***}p<0.01$. Standard errors are clustered at the rural division level. We only consider small farms (area $< 50{,}000 m^2$). Controls on production activity include farm yearly variables such as the share of the farm sown with coffee, crop density, coffee trees age and the square of the trees age, and the share of the farm sown with each seed variety. Controls on weather include farms' mean temperature and rainfall. Data source: Authors' elaboration based on the Colombian Coffee Information System (SICA) and Hansen et al. (2013) data.

3.1.4 | Linking coffee growers and tree cover data

We match tree cover with coffee data, building a buffer around each plot centroid (latitude and longitude), equivalent in area to that reported in SICA. Although actual shape plots are rarely circular, we believe this approach provides a low-bound of real cover, as it might contain most of the actual plot. Figure 2 displays the buffers around each coffee plot, as well as their location. To link coffee crops with their tree cover data, we intersect the GFC tree cover layer with buffers and capture pixels that belong to the crops. We then aggregated these data to the farm level to find the annual tree cover in m^2. Since the plots of a farm are located very close to each other, we avoid buffer overlapping by intersecting the polygons at the farm level. We then use the farm-level buffers to sum the total tree cover of each farm.

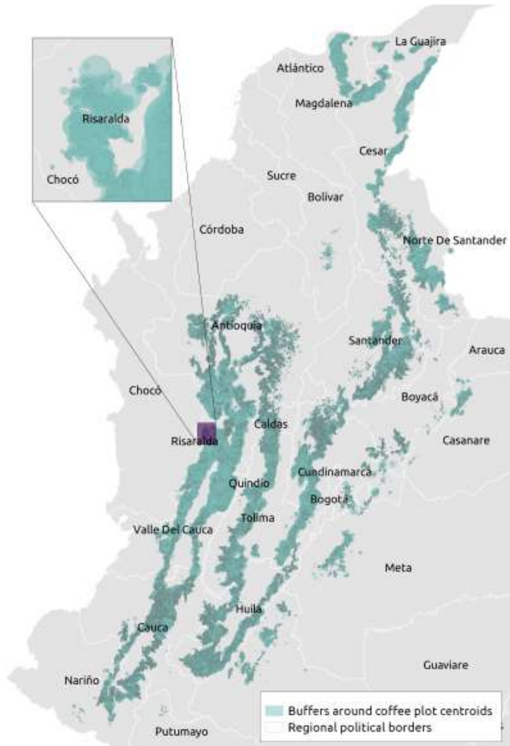

FIGURA 2 Buffers around coffee plots centroids. *Notes:* This map shows the buffers built around the centroid of each coffee plot. The size of the buffer is the area of the plot in m^2. *Source*: Authors' elaboration based on the Colombian Coffee Information System (SICA).

3.1.5 | Balancing the coffee crops and tree cover panel

Although SICA reports coffee crop data for the years 2006 and 2014, the panel is not balanced for all plots. Coffee growers usually only add new entries to SICA when their crops undergo significant changes. Fortunately, the database reports the date of the latest major change made in each plot. This date can represent modifications to the plot's production system, total area or sown area, crop density, or seed variety. Since SICA is updated annually, we can use this information to fill in the missing data in the plots, assuming that there were no significant changes in the crop in the years before this date. Moreover, SICA reports retrospective information up to 2000.

While SICA does not provide a balanced panel of coffee production, this does not imply that the data is unreliable or outdated. Multiple incentives encourage farmers to keep their information as up-to-date as possible. One of the requirements to participate in NFCG programs (extension services, price guarantees, cooperatives, financial support, among others) is to be registered and have up-to-date information in SICA. Furthermore, extensionists visit all NFCG-affiliated farms at least once a year, to provide them with technical assistance, as well as to register them in the database or update their records. Although farmers do not pay any fines or taxes for not updating their information, the assistance and benefits motivate them to do so as much as possible.

We perform this process for each coffee plot to complete the panel as much as possible. The final result allows us to have two types of sample: (i) a fully imputed sample for the years 2005 to 2014, and (ii) a restricted sample for the period 2006 to 2014. The full sample includes both the data reported in SICA plus the data filled by using the latest change date.

The restricted sample focuses on the data for the years that are reported in SICA, but can also use filled data for some farms.

After balancing the coffee plots, we aggregated the panel at the farm level, as coffee growers make their production decisions based on the entire farm and not necessarily individual plots. Furthermore, a plot can be relocated or split within the same farm, it can change its crop type, or it may cease to be used for agricultural purposes. Given that plots can easily change, it is common to lose track of them or find atypical behaviors in their production variables. Aggregation gives us a panel of approximately 500, 000 observations per year during the period 2005 and 2014, which account for around 688,000 unique coffee farms. Further details of panel aggregation are available in the appendix.

With the Hansen et al. (2013) and coffee crops data at the farm level, we can track changes in coffee production and tree cover over the period 2005–2014. We remove outliers in farms' production variables (plot and farm size and sown area), however, we use the entire sample for robustness checks.[8] Further details on the cleaning process are available in Sections A.2 and A.3 of the Appendix.

4 | EMPIRICAL STRATEGY

We exploit the timing and conditioning of the PSF credit program to identify the environmental effects of the policy through its impact on tree cover. This motivates the use of a difference-in-difference specification. We define 2010 as the year of treatment since this year the NFCG started conditioning credits for the renewal of coffee crops on the use of specific seed varieties. We have seen that receiving a credit counseling visit increased the likelihood of changing seeds; thus, treated farms include all small farms that received at least one credit counseling visit between 2010 and 2013, and had at least one traditional plot before the start of the PSF program (hereafter traditional crop treatment). Controls include small farms that did not receive any credit counseling visits between 2007 and 2013 and had at least one traditional plot before the start of the program. We fit the following specification:

$$\mathtt{trees}_{it} = \beta(\mathtt{Treatment}_i \cdot \mathtt{Period}_t) + X'_{it}\delta + \mu_i + \gamma_{\nu t} + \epsilon_{it} \tag{2}$$

Where $\mathtt{trees}_{it}$ is the tree cover of the farm i in period t measured in thousands of square meters. $\mathtt{Treatment}_i$ is a dummy variable that equals one if farm i received credit counseling visits from NFCG extensionists between 2010 and 2013, and 0 otherwise. $\mathtt{Period}_t$ is an indicator equal to 1 after 2010. X'_{it} is a vector of control variables, such as the share of the coffee farm sown, crop density, seed variety, age of the coffee trees, rainfall, and temperature, all interacted with a pre-2010 time trend. $\gamma_{\nu t}$ are year-fixed effects that vary at the rural division level, μ_i are farm-fixed effects, and ϵ_{it} represents the stochastic error term. We cluster standard errors at the rural division level.

To increase our sample size, we alternatively define treatment as small farms that received a credit counseling visit with at least one plot in the technified system (hereafter technified crops treatment). We focus on "young technified crops", that is, crops with coffee

[8]We remove farms' plots that report a size above the area of the 95th percentile, to prevent cases in which extremely large plots are reported by mistake. We also remove those who report a sown area that is larger than the farm's total area.

trees that are 7 years or less of age.[9] Controls include those small farms with plots that remain as technified (and young), as technified but old (because they were not renewed in time), or returned to the traditional production system (however, this is very unusual). For this group, we focus on farms that have previously modernized their crops before PSF, but had not changed their seeds to new and improved varieties.

The key identifying assumption required to interpret β in equation 2 as the environmental impact of the policy is that the evolution of tree cover in treated and untreated farms would have been the same in the absence of the program (Angrist and Pischke, 2008). To assess the plausibility of this assumption, we look for differences in tree cover between treated and nontreated farms prior to 2010. We estimate the following specification that allows to test for pre-trends, and consider the dynamic impacts of the program:

$$trees_{it} = \sum_{j=-4}^{4} \beta_j Treatment_{ij} + X'_{it}\theta + \mu_i + \gamma_{vt} + \varepsilon_{it} \tag{3}$$

where $Treatment_{ij}$ is equal to one if farm i in year t received a credit counseling visit j years ago $(j \geqslant 0)$ or will receive the visit in j years $(j < 0)$. Testing for pre-treatment trends is equivalent to a test on β_j for $j < 0$.

A concern arises since we do not observe directly if a farm applied and received credit for renewal purposes or not, but only whether it received or not a credit counseling visit after 2010. To complement the analysis, we define treatment as receiving a counseling visit intended for different purposes. For example, those extension visits focused on Social Development and Business Management activities (see Table 6 in Robustness Checks, Section 5.1). Null effects could be indicative that tree cover loss was mainly attributed to the conditioning of the credit program for the renewal of coffee crops, and not to other NFCG programs.

We also tested whether receiving a credit counseling visit (or other types of visit) from extensionists is associated with the productive characteristics of the farm. To do this, we link farm characteristics before the NFCG policy change (2005–2009) to having received a credit counseling visit after 2010. Table 2 shows that there are no significant differences between the farms that received counseling and those that did not, and if any, the coefficients are negligible. This result suggests that receiving a visit depends on factors other than the farm characteristics, thereby providing arguments in favor of our treatment assignment being as good as random. Section C of the Appendix replicates this exercise for non-credit visits (Social Development and Business Management). The results are consistent with the previous ones.

[9]We do this since there are also "old technified crops". This type of crop has trees older than 7 years and in need of renewal.

CUADRO 2 Coffee farms productive characteristics and credit counseling visits

	Dependent variable:			
	Credit_visits (Ext.)	Credit_visits (Int.)	Credit_visits (Ext.)	Credit_visits (Int.)
	Traditional crops		Technified crops	
Area sown with coffee (%)	−0.0003**	−0.001***	−0.0004***	−0.001***
	(0.0001)	(0.0002)	(0.0000)	(0.0000)
Crop density	0.0000**	0.0000**	0.0000***	0.0000***
	(0.0000)	(0.0000)	(0.0000)	(0.0000)
Coffee trees age	0.002	−0.0001	−0.004***	−0.01***
	(0.01)	(0.01)	(0.001)	(0.001)
(Coffee trees age)^2	−0.0001	−0.0002	−0.0003***	−0.0003**
	(0.0005)	(0.001)	(0.0001)	(0.0001)
Area sown with non-resistant seeds (%)	−0.0002	−0.0003	−0.0000	−0.0000
	(0.0003)	(0.0004)	(0.0000)	(0.0000)
Temperature shocks	−0.56**	−0.79**	−0.51***	−0.74***
	(0.28)	(0.36)	(0.02)	(0.04)
Rainfall shocks	−0.11	−0.61**	−0.22***	−0.31***
	(0.18)	(0.24)	(0.02)	(0.03)
Farm mean size	18.92	18.92	15.07	15.07
Time frame	2005-2009	2005-2009	2005-2009	2005-2009
Rural division-fixed effect	Yes	Yes	Yes	Yes
Observations	8,815	8,815	377,388	377,388

Notes – This table shows the productive characteristics of the farms (pre 2010) and the likelihood of receiving a credit counseling visit from NFCG extensionists (post 2010). $^{*}p<0.1$; $^{**}p<0.05$; $^{***}p<0.01$. We only consider small farms (area $< 50{,}000 m^2 = 5 has$). Standard errors are clustered at the rural division level. *Source*: Authors' elaboration based on the Colombian Coffee Information System (SICA) data.

