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RESEARCH ARTICLE

The Cost of Armed Conflict to Agriculture in Colombia

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Abstract: Armed conflict in rural areas of Colombia has displaced and killed many people. This violence increases the risk in the agricultural enterprise leading to reductions in investments and technology adoption that could significantly lower agricultural productivity. To explore the relationship between this violence and productivity of the licit agricultural sector, we estimate an aggregate agricultural production function at the department level for 1995–2017 that includes violence levels and incentives for illicit agriculture. We estimate that the Colombian armed conflict was costly to agriculture because it is associated with a decrease in licit agricultural productivity of around 29% from 1995 to 2017.

Keywords: Productivity; Licit and illicit agriculture; Crop yields; Conflict; Violence

1. Introduction

The violent war between insurgent groups and government forces in the rural regions in Colombia may have been costly to agriculture. The Colombian armed conflict has internally displaced more than 5 million people since 1996, killed nearly a quarter of a million since the late 50s, and resulted in kidnappings of around 27 thousand since 1970 [1–4]. These violence shocks alter rural labor and increase the risk and uncertainty in the agricultural enterprise which may lead to lower investments and technology adoption that reduce the sector's productivity①.

Although agriculture is crucial for the Colombian economy, annual growth rates of agricultural production value have fluctuated abruptly over the last two decades, with a low average rate since 1990 of around 1.6% (Figures 1 and 2). This paper explores the relationship between armed conflict and illicit agriculture in rural Colombia, and the productivity of its licit agri-

① The term "productivity" used in this study refers to any potential change in output from a given level of inputs. A productivity change may occur either due to a technology change or fluctuations in the technical efficiency with which the inputs are used[5].

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culture. For this, we estimate an aggregate production function that includes violence shocks and incentives to illicit agriculture with a unique panel dataset that we have developed for twenty-six Colombian departments over the 1995–2017 period. We used two variables to capture these shocks, the number of internally displaced persons (IDP)② and the number of war-related casualties from the armed conflict in rural areas (Figure 3). In addition, we use international retail cocaine price to capture incentives for illicit agriculture that go hand in hand with violence in Colombia.

One relevant conjecture in this study is that conflict imposes costs on productivity. Armed combat and terrorist attacks destroy capital that, in turn, reduce productive capacity of firms, farms, and households, especially in rural areas of Colombia. This mechanism reduces incentives to innovate. Aggression against the civilian population, abductions, killings, and maiming affects incentives to invest in human capital.

The armed conflict has led to massive forced internally displaced persons (IDP) from rural to urban areas of Colombia with an impact on both the availability and the productivity of inputs in agriculture. The increased risk and uncertainty introduced by this violence affects investments in physical and human capital as well as innovations in the sector.

Violent events triggered by the war between insurgent groups and government forces in the rural regions are the main reason for the exodus from rural to urban areas in Colombia.

It is also the case that the areas with more conflict and less rule of law are the areas where illicit agriculture, the production of coca, flourishes. Depending on international market conditions, incentives for illicit production withdraw resources that would have been used in licit agricultural production.

This study provides insights into the extent to which violence may be related to productivity in Colombia's licit agricultural sector over the 1995–2017 period.

The remainder of the paper organizes as follows. Section 2 is a brief summary of the literature, section 3 describes the methodology, section 4 has the empirics and the data, section 5 and 6 presents and discusses the main results, while section 7 concludes.

② The Inter-American Commission on Human Rights[6] describes a displaced person as "... anyone who has been forced to migrate within the national boundaries, leaving aside his/her residence or his/her habitual economic activities because either his/her life, his/her physical integrity or his/her freedom have been either violated or threatened by situations such as armed conflict, generalized violence, violation of human rights, and any other situation that may alter public order...". IDPs are not the same as refugees because they do not cross-national frontiers. The protection of IDPs is primarily the responsibility of the national state concerned (Office of the United Nations High Commissioner for Refugees UNHCR)[7].