4.1 | Descriptive Statistics

This section presents descriptive statistics on the production activity and tree cover of coffee farms. We focus our analysis on small farms (area $< 50{,}000\mathrm{m}^2$ or < 5has), as they are the main target of the PSF program. Overall, there is a clear trend in the Colombian coffee sector in favor of the use of improved seeds. We also find similar production characteristics between our treated and control farms, regardless of the type of crop.

Table 3 summarizes the variables related to coffee production, such as the size of the farm and the area sown with coffee, the density of the crop and the age of the coffee trees. The mean farm has a size of 14.97 thousand m^2 (or 1.5 ha) and allocates 55.5 % of the total area to coffee crops. The size of the farm and the sown area differ either because the farmer decides not to sow the entire farm with coffee or because he/she decides to mix coffee with other crops, such as bananas, beans, or corn. Most of the land's crop area is sown with pest-susceptible seeds (72.13 %). Other characteristics, such as age and tree density, are closely related to crop productivity. The average crop has 50, 876 coffee trees per thousand m^2 with 5,18 years of age, which are typical features of a technified coffee field. Farms have an average of 75.09 thousand m^2 of tree cover. The trees' area can be above the farms' size, since buffers try to cover as much area as possible so as not to leave any crops out of their reach.

Some farms report 0 trees per hectare or trees with 0 years. This happens when the crops have just sown their first coffee trees or have recently renewed the crop, so there is no area covered by coffee trees or any tree density at all. The age of coffee trees can also be reported as 0 if they have not yet reached their first year. On the other hand, a tree cover of $0\mathrm{m}^2$ refers to crops with no tree cover within the farm or in the surrounding area. The maximum farm size is $49{,}900\mathrm{m}^2$, around $4{,}9\mathrm{ha}$, which is considered a small farm by the NFCG. Coffee farms can be larger, but we focus our analysis on small farms since they are the target of the PSF program. The crops in this sample are at most 20 years old, which is consistent with the productive life of coffee trees (Arcila et al., 2007).

Table 4 replicates the exercise in Table 3 but makes a distinction by type of crop (traditional or technified) and by treatment and control groups. We find that the treated farms are slightly larger than the control farms (3.58 thousand m^2 more) and have between 2pp and 2.6pp less of their area sown with pest-vulnerable seeds (on average). They also had higher tree cover in the pre-treatment period (between 30.55 and 48.44 thousand m^2 more).

Figure 3 presents the share of the farm that is sown with resistant and non-resistant seeds. Colombia, Castillo, and Tabi are the latest seeds resistant to pests, and the Tipica and Caturra varieties are susceptible to coffee rust and other diseases. We classify farms according to the treatment and control definition shown in Section 4. In Appendix B.1, Table A.7, we provide the mean area seeded with each type of seed per year. There has been a decrease in the share of the area sown with susceptible seeds and an increase in resistant varieties since 2010. This shift is more evident for the farms that received credit counseling from NFCG extensionists, and is accentuated over the years. In 2014, approximately 75 % of the treated farm area was seeded with resistant varieties, compared to 55 % of the control farm area. At the plot level, there is also an increase in the share of crops with pest-resistant seeds (see Appendix B.1.1, Figure A.5).

CUADRO 3 General descriptive statistics of coffee farms sample (2005–2009)

Variable	Mean	Min	Max
Farm size	14.97	0.10	49.90
Share of the farm sown with coffee (%)	55.50	0.00	100.00
Crop density	50876.55	0.00	833330.00
Coffee trees age (years)	5.18	0.00	17.93
Share of the farm sown with pest-vulnerable seeds (%)	72.13	0.00	100.00
Temperature (Celsius)	18.20	10.96	27.53
Rain (mts of water)	4.17	0.67	19.74
Farm tree cover	75.09	0.00	9413.21

Notes – This table shows general descriptive statistics of the production activity and forest cover of coffee farms. All variables except for coffee trees age are in thousands of m^2. Crops density refers to the number of coffee trees per thousand m^2. We only consider small farms (area $< 50{,}000m^2$) within our treatment and control groups. *Source*: Authors' elaboration based on the Colombian Coffee Information System (SICA) and Hansen et al. (2013) data.

CUADRO 4 Differences in means between treatment and control farms (2005–2009)

Variable	Mean difference	Mean (treated)	Mean (controls)	P-value
Traditional crops				
Farm size	3.58	21.88	18.29	0.00
Share of the farm sown with coffee (%)	0.25	50.22	49.96	0.6
Crop density	2348.37	32998.01	30649.65	0.00
Coffee trees age (years)	-0.30	7.28	7.58	0.00
Share of the farm sown with pest-vulnerable seeds (%)	-2.60	92.28	94.87	0.00
Temperature (Celsius)	0.06	18.03	17.96	0.17
Rainfall (mts of water)	0.19	4.13	3.94	0.00
Farm tree cover	48.44	128.36	79.92	0.00
Technified crops				
Farm size	2.42	16.89	14.47	0.00
Share of the farm sown with coffee (%)	-1.56	54.86	56.43	0.00
Crop density	-30.31	51160.45	51190.76	0.31
Coffee trees age (years)	-0.43	5.22	5.65	0.00
Share of the farm sown with pest-vulnerable seeds (%)	-1.99	71.74	73.73	0.00
Temperature (Celsius)	0.25	18.40	18.14	0.00
Rainfall (mts of water)	0.13	4.30	4.17	0.00
Farm tree cover	30.55	99.27	68.72	0.00

Notes – This table shows the differences in means between treated and control farms' productive characteristics. All variables except for coffee trees age are in thousands of m^2. Crops density refers to the number of coffee trees per thousand m^2. We only consider small farms (area $< 50{,}000m^2$) within our treatment and control groups.$^*p<0.1$; $^{**}p<0.05$; $^{***}p<0.01$. *Source*: Authors' elaboration based on the Colombian Coffee Information System (SICA) and Hansen et al. (2013) data.

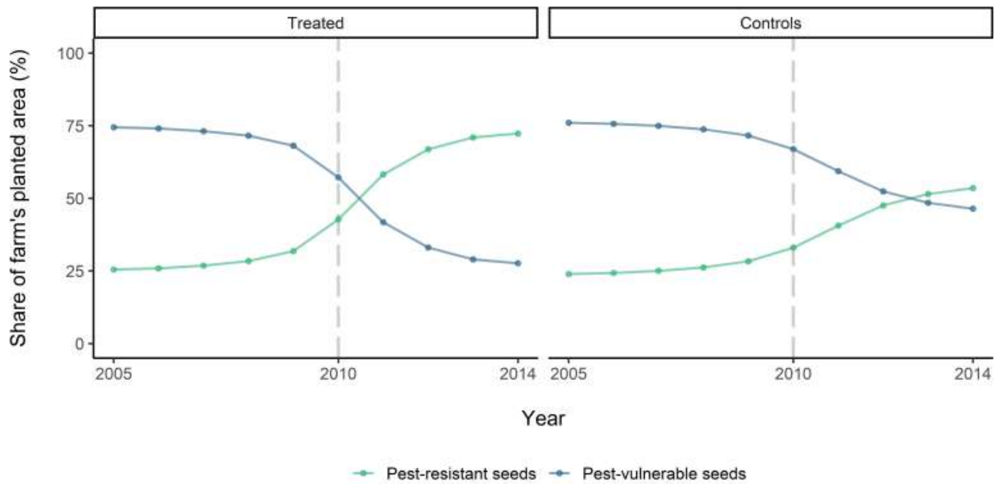

FIGURA 3 Share of the farm sown with pest-resistant seeds by group, 2005–2014. *Notes* – This graph shows the share (%) of the total area sown that coffee farms allocate to each seed variety. Caturra and Tipica are pest-susceptible seed varieties, while Castillo, Colombia, and Tabi are pest-resistant and highly productive. We include only small farms (area $< 50{,}000\text{m}^2$). *Source*: SICA.

5 | RESULTS

This section presents evidence of the effect of conditioning credit programs on environmental outcomes. Figure 4 presents graphical evidence of the impact for the traditional treatment groups (left panel) and the technified treatment groups (right panel). The graphs in each panel plot the estimated β_j's of Equation (3). Each point represents the effect of receiving a counseling visit j years before or after conditioning started. There is no evidence that farms that were eventually treated experienced different trends in tree cover than controls before receiving credit counseling visits. The estimated β_j's are close to 0 for each $j < 0$ for both treatment groups.

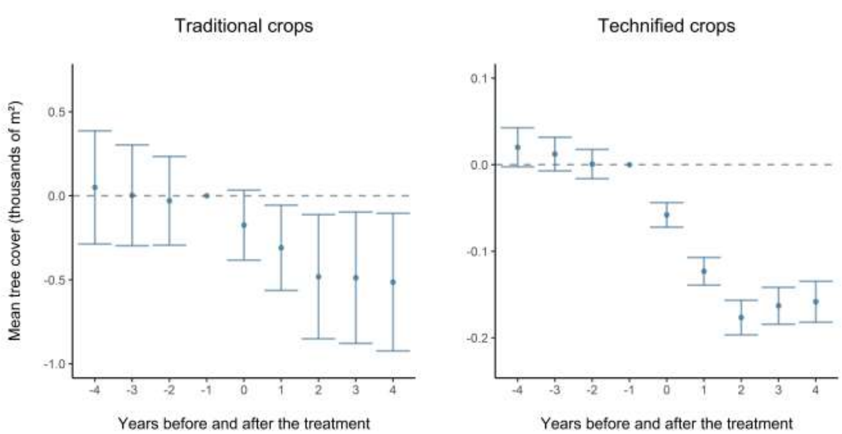

FIGURA 4 Difference-in-Differences validity check. *Notes* – This graph shows the conditional mean of the tree cover of coffee farms by crop type. The tree cover is in thousands of m^2. We include controls on production activity and weather conditions of farms, farm-level, and rural division-year fixed effects. We include only small farms (area $< 50{,}000\text{m}^2$). *Source*: SICA and Hansen et al. (2013) data.