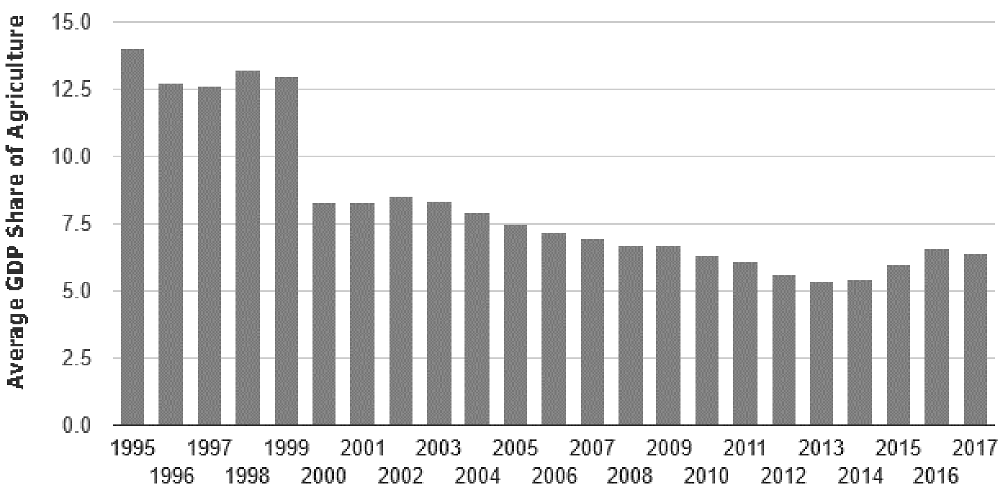

Figure 1. Colombian GDP Share of Agriculture in 1995–2017.

Source: Own calculations based on data from the World Bank[5].

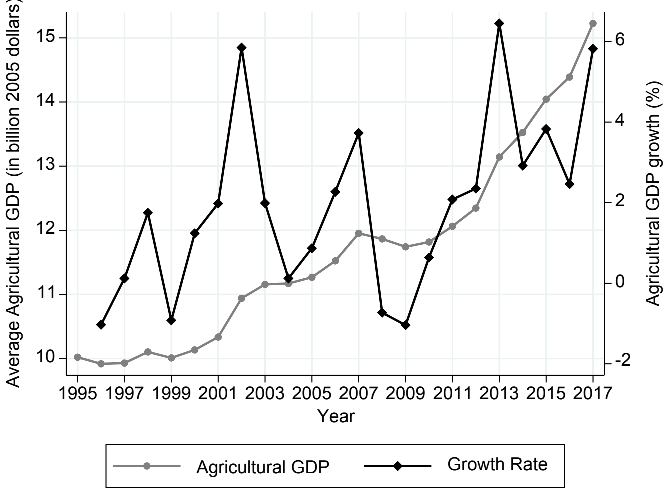

Figure 2. Colombian Agricultural GDP and its Growth Rates, 26 Departments.

Source: Own calculations based on data from DANE[9].

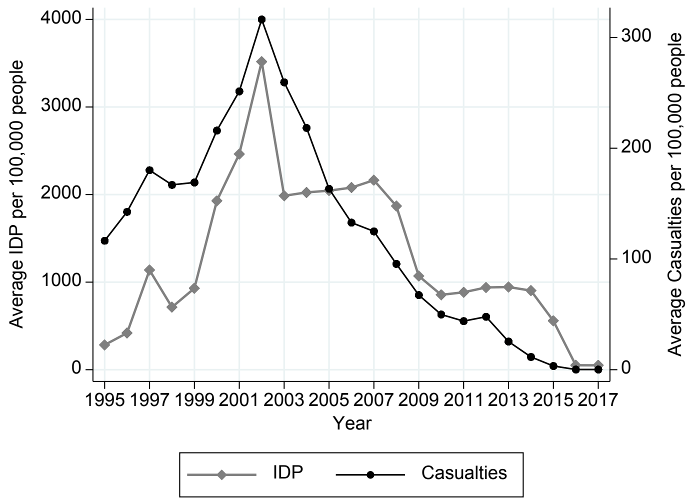

Figure 3. Evolution of the IDP and Conflict-Related Casualties in Colombia, 26 Departments.

Source: Own calculations based on data from URS[10] and UCDP[11].

2. Relevant Literature

The literature on the economic impact of civil wars, armed conflicts and violence is vast. We restrict our literature review to some of the most important studies that directly relate to the Colombian case ③. A series of studies by Blattman and Miguel [12], Collier [16], Ibáñez and Moya [17], Justino [18], Arias *et al.*[19], Nino *et al.* [20] and Bernal *et al.* [21] have shown that armed combat and terrorist attacks in rural areas depreciate capital and assets, lowering incentives to innovate.

Studies by Camacho [22]; Arias *et al.* [19], Bernal *et al.* [21] have shown that aggression against the civilian population (abductions, killings, and maiming) has reduced incentives to invest in human capital. While studies by Gaviria and Vélez [23], Riascos and Vargas [24], Skaperdas *et al.* [25], Pshisva and Suarez [26], Thomson [27], Dube and Vargas [28], Maher [29,30], and Nino *et al.* [20] have considered whether this violence has either reduced labor supply or increased capital costs.

Comparison with relevant results in the literature follows in the discussion of results section.

3. Methodology

We hypothesize that conflict, not only has affected licit production, but it has affected innovations and ef-

③ Blattman and Miguel [12], Thies and Baum [13], Le, T.H., Bui, M.T. and Uddin [14], and De Groot, O.J., Bozzoli, C., Alamir, A. and Brück, T. [15] have broad literature reviews of this topic.

ficiency in use of resources, that is productivity of the farm sector. It is this permanent impact of violence that we try to capture. In order to do this, we use a model that allows elements related to this violence to change the isoquant map or shift the production function.

The theoretical model used is based on Mundlak [31], Fulginiti and Perrin [32] and Mundlak *et al.* [33]. They establish that output is produced with inputs conditional on "state variables" [33] or "technology changing" variables [32]:

$$Y^* = F(\boldsymbol{X}; \boldsymbol{S}) \tag{1}$$

where Y^* is maximum output, $\boldsymbol{X}$ is a vector of inputs and $\boldsymbol{S}$ is a vector of "state" or "technology changing" variables. Changes in the variables $\boldsymbol{S}$ causes simultaneous variations in $\boldsymbol{X}$ and Y. These $\boldsymbol{S}$ variables not only change output and inputs but generate a different set of implemented techniques [31] that imply shifts in the production function or changes in productivity. Productivity changes here refer to the changes in the maximum output that can be obtained from a given set of inputs. State or technology changing variables could be those representing the environmental and institutional circumstances including those that affect incentives to innovate. It is thus assumed that the state or technology changing variables used in this paper to capture violence as well as incentives for illegal production are among the technology-changing variables that can affect the choice of technique and thus productivity. The model introduces the concept of productivity elasticity [32] representing the shift in the production function due to changes in state/technology changing variables.

This model has been used in the literature to capture the effects of R&D, policies, past prices and changes in quality of resources on the adoption of new techniques. In particular, the model has been used to capture price-induced technical change, in which past output prices are used as a technology changing variables because they affect technology adoption and the technology in a subsequent period [31,32,34–40].

In this paper we assume the production function

$$Y = f(\boldsymbol{X}; \boldsymbol{\beta}) \tag{2}$$

to be a real-valued function characterizing the maximum amount of output $\boldsymbol{Y}$ produced from a given set of conventional inputs $\boldsymbol{X} = (X_1, \ldots, X_n)$, where $\boldsymbol{\beta}$ designates the vector of parameters. The production function is assumed to be continuous and twice differentiable implying that $f_{X_i} > 0$, and $f_{X_iX_i} < 0 \ \forall \ X_i$, $i = 1, \ldots, n$.

Let v_k, $k = 1,\ldots,m$ represent technology changing variables that determine the production function parameters according to

$$\beta_i = G_i(v_1, \ldots, v_m) \tag{3}$$

The parameters $\boldsymbol{\beta}$ are assumed to be variable and determined at any place and time by previous choices as well as the current technological, natural, and institutional environment. It is possible then to obtain elasticities of productivity with respect to the technology changing variables v_k's defined as

$$\varphi_k = \frac{dlny}{dlnv_k} \tag{4}$$

which indicates the percentage by which a productivity index (percentage output change when inputs are given) would change due to a 1% change in v_k.