Table 5 shows the results of the fitting equation 2 for both traditional (columns (1) to (3)) and technified treatment (columns (4) to (6)) groups. Regardless of the treatment group, conditioning renewal credits on a change in seed triggers cover loss in treated farms. Columns (1) and (4) include only controls that interacted with pre-2010 time trends and farm fixed effects, and columns (2 and 5) and (3 and 6) add common time trends at the municipality level and at the vereda level, respectively. Our most conservative specification for the traditional treatment group (column (3)) shows that treatment farms lost on average $390m^2$ of forest cover (2.0 % of average farm size). For the technified group, treated farms lost on average $140m^2$ (1 % of average farm size). Extending these estimates to all treated farms implies that the loss of tree cover was 10,318 thousands of m^2 (1,031 has). Given the carbon storage capacity of tropical agricultural soil, this results in a release of 61,912 tons of carbon (61,9 kilotons) on treated farms (Kanninen, 2003).

Table 6 presents the results of the fitting equation 2 using alternative types of counseling visits, which are not expected to address credit programs and are focused on sharing information related to farm and crop management skills (business management visits) and strengthening community organizations among coffee growers (Social Development visits). These results suggest that tree cover loss occurs through credit counseling visits that provide information on available credits to renew crops and the condition to use pest-resistant varieties, rather than other extension visits. We find significant, albeit small, effects of the Business Management visits on technified crops. This may be a consequence of training farmers on the better management of their farms, which may motivate them to improve their production, for example, by renewing or expanding their crops. As a result, this would affect the cover of the farm trees.

To further explore whether changes in forest cover were attributed to visits related to the credit program and the policy condition, we separate our analysis into small and medium/large farms. Only farms smaller than 5 ha were eligible to participate in PSF, so we do not expect any effect on non-eligible coffee growers. Table 7 presents estimates of equation 2 for small ($\leqslant 5ha$), and medium/large ($\geqslant 5ha$) separately for both treatment groups.[10] In traditional and technified crops, the drop in forest cover is mainly attributed to small farms (-0.39 and -0.14, respectively). For medium and large farms, forest cover actually increased (0.46 non-significant at conventional levels in traditional crops and 0.75 in technified treatment).

[10]As farm size can vary over time, we take the size reported in the earliest available year for each farm. In this way, we prevent farms from changing their classification over time.

CUADRO 5 Baseline results. The effect of agriculture modernization on tree cover

	Dependent variable:					
	Coffee crops tree cover (thousands of m^2)					
	Traditional crops			Technified crops		
	(1)	(2)	(3)	(4)	(5)	(6)
Treatment ∗ Period	−0.46***	−0.42**	−0.39*	−0.22***	−0.15***	−0.14***
	(0.15)	(0.17)	(0.21)	(0.02)	(0.02)	(0.02)
Mean of dependent variable	83.31	83.31	83.31	71.32	71.32	71.32
Farm mean size	18.9	18.9	18.9	15.23	15.23	15.23
Time frame	2005-2014	2005-2014	2005-2014	2005-2014	2005-2014	2005-2014
Farm-fixed effect	Yes	Yes	Yes	Yes	Yes	Yes
Municipality and year-fixed effect	No	Yes	No	No	Yes	No
Rural division and year-fixed effect	No	No	Yes	No	No	Yes
Controls on weather and production activity	Yes	Yes	Yes	Yes	Yes	Yes
Observations	77,865	77,865	77,865	3,035,344	3,035,344	3,035,344

Notes – This table reports the Difference-in-Differences estimates of the effect of agriculture modernization on the tree cover of coffee farms. *$p<0.1$; **$p<0.05$; ***$p<0.01$. Standard errors are clustered at the rural division level. The treated are the farms with traditional/technified crops that received at least 1 credit counseling visit from NFCG's extension services during 2010–2013. The controls are the farms with traditional/technified crops that didn't received any credit counseling visit. We only consider small farms (area $< 50{,}000m^2$). Controls on production activity include farm yearly variables such as the share of the farm sown with coffee, crop density, coffee trees age and the square of the trees age, and the share of the farm sown with each seed variety. Controls on weather include farms' mean temperature and rainfall. *Source*: Authors' elaboration based on the Colombian Coffee Information System (SICA) and Hansen et al. (2013) data.

CUADRO 6 Placebo test. The effect of non-credit visits on the tree cover of coffee farms

	Dependent variable:					
	Coffee crops tree cover (thousands of m^2)					
	Traditional crops			Technified crops		
Treatment ∗ Period	−0.39*	−0.11	−0.95	−0.14***	−0.07***	0.08
	(0.20)	(0.14)	(0.74)	(0.02)	(0.03)	(0.09)
Visit type	Credit	Business mgmt.	Social dev.	Credit	Business mgmt.	Social dev.
Mean of dependent variable	83.31	85.16	85.49	71.32	73.25	73.88
Farm mean size	18.9	19.01	19.04	15.23	15.35	15.4
Time frame	2005-2014	2005-2014	2005-2014	2005-2014	2005-2014	2005-2014
Farm-fixed effect	Yes	Yes	Yes	Yes	Yes	Yes
Rural division and year-fixed effect	Yes	Yes	Yes	Yes	Yes	Yes
Controls on weather and production activity	Yes	Yes	Yes	Yes	Yes	Yes
Observations	77,866	81,958	82,820	3,035,344	3,333,471	3,388,772

Notes – This table reports the Difference-in-Differences estimates of the effect of agriculture modernization on the tree cover of coffee farms. $^{*}p<0.1$; $^{**}p<0.05$; $^{***}p<0.01$. Standard errors are clustered at the rural division level. The treated are the farms with traditional/technified crops that received at least 1 Credit Counseling, Business Management or Social Development visit from NFCG's extension services during 2010–2013. The controls are the farms with traditional/technified crops that didn't received any business management, social development or credit counseling visit. We only consider small farms (area $< 50{,}000m^2$). Controls on production activity include farm yearly variables such as the share of the farm sown with coffee, crop density, coffee trees age and the square of the trees age, and the share of the farm sown with each seed variety. Controls on weather include farms' mean temperature and rainfall. *Source*: Authors' elaboration based on the Colombian Coffee Information System (SICA) and Hansen et al. (2013) data.

CUADRO 7 Placebo test. The effect of agriculture modernization on the tree cover by farm size

	Dependent variable:			
	Coffee crops tree cover (thousands of m^2)			
	Traditional crops		Technified crops	
$Treatment * Period$	−0.39*	0.46	−0.14***	0.75***
	(0.20)	(0.61)	(0.02)	(0.22)
Farm size	Small	Med. and large	Small	Med. and large
Mean of dependent variable	83.31	360.48	71.32	429.03
Farm mean size	18.9	195.52	15.23	158.82
Time frame	2005-2014	2005-2014	2005-2014	2005-2014
Farm-fixed effect	Yes	Yes	Yes	Yes
Rural division and year-fixed effect	Yes	Yes	Yes	Yes
Controls on weather and production activity	Yes	Yes	Yes	Yes
Observations	77,866	38,884	3,035,344	753,844

Notes – This table reports the Difference-in-Differences estimates of the effect of agriculture modernization on the tree cover of coffee farms. $^{*}p<0.1$; $^{**}p<0.05$; $^{***}p<0.01$. Standard errors are clustered at the rural division level. The treated are the farms with traditional/technified crops that received at least 1 credit counseling visit from NFCG's extension services during 2010–2013. The controls are the farms with traditional/technified crops that didn't received any credit counseling visit. We consider small ($< 50{,}000m^2$ or 5ha), medium ($\geqslant 50{,}000m^2$ and $< 150{,}000m^2$, or 5ha–150ha), and large farms ($\geqslant 150{,}000m^2$ or 15ha). Controls on production activity include farm yearly variables such as the share of the farm sown with coffee, crop density, coffee trees age and the square of the trees age, and the share of the farm sown with each seed variety. Controls on weather include farms' mean temperature and rainfall. *Source*: Authors' elaboration based on the Colombian Coffee Information System (SICA) and Hansen et al. (2013) data.

5.1 | Robustness Checks

We perform multiple robustness checks to confirm the baseline results. The first robustness check accounts for the possibility that changes in farms' tree cover are not due to the PSF program, but to underlying trends at the farm level and the productive cycles of trees. We narrowed the sample to farms that had coffee plots at the beginning and end of their productive cycle in 2009. The productive cycle of the coffee tree is between 6 and 8 years after sowing, and after that point, the productivity of the tree decreases rapidly (Arcila et al., 2007). For traditional farms, this meant that those with crops that were 9 years old or older in 2009 had to decide whether to renew their crops under a new production system, renew them with the same system, or allow the trees to continue to grow old. In technified crops, this threshold would be crossed at 7 years, just before the crops are considered as Old–Technified. Based on this, we can split our sample in two ways: (i) those farms with crops that were at the beginning of their cycle in 2009; (ii) the farms with crops that were at the end of their cycle (in 2009). In the first sub-sample, we want to compare the tree cover of farms that did not need to renew but decided to do so, with the tree cover of farms that did not renew at all. In the second sub-sample, we compare the farms that needed to renew their crops after 2010, regardless of the PSF incentives.

Once we identified the farms by their productive phase, we built the comparison groups using the same criteria as in the previous estimates. Table 8 shows the results of the robustness check for the two comparison groups at the beginning (columns 1 and 3) and the end (columns 2 and 4) of their cycles. We find that traditional farms that did not need to renew, but decided to do so (column 1), lost more tree cover than those that renewed their crops when strictly necessary (column 2). However, the results are not statistically significant. We believe that this may be a consequence of splitting and reducing the size of our sample. In technified farms (columns 3 and 4), renewal at the beginning or at the end of the cycle leads to the same loss in tree cover (170 m^2 per farm, on average). A possible explanation is that these are farms that by definition have young trees and do not need immediate renewal and that if they do change the crop, it would be to modify the seed variety. These suggest that the policy had the desired effect of inducing a seed change.

Our second robustness check compares the environmental effect of conditioning credits with the number of extension workers in each municipality.[11] We expect that in municipalities with a higher presence of extension workers, there would be more activities to promote credit programs, which would increase the number of coffee growers applying for (and receiving) credits. Therefore, this may result in further changes to the farms' tree cover. Table 9 shows the results of comparing the presence of extensionists with the results of the tree cover. Columns 1 and 3 focus on municipalities where the number of extensionists is higher than the average of all municipalities, and columns 2 and 4 focus on municipalities where the number of extension workers is below the average. We found that the loss of tree cover associated with the PSF program was greater in farms located in municipalities with a stronger presence of extension workers. This is true for both Traditional and Technified farms. However, in traditional farms, the effect is not statistically significant in one of the cases (column 1). We believe that this could be the result of splitting our sample.

We conducted a third robustness check to link the environmental effect of the renewal credit with the intensity of the La Niña rainfall shock on the farms. To this end, we compare farms located in areas that experienced excess or rainfall deficit (we will refer to them as

[11] Municipalities are the main administrative and political division in Colombia; they are autonomous in taking fiscal, political, and administrative decisions. There are about 1,122 municipalities in the country, and they can group several rural/veredas divisions

"affected") with farms that did not experience significant weather changes (we will refer to them as "unaffected"). Table 10 presents the results of this test. We find that traditional farms located in municipalities that were strongly affected by the 2010-2011 rainfall shock (column 1) lost 5 times more tree cover than those that were not affected (column 2). This suggests that the most affected farmers tried to adapt their crops by changing their seed variety to protect themselves against future shocks. We observe the opposite effect in the technified farms. The loss of tree cover was greater in farms that were not affected by rainfall variations. In this case, the less affected farmers renewed more of their crops with pest-resistant seeds.

CUADRO 8 Robustness check. Farms with coffee crops at the beginning and end of their productive cycle

	Dependent variable:			
	Coffee crops tree cover (thousands of m^2)			
	Traditional crops		Technified crops	
	(1)	(2)	(3)	(4)
$\mathtt{Treatment} * \mathtt{Period}$	−0.49	−0.44	−0.17***	−0.17***
	(0.31)	(0.28)	(0.02)	(0.05)
Mean of dependent variable	84.69	79.82	64.5	79.27
Farm mean size	19.5	17.45	14.25	16.47
Stage of productive cycle	Beginning	End	Beginning	End
Time frame	2005-2014	2005-2014	2005-2014	2005-2014
Farm-fixed effect	Yes	Yes	Yes	Yes
Rural division and year-fixed effect	Yes	Yes	Yes	Yes
Controls on weather and production activity	Yes	Yes	Yes	Yes
Observations	55,027	22,838	1,387,966	460,186

Notes – *p<0.1; **p<0.05; ***p<0.01. This table shows the tree cover loss of coffee farms based on the coffee production cycle stage of their crops. Standard errors are clustered at the rural division level. The treated are the farms with crops that were at the beginning/end of their productive cycle in 2009, i.e., farms with coffee trees younger/older than 9 years (for Traditional crops) or 7 years (for Technified crops). We only consider small farms (area $< 50{,}000m^2$). *Source*: SICA and Hansen et al. (2013) data.

CUADRO 9 Robustness check. Coffee farms located in municipalities with FNC extension workers.

	Dependent variable:			
	Coffee crops tree cover (thousands of m^2)			
	Traditional crops		Technified crops	
	(1)	(2)	(3)	(4)
$Treatment * Period$	−0.87	−0.33**	−0.18***	−0.12***
	(0.71)	(0.15)	(0.03)	(0.02)
Mean of dependent variable	104.17	84.32	81.66	68.63
Farm mean size	20.26	18.32	15.75	14.71
Number of extension workers in municipality	Above average	Below average	Above average	Below average
Time frame	2005-2014	2005-2014	2005-2014	2005-2014
Farm-fixed effect	Yes	Yes	Yes	Yes
Rural division and year-fixed effect	Yes	Yes	Yes	Yes
Controls on weather and production activity	Yes	Yes	Yes	Yes
Observations	21,420	37,740	1,234,170	1,287,032

Notes – *p<0.1; **p<0.05; ***p<0.01. This table presents the robustness test that compares the change in the farms' tree cover with the number of FNC extension workers within the municipalities. Standard errors are clustered at the rural division level. This test splits the sample into farms located in municipalities with an above and below average number of NFCG extensionists. We only consider small farms (area $< 50{,}000m^2$). *Source*: SICA and Hansen et al. (2013) data.

CUADRO 10 Robustness check. Coffee farms affected by "La Niña" rainfall shocks during 2010–2011.

	Dependent variable:			
	Coffee crops tree cover (thousands of m^2)			
	Traditional crops		Technified crops	
	(1)	(2)	(3)	(4)
Treatment ∗ Period	−0.50*	−0.10	−0.11***	−0.28***
	(0.28)	(0.09)	(0.02)	(0.03)
Mean of dependent variable	91.26	66.07	70.13	75.57
Farm mean size	19.36	19.06	14.96	16.19
Affected by "La Niña" phenomenon	Yes	No	Yes	No
Time frame	2005-2014	2005-2014	2005-2014	2005-2014
Farm-fixed effect	Yes	Yes	Yes	Yes
Rural division and year-fixed effect	Yes	Yes	Yes	Yes
Controls on weather and production activity	Yes	Yes	Yes	Yes
Observations	63,358	20,852	2,370,310	665,904

Notes – *p<0.1; **p<0.05; ***p<0.01. This table presents the robustness check that compares the change in farm tree cover with the impact of "La Niña" phenomenon. We classify coffee farms according to whether they were affected by the "La Niña" phenomenon during 2010–2011. Standard errors are clustered at the rural division level. The affected farms are those that experienced major alterations in their average rainfall. We only consider small farms (area $< 50{,}000\text{m}^2$). *Source*: SICA, Hansen et al. (2013) and IDEAM (2014) data.

5.2 | Staggered treatment – Callaway and Sant'Anna (2020)

Although all crop renewal credits were conditional on the use of pest-resistant seeds in 2010, farmers could apply for (and receive) the grant in subsequent years. Therefore, farms can renew their crops in 2010 and 2014, so the treatment was progressively implemented. The emerging literature on difference-in-differences shows that this type of design can lead to biased estimates when there is heterogeneity in treatment effects, for example, if the intervention is not fully adopted after a time point but in stages (Goodman-Bacon, 2021; Callaway and Sant'Anna, 2020; Sun and Abraham, 2020; Borusyak et al., 2021). An alternative is to use a staggered difference-in-differences design, or "staggered DID". Callaway and Sant'Anna (2020) provide an estimation method that allows identifying causal effects in an "Staggered DID" even when there are differences in the observable characteristics of the treatment groups. Taking this into account, we replicated our baseline results using the Callaway and Sant'Anna (2020) method to check if the effects we found using the two-way fixed effects DID estimator are biased due to heterogeneity in the treatment year. Section C.1 in the Appendix provides technical details on the estimation process.

A feature of the staggered DID design is that it requires splitting the treatment group based on the start of the intervention for each treated unit, without affecting the composition of the control group. This is an important limitation for our first treatment group (Traditional crops) since each treatment group would have around 100 farms that we must compare with more than 7,000 control farms. This imbalance can affect the accuracy of our results. However, our second comparison group (Technified crops) is not affected by this problem, since the sample size per treatment is much larger.[12] Based on this, we will focus our staggered DID estimates on our Technified crops group. We maintain all the baseline criteria used to define our treated and control farms.

Table 11 shows the average aggregate treatment effect of conditioning renewal credits on the use of resistant seeds on the tree cover of farms, using a Staggered DID design following Callaway and Sant'Anna (2020). We find the same result as our baseline estimates: a decrease in the tree cover of the farms that received the conditioned renewal credits. Under this method, the average farm lost 6.606m^2 (0.6ha) after renewing its technified crops with pest-resistant seeds. Callaway and Sant'Anna (2020) also allows us to disaggregate the effect of treatment by exposure time (in the style of an event study) and by treatment group. Table 12 shows the first case. We find that before the NFCG announced the change in credit policy, there were no statistically significant differences between the treated and control farms. However, once the policy change was announced in 2010, the farms that renewed their crops lost more tree cover than those that decided to keep their crops with non-resistant seeds. When we analyze the effect by treatment group (Table 13), we find that tree cover loss is greater in those farms that received credit counseling between 2010 and 2012, while the effect disappears in 2013. This is consistent with the fact that 65 % of the PSF credits issued between 2008 and 2014 were distributed between 2010 and 2012 (Echavarría et al., 2018). Therefore, we can expect a more intense impact on tree cover during this period. Furthermore, farms that received credit counseling in 2013 may not have applied for credit immediately, may have applied for credit and are waiting for it to be disbursed, or may have received the grant and have not renewed their crops yet.

CUADRO 11 Robustness check. Aggregated Average Treatment Effect (ATT) of agriculture modernization on tree cover using staggered treatment. Technified crops.

ATT	Std. error	Inf. Lim.	Sup. Lim.	P-value
-6.06	1.35	-8.7	-3.42	***

Notes – *p<0.1; **p<0.05; ***p<0.01; $^{-}$p>0.1. This table shows the aggregated results of estimating the effect of agricultural modernization on the tree cover of coffee farms using staggered treatment (Callaway and Sant'Anna, 2020). Standard errors are doubly robust and clustered at the rural division (vereda) level. We include farm and year fixed effects. We only consider small farms (area $< 50{,}000m^2$). *Source*: SICA and Hansen et al. (2013) data.

[12] In our baseline results we have 959 treated and 7,719 control farms in the Traditional crops group, and 71,034 treated and 344,461 control farms in the Technified crops group.

CUADRO 12 Robustness check. Dynamic Aggregated Average Treatment Effect (ATT) of agriculture modernization on tree cover using staggered treatment. Technified crops.

Year	ATT	Std. error	Inf. Lim.	Sup. Lim.	P-value
-7	0.64	1.49	-3.45	4.73	-
-6	-0.54	1.13	-3.66	2.58	-
-5	0.18	1.80	-4.77	5.13	-
-4	0.50	8.89	-23.96	24.97	-
-3	-5.57	4.70	-18.50	7.36	-
-2	-2.85	2.37	-9.36	3.66	-
-1	0.56	2.15	-5.37	6.49	-
0	-5.05	1.65	-9.59	-0.52	**
1	-6.65	2.46	-13.41	0.11	*
2	-5.53	1.62	-10.00	-1.07	**
3	-5.93	1.64	-10.43	-1.43	***
4	-9.23	3.15	-17.91	-0.56	**

Notes – *p<0.1; **p<0.05; ***p<0.01; $^{-}$p>0.1. This table shows the dynamic aggregated results of estimating the effect of agricultural modernization on the tree cover of coffee farms using staggered treatment (Callaway and Sant'Anna, 2020). Standard errors are doubly robust and clustered at the rural division (vereda) level. We include farm and year fixed effects. We only consider small farms (area < 50,000m^2). *Source*: SICA and Hansen et al. (2013) data.