We use this theoretical model and include institutional/environmental variables that capture violence (internally displaced people and casualties), incentives for illegal agriculture (price of cocaine), incentives for legal agriculture (past prices of legal crops), as well as precipitation and temperature as state/technology changing variables. We hypothesize that these variables have affected the choice of technique and adoption of new technologies and therefore productivity of the agricultural sector in Colombia during the 1995–2017 period.

4. Empirical Approach and Data

The theoretical model above is implemented following Fulginiti and Perrin [32] and Mundlak *et al.* [33]. We specify and estimate an aggregate department-level production function for Colombian agriculture that includes state/technology changing variables measuring the extent of violence, namely the number of internally displaced persons and the number of conflict-related casualties as well as the past price of illicit and licit crops. We do this by specifying a Cobb-Douglas variable coefficients production function in which the coefficients are a function of the technology changing variables. As a result, in addition to estimating production elasticities that are affected by these technology changing variables, we also estimate productivity elasticities [32] that indicate the shift of the production function due to technology changing variables.

At the level of aggregation used in this study, we assume constant returns-to-scale (CRS), dividing the output and the inputs by agricultural land, and specify yield (y, output per unit of land) as a function of inputs (x_i per unit of land) and technology changing variables, v_k :

$$y(\boldsymbol{x};\boldsymbol{\beta}) = A(\boldsymbol{v})\prod_{i=1}^{n} x_i^{\beta_i(\boldsymbol{v})} \tag{5}$$

where

$$lnA = \alpha_0 + \sum_{k=1}^{m}\gamma_k lnv_k + \delta_0\tau + u_0, \qquad k = 1, \ldots m \tag{6a}$$

$$\beta_i = \alpha_{i0} + \sum_{k=1}^{m}\alpha_{ik} lnv_k + \delta_i\tau + u_i, \qquad i = 1, \ldots n \tag{6b}$$

Here the v_k's are the technology-changing variables in vector $\boldsymbol{v} = (v_1, \ldots, v_m)$; τ denotes time (years) as a proxy for exogenous technical change; the α's, γ's and δ's represent fixed parameters to be estimated; u_0 represents a random variable distributed independently of the x's, τ, and the v's; u_i's are random variables independent of the v_k's and τ, with mean zero and finite positive semi-definite covariance matrix. The elements of β are variable elasticities of production for each of the variable inputs x. These production elasticities are thus affected by the technology-changing variables. The technology changing variables v determine the production elasticities and are taken by the decision maker as parameters for the current production period.

We obtain the following econometric model by expressing equation (5) in natural logs as

$$lny = \alpha_0 + \sum_{i=1}^{n}\alpha_{i0} lnx_i + \sum_{i=1}^{n}\sum_{k=1}^{m}\alpha_{ik}(lnv_k \cdot lnx_i) + \delta_0\tau + \sum_{i=1}^{n}\delta_i(\tau \cdot lnx_i) + \sum_{k=1}^{m}\gamma_k lnv_k + \sum_{i=1}^{n}u_i lnx_i + u_0 \tag{7}$$

With this specification, it is feasible to estimate technological impacts of violence shocks as measures of armed conflict and of incentives (prices) for both licit and illicit agricultural production.

We find it convenient to describe the elasticity of productivity of technology-changing variables v_k indicating the percentage by which output would change in response to a change in technology-changing variables v_k, for a given level of other inputs. From equation (4), the equation for the productivity elasticity of v_k is

$$\varphi_k = \frac{dlny}{dlnv_k} = \sum_{i=1}^{n}\alpha_{ik} lnx_i + \gamma_k \tag{8}$$

The impact of violence and other technology changing variables on current productivity is given by these productivity elasticities.

The production elasticities as specified in equation (6b) depend on the variables that condition choice, so they differ by observation. Casualties and internally displaced people, price of illicit and licit crops, and weather combine to determine the productivity of each input.