CUADRO 13 Robustness check. Group Aggregated Average Treatment Effect (ATT) of agriculture modernization on tree cover using staggered treatment. Technified crops.

Treatment group	ATT	Std. error	Inf. Lim.	Sup. Lim.	P-value
2010	-6.85	2.06	-11.59	-2.11	***
2011	-5.91	2.38	-11.39	-0.43	**
2012	-6.83	3.42	-14.72	1.06	*
2013	-2.32	6.18	-16.57	11.94	-

Notes – *p<0.1; **p<0.05; ***p<0.01; $^{-}$p>0.1. This table shows the group aggregated results of estimating the effect of agricultural modernization on the tree cover of coffee farms using staggered treatment (Callaway and Sant'Anna, 2020). Standard errors are doubly robust and clustered at the rural division (vereda) level. We include farm and year fixed effects. We only consider small farms (area < 50,000m^2). *Source*: SICA and Hansen et al. (2013) data.

5.3 | Heterogeneity Analysis

Conditioning the renewal credits was motivated by the rainfall shock caused by the climatic phenomenon of ENSO La Niña 2010–2011, which damaged coffee production throughout the country. In response and anticipating that climate change may increase the frequency of such weather events, the NFCG promoted the renewal of crops with resistant seeds to protect the coffee sector from future shocks. Therefore, there is the possibility that seeds changes were further encouraged in areas that are more vulnerable to climate change or that coffee growers in these areas had a special interest in protecting their crops. Table 14 presents a heterogeneity analysis in which we classify the farms of each comparison group according to their degree of vulnerability to climate change: high or very high and low or medium.

Classification of vulnerability to climate change was provided from the IDEAM Climate Change Vulnerability Index (Cabrera et al., 2011), the institution responsible for collecting and analyzing information on the environmental, hydrological, and meteorological conditions of Colombia. The index classifies the vulnerability of ecosystems into 4 categories: very high, high, medium, and low (Cabrera et al., 2011). The results of Table 14 show that traditional farms located in areas of low or medium risk to climate change renewed their crops the most (and lost more tree cover) than those with higher vulnerability. In this case, coffee farmers with lower vulnerability to climate shocks were the ones who adapted their crops the most with pest-resistant seeds. The opposite is true for technified farms: farms located in highly vulnerable areas renewed their crops much more than those with a lower degree of vulnerability. Therefore, the loss of tree cover was greater for farms with a high vulnerability to climate change.[13]

[13]The implications of these estimations will be developed in future versions of the paper.

CUADRO 14 Heterogeneity analysis. The environmental effect of agricultural modernization on tree cover based on farms' vulnerability to climate change.

	Dependent variable:			
	Coffee crops tree cover (thousands of m^2)			
	Traditional crops		Technified crops	
	(1)	(2)	(3)	(4)
Treatment ∗ Period	−0.34	−0.52**	−0.17***	−0.07*
	(0.30)	(0.25)	(0.01)	(0.04)
Mean of dependent variable	82.38	85.0	64.94	86.13
Farm mean size	19.23	18.24	15.05	15.66
Vulnerability degree	High or Very high	Low or Medium	High or Very high	Low or Medium
Time frame	2005-2014	2005-2014	2005-2014	2005-2014
Farm-fixed effect	Yes	Yes	Yes	Yes
Rural division and year-fixed effect	Yes	Yes	Yes	Yes
Controls on weather and production activity	Yes	Yes	Yes	Yes
Observations	51,752	26,113	2,122,212	914,028

Notes – *p<0.1; **p<0.05; ***p<0.01. This table shows the heterogeneity analysis for the two comparison groups. We separate the change in tree cover based on the farms' vulnerability to climate change. Standard errors are robust to heteroscedasticity. We classify farms based on IDEAM climate change vulnerability index for 2071–2100. We only consider small farms (area $< 50{,}000 m^2$). *Source*: SICA, Hansen et al. (2013) and IDEAM (Cabrera et al., 2011) data.

6 | DISCUSSIONS

Crop renewal programs are important in protecting coffee production from extreme weather events, as well as improving the productivity and profitability of coffee production. NFCG has highlighted the effectiveness of seed-conditioned renewal credits in modernizing the coffee sector, each year reporting a more robust productive structure. In 2014, 66 % of the crops were planted with pest-resistant varieties, 96 % used a technified system and 82 % were made up of young trees (Bernal, 2016; NFCG, 2014a).

Based on this, we conducted a back-of-the-envelope cost-benefit analysis to estimate the profits perceived by producers who renewed their crops with pest-resistant varieties compared to those who decided to keep the more traditional seeds. To do this, we calculated the mean productivity, income, production costs, and benefits for each hectare planted with pest-resistant and non-resistant varieties (Duque-Orrego et al., 2005).[14] We also estimated the sunk environmental costs of crop renewal, in terms of the cost of emitting carbon dioxide into the environment (considering the carbon tax in Colombia (DIAN, 2022)) and the opportunity cost of not receiving payments for environmental services (using the payment per hectare of preserved forest in Colombia (DNP, 2017)).

We find that, on average, treated farms (those that renewed their crops with the new seeds) report higher income and yield levels than control farms (those that kept their crops planted with non-resistant seeds). The production and environmental costs of the treated farms are also higher than those of the control farms. Finally, we find that the average benefit of farms that renewed their crops is significantly larger than those that kept their crops with the traditional seeds.[15] The average treated farm receives a benefit of around 10 and 16 million pesos (USD $5,000-8,000$), while control farms receive between 3 and 10 million pesos (USD $1,500-5,000$).[16] Therefore, the renewal of crops with the new varieties can be associated with improved economic results for coffee growers. The D section of the appendix provides more technical details on the cost-benefit analysis and its results.

Nevertheless, acknowledging the economic benefits of pest-resistant crops does not imply overlooking their unintended environmental effects. The increasing share of crops exposed to sunlight (> 60 % in 2014) translates into a reduction in the tree cover of coffee crops and therefore a higher emission of carbon dioxide (Bernal, 2016; Kanninen, 2003; Arcila et al., 2007). Furthermore, pest-resistant varieties are more dependent on a particular type of fertilization (*edaphic fertilization*) that has been associated with higher CO^2 emissions (Bernal, 2016).

Similarly, the farmer's cost-benefit analysis does not include the private and social costs that arise as a consequence of deforestation. On the one hand, cutting shade trees implies a reduction in carbon sequestration capacity, and on the other hand, a greater vulnerability to future weather shocks. If we aggregate the total emissions from crop renewal deforestation (61,912 tons) on treated farms and translate them into monetary costs using the carbon tax, the environmental cost of emissions amounts to 59 billion pesos, about 15.6 % of Colombia's GDP in 2014. Deforestation also results in coffee farmers missing out on cash transfers for environmental services by not preserving the forest surrounding their crops. If we add the deforested area in treated farms and express it in terms of preservation payments, coffee growers face an opportunity cost of 349 million pesos (USD $71,500) in lost incentives.

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[14]We use the Castillo seed as a reference, based on Duque-Orrego et al. (2005) research.

[15]We calculate the benefit per hectare as the difference between the hectare's total income and cost, $\pi_i = I_i - C_i$, including the environmental and production costs.

[16]Calculations based on 2014 USD to the COP exchange rate.

The forest loss of thousands of small coffee farmers can lead to substantial social costs not considered by policymakers in the formulation of renewal programs. While renewal programs help ensure the productivity and competitiveness of coffee crops, such initiatives must be paired with conservation strategies to mitigate their medium and long-term environmental effects, to avoid leaving coffee growers even more vulnerable to the adverse effects of climate change.

7 | CONCLUSIONS

Improved technologies and policies are the keys to providing adaptation opportunities in the agricultural sector on the brink of climate change. These policies may have proven beneficial in improving productivity in the short run but often overlook the potential environmental costs of such processes. In this article, we advance our understanding of the unintended environmental effects of an adaptation policy in the context of the Colombian coffee sector. We focus on conditioning credit programs for coffee crop renewal on the use of pest-resistant varieties, which were designed to protect farmers against the occurrence of weather shocks.

Using a newly assembled panel that includes coffee grower production decisions matched with tree cover satellite data, we find that coffee farms that renewed their crops lost on average more tree cover than those that kept their production systems unchanged. Using a difference-in-difference design, we find that, on average, treated coffee growers lost tree coverage equivalent to approximately 2 % of their farm size. These results imply that the treated farms lost 1,031 hectares in total, which is equivalent to a release of 61,912 tons of carbon. When we translate the total emissions using the carbon tax, we find that the environmental cost of deforestation amounts to 15.6 % of Colombia's GDP in 2014.

Our results take into account the potential and unintended negative effects of adaptation policies on tree cover. Although renewing and protecting coffee crops against pests is likely to improve productivity, stability, and quality of harvests (Arcila et al., 2007; NFCG, 2009, 2010, 2018), the loss in tree cover can also increase vulnerability to weather shocks, which are expected to become more frequent in the future. Tree cover reduces crop temperature, promotes forest-like biodiversity, helps maintain soil fertility, and controls soil erosion, among other environmental benefits. In addition, there is an additional social cost related to a decrease in carbon sequestration. A full cost-benefit analysis of such policies should include the tree-loss cost, or include strategies to mitigate the potential environmental effects.

Future work considers exploring the possibility that coffee farmers clear more trees than is required under resistant seed varieties. We are working with NFCG extensionists to understand whether there is an optimal shade level for pest-resistant crops to compare this with farms' tree cover data. Our goal is to find out if there are differences in tree cover and if there are incentives that could trigger excessive deforestation.

Finally, we want to try to measure other environmental effects within farms related to the reduction in tree cover. Such private costs could be changes in soil quality, water sources, and loss of biodiversity, among others. We are looking for data to measure these different types of environmental costs.

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A | DATA

A.1 | Coffee crops panel

Every time a plot undergoes a significant change in its production system, total area or sown area, crop density, or seed variety, it reports the change date in SICA. Considering that SICA is updated annually, we can identify year-to-year changes in each plot. For example, a plot with information between 2006 and 2014 whose most recent change dates correspond to the years 2001 and 2012, did not have significant changes between 2001 and 2011. Therefore, we can complement its data from 2001-2005 with information from 2006-2011. This way a plot with data between 2006 and 2014 will now have information from 2001 to 2014. Then we can use the ENC data to assign the 1997 information to the year 2000 and thus complete the 2000-2014 period.