We also include an exogenous rate of technical change obtained as

$$\frac{dlny}{d\tau} = \delta_0 + \sum_i \delta_i lnx_i \tag{9}$$

Data

We use data from several sources for each of the twenty-six departments for the 1995–2017 period (598 observations). The Colombian regions considered are: Amazon comprising the departments of Caquetá and Putumayo; Andean consisting of Antioquia, Boyacá, Caldas, Cundinamarca, Huila, Norte de Santander, Quindío, Risaralda, Santander, and Tolima; Caribbean consisting of Atlántico, Bolívar, Cesar, Cordoba, La Guajira, Magdalena, and Sucre; Orinoco comprising Arauca, Casanare, and Meta; and Pacific which includes the departments of Cauca, Chocó, Nariño, and Valle del Cauca ④.

Output is licit agricultural GDP (in 2005 dollars). Inputs are land, labor, and livestock (as a proxy for capital as in Hayami and Ruttan [41]). Technology-changing variables are internally displaced persons, casualties, price of cocaine, temperature, precipitation, price of licit crops, and exogenous technical change. Table 1 presents summary statistics of the variables used in the analysis.

Agricultural GDP per department is from the Agriculture, Livestock, Forestry, and Fishing Added Value Series from the National Administrative Department of Statistics (DANE) [9].

Land in production is hectares of arable and permanent cropland and permanent pastures obtained from two different sources. For 1995–2009 the information is from the Survey of Agricultural Evaluations (EVA) of

④ We do not include in the analysis the traditionally non-agricultural departments of Amazonas, Guainía, Guaviare, Vichada, and Vaupés. The island of San Andrés Island and Providencia is not included due to the lack of data.

the Colombian Ministry of Agriculture and Rural Development (MARD) - EVA-MARD [42] and for 2010-2016 it is from DANE [43].

Labor is from the Population and Demography Series from DANE [43]. DANE provides departmental projections of the urban/rural population by age groups for the 1985–2020 period. For labor we use the number of people aged ten years and over in rural areas.

Livestock information is obtained from EVA-MARD [44] for 1995–2009 and from DANE [43] for 2010–2016. Cows, horses, pigs, sheep, and lambs, among others, are combined using Hayami and Ruttan's [41] equivalent units procedure considering the following weights: 1.00 for non-dairy cattle; 1.25 for dairy cows, buffalo, and horses; 1.00 for asses, mules, and other camelids; 0.25 for pigs; 0.13 for goats and sheep; and 0.0125 for poultry species.

The displacement data used to construct the Internally Displaced Persons (IDP) variable are from the Colombian government's Unique Registration System (URS) [10].⑤ We use the number of armed conflict victims classified as displaced due to violence. Internally Displaced Persons (IDP) is the ratio of the annual number of displaced persons per 100 thousand inhabitants in a department. During 1995–2017 there were a total of 7,053,250 internally displaced persons.

The casualties variable was constructed using a unique event-based dataset from the Uppsala Conflict Data Program (UCDP) of the Department of Peace and Conflict Research at Uppsala University in Sweden [11]. We use the annual armed conflict-related deaths of civilians per 100 thousand inhabitants at the department level as a proxy for direct political violence. Based on this data the Colombian armed conflict resulted in at least 78,560 deaths during 1995–2017.

We use weighted past cocaine prices as a technology changing variable. The international retail cocaine price (street prices) in 2018 U.S. dollars per gram is from the United Nations Office on Drug and Crime (UNODC)[45,46].⑥ Nineteen of the twenty-six departments in our sample grew coca during 1995–2017. UNODC[47] ⑦ has area planted from 2001 on. Area planted for previous years was obtained from Angrist and Kugler [48], Ramírez [49], and Uribe [50].