This process was performed for each plot considering the most recent changes reported in SICA, with the aim of completing the coffee panel as much as possible. The first date of change taken into account corresponds to 1995 since the life expectancy of a coffee crop is approximately 20 to 25 years (Arcila et al., 2007). We identified four types of plots according to the availability of information in SICA and the ENC:

- *Type 1*: Plots reported in SICA between 2006 and 2014, whose latest change date is before 2000, allowing us to complete the entire 2000-2014 period.
- *Type 2*: Plots reported in SICA between 2006 and 2014 but whose latest change date is above 2000, making it impossible to complete the period. For these plots, we used the 1997 ENC to fill the year 2000 and then used the available information from 2006-2014 to complete as much as possible the period 2001-2005.
- *Type 3*: Plots reported in SICA between 2006 and 2014 whose latest change date is greater than 2000 and with no information in the ENC. These plots were filled in as much as possible according to the latest change date but generally remain incomplete.
- *Type 4*: The plots were only reported in SICA in 2014, and their last change date corresponds to 2014. These plots are impossible to fill for 2000-2013, so they were removed from the panel.

A.2 | Tree cover panel

We calculated the annual tree cover as the difference between the base cover and the annual deforestation of each plot, based on the following formula:

$$trees\_year_{it} = base\_trees_i - (deforestation_{i1} + deforestation_{i2} + ... + deforestation_{it})$$

With $trees\_year_{it}$ being the tree cover of plot i in period t, $base\_trees_i$ the baseline tree cover of plot i (corresponding to 2000), and $deforestation_{it}$ the deforested area of plot i in period t. All of the former variables are measured in square meters.

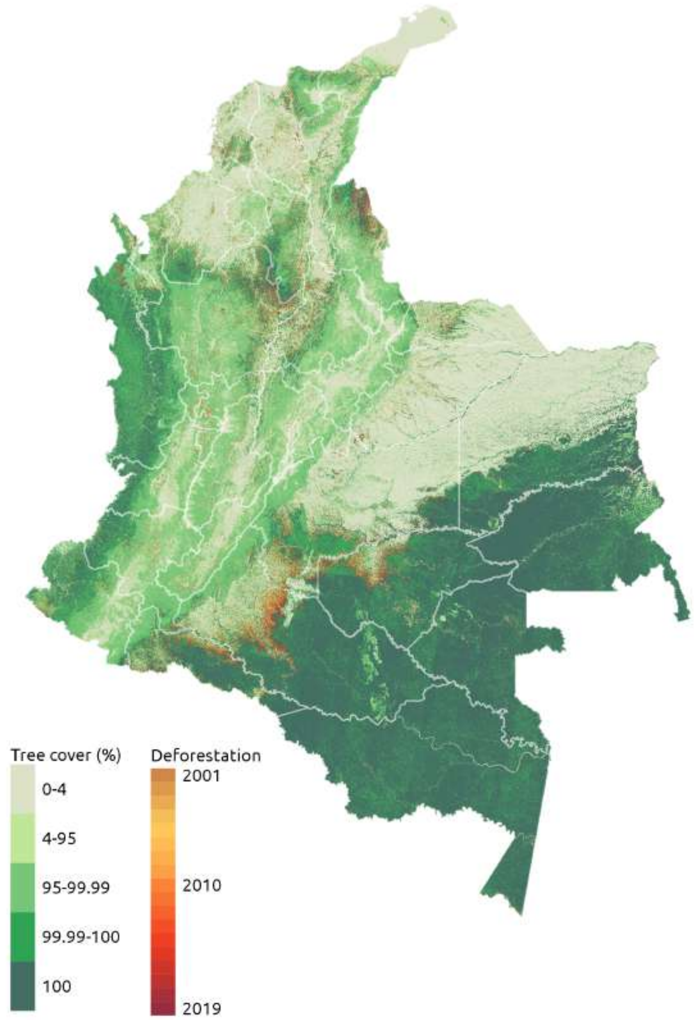

FIGURA A.1 Tree cover and deforestation in Colombia, 2000–2019. *Notes* – This map shows Colombia's tree cover in 2000 and deforestation between 2001 and 2019, at a 30m^2 resolution. The tree cover is presented as the percentage of a pixel that is covered by trees. *Source:* Authors' elaboration based on Hansen et al. (2013) data.

A.3 | Outliers in coffee plots size

Once the coffee and tree cover panel was completed, we treated outliers in plot size. In particular, we deleted all plots from the 95th percentile onward, whose large size is likely due to erroneous reporting. The oversize plots affect the tree cover statistics, as shown in Table A.1. The results in Table A.1 are not exactly the same as the descriptive statistics shown in Table 3 since the panel was further cleaned for the difference in difference estimations. Figure A.2 presents the distribution of the tree cover of the plots before and after removing outliers.

CUADRO A.1 General descriptive statistics of coffee plots' tree cover.

	With outliers	Without outliers
Min.	0	0
1st Qu.	12, 401,4	11, 603,4
Median	33, 975,9	30, 998,4
Mean	107, 358,2	55, 997,5
3rd Qu.	88, 009,2	74, 405,4
Max.	19, 124, 677,0	335, 466,6

Notes – This table reports general descriptive statistics of the tree cover of coffee plots before and after treating outliers. *Source*: Authors' elaboration based on the Colombian Coffee Information System (SICA) and Hansen et al. (2013) data.

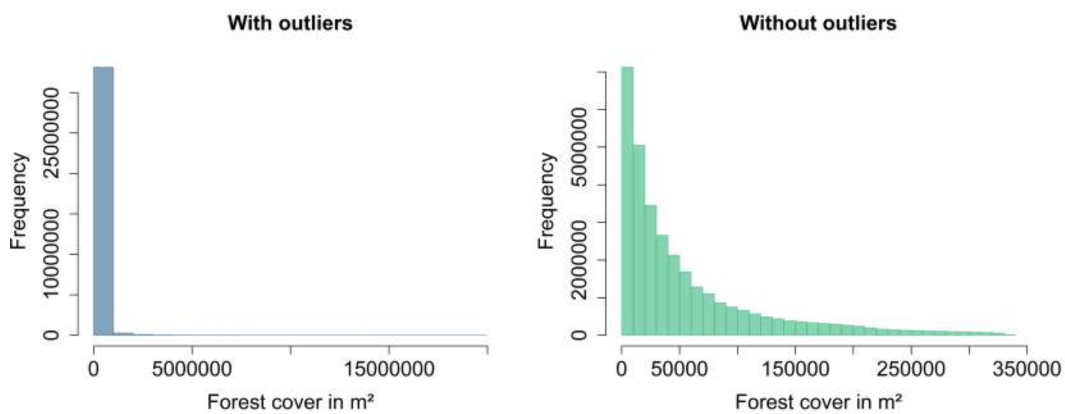

FIGURA A.2 Coffee crops tree cover distribution before and after treating outliers in the size of the plot. *Notes* – This graph shows the distribution of the tree cover of coffee plots before and after treating outliers in the plots' size. *Source*: Authors' elaboration based on the Colombian Coffee Information System (SICA) and Hansen et al. (2013) data.

A.4 | Coffee farms panel

To aggregate the SICA-Hansen panel at the farm level, we follow the steps below.

- We created a dummy variable to identify the number of plots per farm.
- For each plot we created variables for the area allocated to traditional, young-technified, or old-technified crops. For example, a traditional plot of $1000m^2$ will have variables $area\_lote\_trad = 1000$, $area\_lote\_old = 0$ and $area\_lote\_young = 0$, where the last two are equal to zero because each plot uses only one production system.
- We repeated the previous step for the coffee sown area ($area\_cultivation\_trad$, $area\_cultivation\_young$, $area\_cultivation\_old$), for all varieties of seeds, types of luminosity, and labor (sowing renewal, zoca renewal, new sowing, and crop elimination).

  We add the plot area by system type, seed, luminosity, and labor at the farm level. In this way, each farm has variables that indicate the area allocated to each production system, seed, and others. Since farms can have several plots, some will have areas with Traditional and Technified crops at the same time. In addition:

- We added the area of the coffee-sown plots to obtain the farm's sown area. We did the same with the plots' tree cover.
- We averaged continuous variables such as the age and density of the crop. That is, to obtain the age of the trees on a farm, we averaged the age of its plots.

Finally, since farms can have several production systems at once, to identify changes in plot systems, we created dummy variables before aggregating the panel. That is,

- Each plot has a dummy that indicates whether its production system before 2010 was traditional, young-technified, or old-technified. They also have dummies to know their production system after 2010.
- We created additional dummy variables to identify plots that remained in the traditional system throughout the period, whether they went from traditional to young technified, or from traditional to old technified.

We also deleted plots whose area exceeded the total area of the coffee farm, as well as those that had reported areas equal to zero or did not report any area at all. Regarding the type of production system, we also deleted the plots without information for this variable.

B | DESCRIPTIVE STATISTICS

B.1 | Coffee plots descriptive statistics

The following section contains descriptive statistics on the Colombian coffee sector at the plot level.

FIGURA A.3 Spatial distribution of coffee farm plots, 2006-2014. *Notes* – This map shows the spatial distribution of coffee plots in Colombia from 2006–2014. A coffee farm is composed of at least one coffee plot. *Source*: Authors' elaboration based on the Colombian Coffee Information System (SICA).

B.1.1 | General descriptive statistics of coffee plots

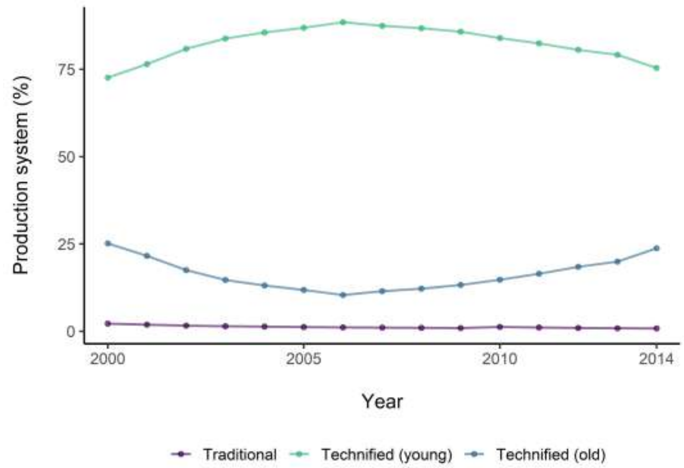

FIGURA A.4 Annual share of production systems used in coffee plots, 2000–2014. *Notes* – This graph shows the annual share of the production systems used in the Colombian coffee sector between 2000 and 2014. Shares are understood as the ratio between the number of plots that use a particular production system and the sum of all plots. *Source*: Authors' elaboration based on the Colombian Coffee Information System (SICA).