Temperature and rainfall are from the Agrometeorological Indicators produced on behalf of the Copernicus Climate Change Service from Boogaard *et al.* [51].⑧ We use the daily average air temperature two meters above the surface; and the total volume of liquid water precipitated over the period 00h–24h per unit of area (mm^2).⑨

Past prices of licit agricultural output (to identify price-induced technological change) are measured by multilateral Törnqvist-Theil indexes of output prices received in each department. The data on crop production are from the EVA-MARD [55] and include sesame, cotton, rice, barley, beans, corn, potatoes, soy, sorghum, wheat, banana, coffee, cocoa, sugarcane, yam, palm oil, tobacco, and cassava. Prices for all crops (except yam and tobacco) are from the FAO [56], and for yam and tobacco, are from EVA-MARD [57]. All price series are in 2005 U.S. dollars at the official exchange rate. The inclusion of past output prices might also mitigate concerns about reverse causality regarding the relationship between agricultural income shocks and violence. In the economics literature this impact is not clear. Some authors find that prices of agricultural commodities have been associated negatively with armed conflict: high output prices lead to a decline in violence from armed conflicts [28,58]. Others have found just the opposite: positive income shocks lead to more violent conflicts and raise the IDP in areas with weak property rights and illegal institutions [4,59,60].

⑤ We used statistical information from Information System on Human Rights and Displacement – URS on the number of forced IDPs that exited the municipality/department from year to year. IDP here refers to migrants forced to abandon their physical residence and employment (economic) activity because of the Colombian armed conflict, generalized violence, massive human rights violations, or other circumstances that threaten or drastically alter public order. In describing internal displacement, the URS distinguishes between municipalities and departments where the displacements occurred and the municipalities and departments where displaced persons relocated.

⑥ This is a weighted average by population (in European and USA cities) in constant 2018 dollars.

⑦ The UNODC[47] uses satellite photography to measure the number of hectares of coca in a given area (usually a municipality) at the end of each year. With this information, the UNODC and the US State Department make annual estimations of the size of the illicit coca and cocaine industries. The present study uses estimations available at https://www.unodc.org/unodc/en/crop-monitoring/?tag=Colombia.

⑧ The dataset is based on the hourly ECMWF-ERA5 data geo-localized and available at a spatial (horizontal) resolution of 0.1° × 0.1° (about $10km^2$) which is here averaged to the department level.

⑨ According to the Global Climate Risk Index[52] (Harmeling, 2011), Colombia ranked third (after Pakistan and Guatemala) in 2010 among the most affected countries by weather-related events such as droughts, floods, and heatwaves. The number of disaster events registered in Colombia in the first decade of the 2000s increased more than 60% relative to the 1970–99 period[53,54].

Table 1. Descriptive Statistics of the Variables Used in the Production Function (equation 4) for Colombian Agriculture, 26 Departments, 1995 to 2017.

	Short Description	Mean	SD	Min	Max
Production Variables:					
Y	Ag. GDP (million 2005 USD$)	658.9	590.6	29.73	3,064.4
X_0	Land (thousand ha)	1,393.4	1,080	50.24	5,221.2
X_1	Labor (thousand persons)	311.4	236.3	11.97	1,116.2
X_2	Livestock (cow equivalent, thousand animals)	909.5	790	30.93	9,249.5
Technology-Changing Variables:					
v_1	IDP per 100,000 inhabitants	1,296	1,967	1	17,798
v_2	Casualties per 100,000 inhabitants	19	215	0	5,065
v_3	Wgt. cocaine price per gram ($)	2.61	5.33	0	35.31
v_4	Mean temperature (Celsius)	21.04	3.89	13.67	27.55
v_5	Mean precipitation (mm)	9.56	5.67	1.83	28.87
v_6	Törnqvist output price index	1.26	0.32	0.43	2.44
τ	Time trend	12	6.64	1	23

5. Results and Discussion

The following production function is estimated:

$$lny_{dt} = \alpha_0 + \sum_{i=1}^{2} \alpha_{i0} lnx_{idt} + \sum_{i=1}^{2}\sum_{k=1}^{6} \alpha_{ik}(lnv_{kdt} \cdot lnx_{idt}) + \delta_0 \tau + \sum_{i=1}^{2} \delta_i(\tau \cdot lnx_{idt}) + \sum_{k=1}^{6} \gamma_k lnv_{kdt} + \sum_{i=1}^{2} u_{idt} lnx_{idt} + u_{0dt} \quad (10)$$

where $y = \frac{Y}{X_0}$ (output per hectare), the vector of labor and livestock per hectare is $x = (x_1, x_2)$, where $x_i = \frac{X_i}{X_0}$, $i = 1, 2$, $v = (v_1..., v_6)$ are technology-changing variables other than unexplained exogenous technical change, τ is a time trend, and $u's$ are error terms. We include fixed effects by department and interactions with continuous time. The subscripts d (= 1..., 26) represent departments and year t (= 1995..., 2017).