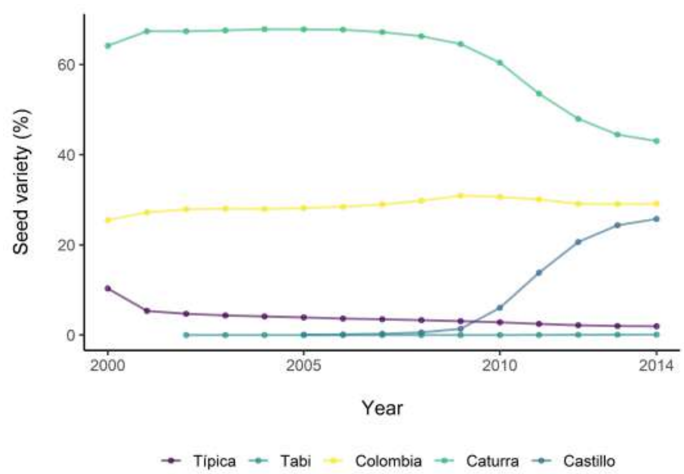

FIGURA A.5 Annual share of seed varieties used in coffee plots, 2000–2014. *Notes* – This graph shows the annual share of the seed varieties used in the Colombian coffee sector between 2000 and 2014. Shares are understood as the ratio between the number of plots that use a particular seed and the sum of all plots. *Source*: Authors' elaboration based on the Colombian Coffee Information System (SICA).

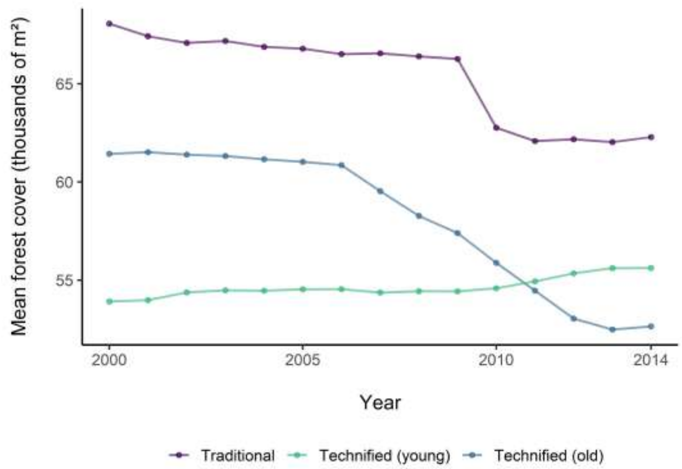

FIGURA A.6 Average tree cover in coffee plots by the production system, 2000–2014. *Notes* – This graph shows the average tree cover in coffee crops between 2000 and 2014. Tree cover is in thousands of m^2. *Source*: Authors' elaboration based on the Colombian Coffee Information System (SICA) and Hansen et al. (2013) data.

C | EMPIRICAL STRATEGY AND RESULTS

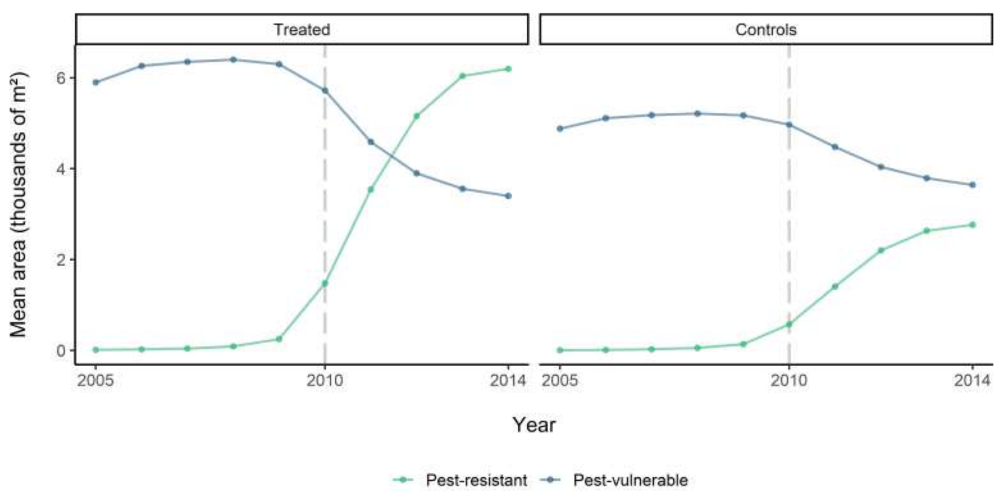

FIGURA A.7 Mean farm area by group and seed variety, 2005–2014. *Notes* – This graph shows the mean area that coffee farms allocate to each seed variety. Caturra is a pest-susceptible seed variety, while Castillo is pest-resistant and highly productive. We only include small farms (area $< 50{,}000 m^2$). *Source*: SICA.

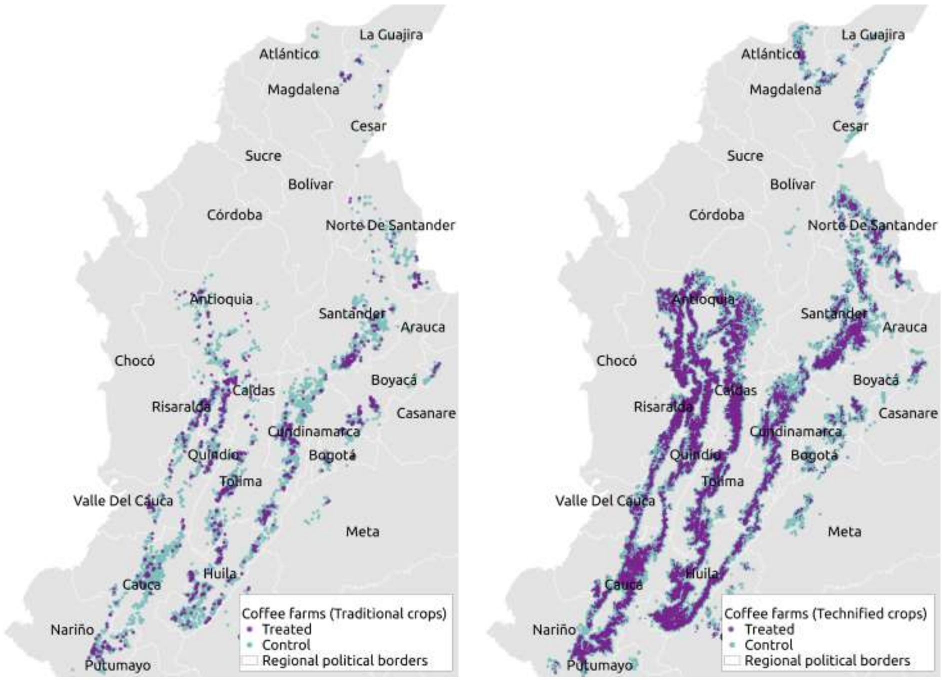

FIGURA A.8 Spatial distribution of treated and control coffee farms by group. *Notes* – This map shows the spatial distribution of the treated and control farms with Traditional/Technified crops. We only consider small farms (area < 50,000m^2). *Source*: Authors' elaboration based on the Colombian Coffee Information System (SICA) and Hansen et al. (2013) data.

C.1 | Staggered Difference-and-Differences

To implement the "Staggered DID" method of Callaway and Sant'Anna (2020) we do the following:

- We built four treatment groups based on the first year that a farm received a credit visit after the NFCG conditioning (2010). That is, there is a treatment group for 2010, 2011, 2012, and 2013 [17]. A farm is considered (and remains) treated after the first credit visit.
- Farms in the control group did not receive credit visits from 2007–2013. We also do not include those farms that have not yet been treated as controls. The four treatment groups are compared with the same control group.

D | COST-BENEFIT ANALYSIS: RESISTANT VS. NON-RESISTANT COFFEE CROPS

The cost-benefit analysis considers the production costs as well as the environmental costs of crop renewal. The values associated with the environmental costs were taken from the carbon tax in Colombia (payment for each ton of carbon emitted, DIAN (2022)) and the opportunity cost of not receiving payment for environmental services (PES) for the preservation of the tropical forest of the coffee farms (compensation per preserved hectare, DNP (2017)). The values assigned to productivity and production costs for each type of variable were collected from (Duque-Orrego et al., 2005).

- We calculate the income using the selling price of coffee in 2014 (NFCG, 2014b). We

[17] We only have information on credit counseling visits made by extensionists for the years 2007–2013.

use the Colombian Consumer Price Index to adjust the production costs reported by Duque-Orrego et al. (2005) from 2005 to 2014.

- Income per hectare at 2014 prices is calculated as the product between the price of coffee sales and the level of production per hectare reported by Duque-Orrego et al. (2005).
- The carbon emissions of crop renewal (CO_2) are calculated as the product between the number of deforested hectares in the farm between 2010–2014, the number of $C0_2$ ton emitted from the deforestation of a hectare of tropical forest, and the carbon emission tax set by the Colombian Government in 2014 prices.
- The opportunity cost of deforestation is calculated as the product between the number of deforested hectares in the farm between 2010–2014, and the payment per preserved hectare of tropical forest set by the Colombian Government in 2014 prices.
- The profit/benefit per hectare is calculated as the difference between income and costs per hectare in 2014 prices. The total cost includes the environmental cost and the production cost.

After the calculations per hectare, we aggregate the production, income, costs, and benefits of each type of crop at the farm level. Finally, we average the results of the treatment and control farms to estimate their financial results after crop renewal. Figures A.9, A.10, A.11, and A.13 show the results of this process.

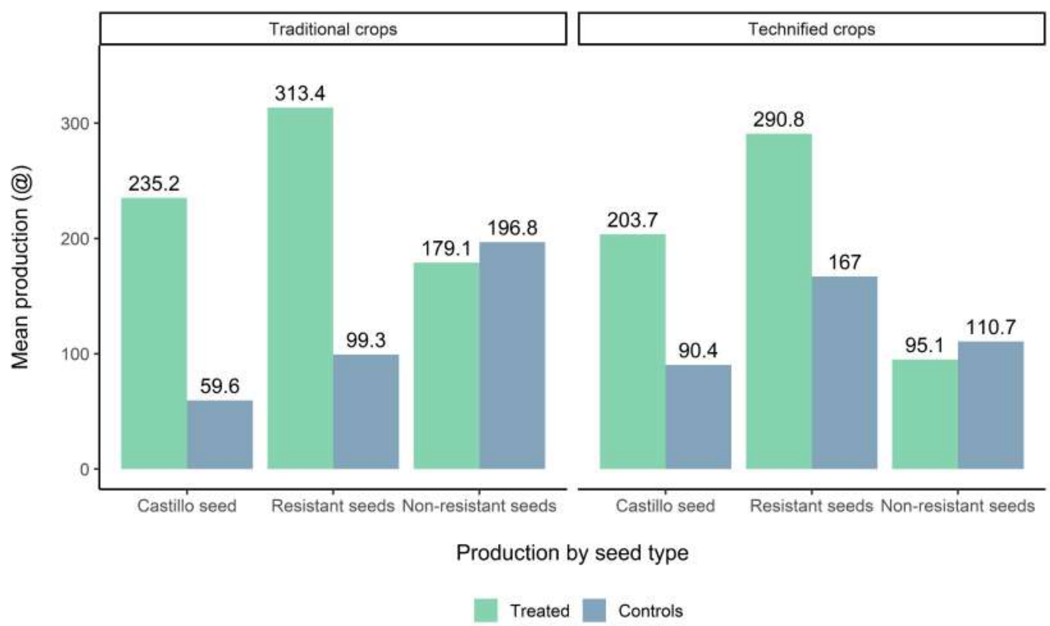

FIGURA A.9 Average total production in treatment and control farms by seed type and comparison group. *Source*: Authors' elaboration based on SICA and Duque-Orrego et al. (2005).

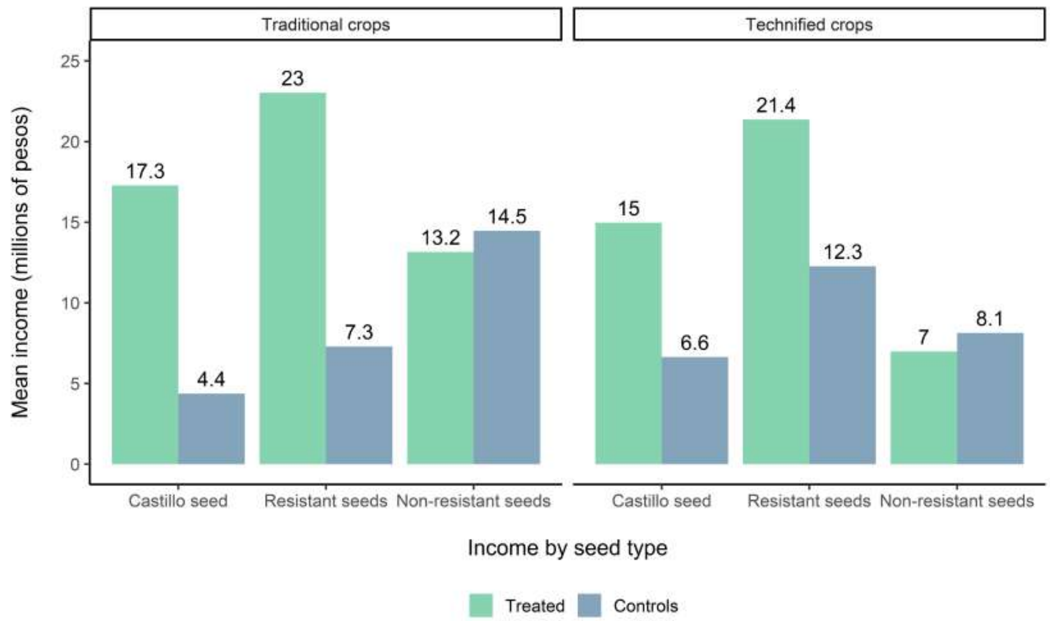

FIGURA A.10 Average total income in treated and control farms by seed type and comparison group. *Source*: Authors' elaboration based on SICA and Duque-Orrego et al. (2005).

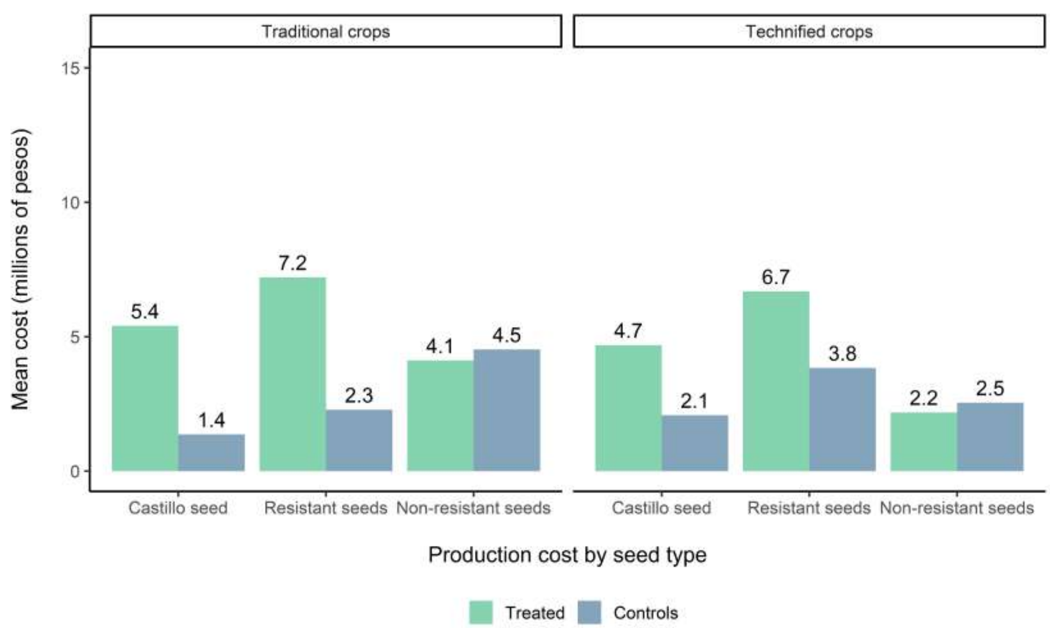

FIGURA A.11 Average total production cost in treated and control farms by seed type and comparison group. *Source*: Authors' elaboration based on SICA and Duque-Orrego et al. (2005).

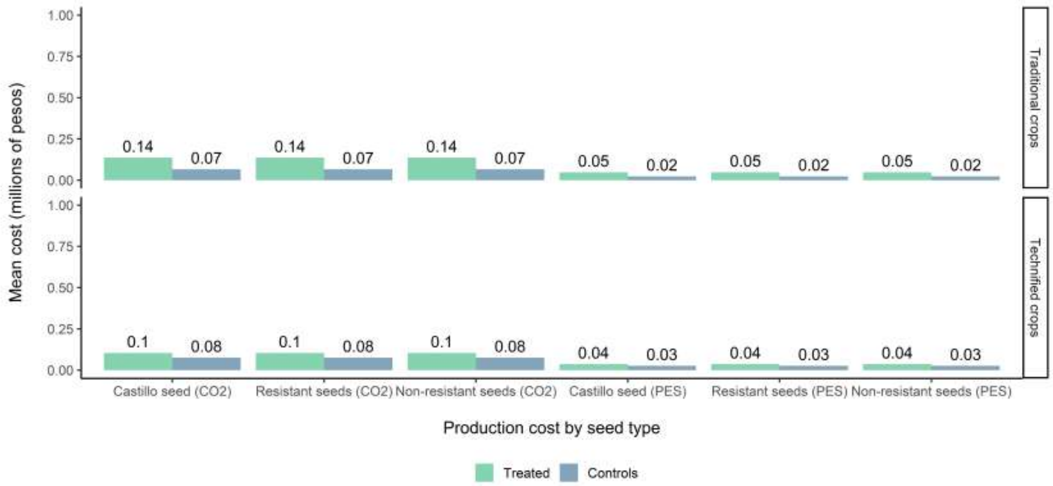

FIGURA A.12 Average total environmental cost in treated and control farms by seed type and comparison group. *Source*: Authors' elaboration based on SICA, Kanninen (2003); DNP (2017); Duque-Orrego et al. (2005).

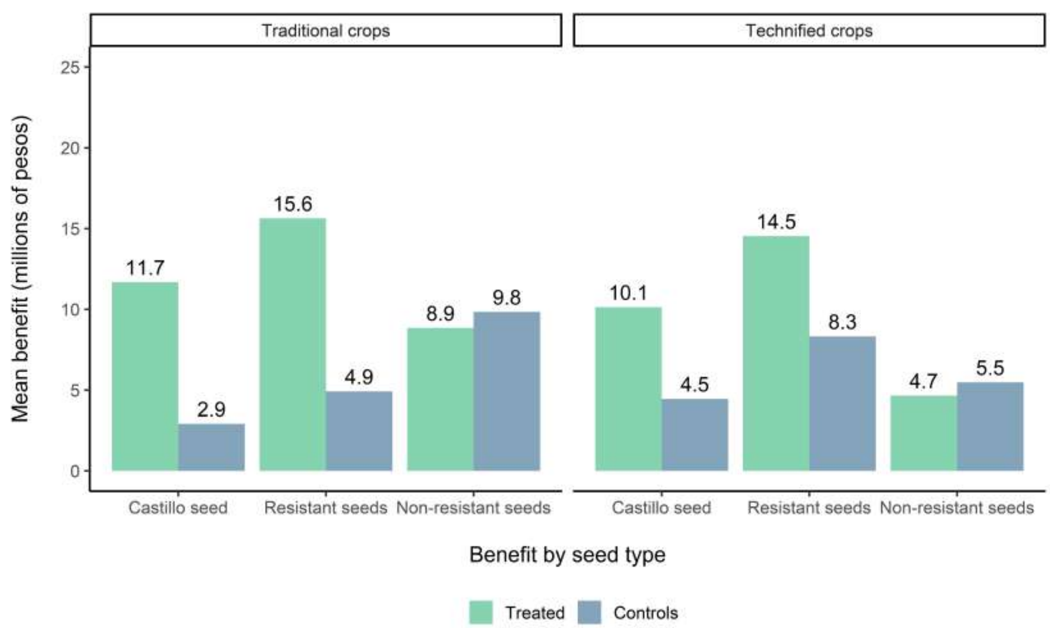

FIGURA A.13 Average total benefit/profits in treated and control farms by seed type and comparison group. *Source*: Authors' elaboration based on SICA and Duque-Orrego et al. (2005).