Table 2 shows the estimated coefficients of the parameters in equation (10). This table contains twenty-two coefficients (excluding the fixed effects by department and their interactions with time), seven of which are significant at the 1% level, three at the 5% level, and four at the 10% level.[10]

We use the estimates from equation (10) to obtain the production and productivity elasticities calculated for each observation. The weighted average elasticities are displayed in Table 3. Production elasticities indicate the percentage change in yields due to a one percent change in traditional inputs (land, labor, livestock). The productivity elasticities indicate the percentage change in yields, given traditional inputs, due to a one percent change in the technology-changing variables (a shift of the production function). The productivity elasticities in Table 3 show significant impacts for most of the technology-changing variables.

[10] Table A1 in the Appendix shows alternative specifications for equation (9) that we estimated to check for robustness of the coefficients used in the analysis. Given the similarity in coefficients estimated as well as their significance among alternative specifications, we chose the model in column (1) for the analysis in this study.

Table 2. Parameter Estimates of the Production Function for Colombian Agriculture (equation (9), 26 Departments, 1995–2017 (Dependent Variable is Logarithm of Yields, $\ln(\frac{Y}{X_0})$).

	Input Parameters		Intercept
	Labor	Livestock	(α_0, γ_k, δ_0)
Linear terms (α_{i0})	–0.5642	–1.7590	–4.1469
	[0.5347]	[0.7528]**	[0.7062]***
IDP (α_{i1})	0.0112	0.0497	
	[0.0092]	[0.0291]*	

Table 2 continued

	Input Parameters		Intercept
Casualties (α_{i2})	−0.0104	0.0570	
	[0.0144]	[0.0343]*	
Past Cocaine Price (α_{i3})	−0.0378	−0.3762	−0.8501
	[0.0490]	[0.1967]*	[0.1568]***
Temperature (α_{i4})	0.1770	0.4609	−1.0925
	[0.1616]	[0.2527]*	[0.2156]***
Rainfall (α_{i5})	0.2042	0.2087	0.6383
	[0.0463]***	[0.0829]**	[0.0737]***
Past Output Price (α_{i6})	−0.2035	−0.1540	0.0403
	[0.0781]***	[0.1622]	[0.1456]
Trend (τ) (δ_i)	0.0064	0.0100	0.0243
	[0.0028]**	[0.0072]	[0.0055]***

Notes: Regional fixed effects and fixed effects x time not reported.
Robust standard errors in brackets. The estimates are based on 598 observations during the years 1995 and 2017. Overall R^2=0.85.
*** Significant at the 1 percent level. ** Significant at the 5 percent level. * Significant at the 10 percent level.

Table 3. Average Productivity (equation 7) and Production Elasticities (equation 5b) for Colombian Agriculture, 26 Departments, 1995–2017.

	Regression Model	
	Variable Elasticity[a]	Fixed Elasticity[b]
Productivity elasticity for technology-changing variable:		
IDP (φ_1)	−0.0436	
	[0.0195]*	
Casualties (φ_2)	−0.0139	
	[0.0293]	
Past Cocaine Price (φ_3)	−0.2331	
	[0.0445]**	
Temperature (φ_4)	−1.5136	
	[0.1933]***	
Rainfall (φ_5)	0.2888	
	[0.0639]*	
Past Output Price (φ_6)	0.4161	
	[0.1272]**	
Production elasticity for input variable and trend:		
Labor	0.4672	0.7333
	[0.0515]***	[0.0357]***
Livestock	0.3323	0.1194
	[0.1039]*	[0.0271]***
Trend (Exogenous Technical Change)	0.0119	0.0082
	[0.0047]	[0.0012]***

Notes: These are weighted average elasticities. Weights used are number of conflict-related internally displaced individuals and deaths for IDP and Casualties respectively, area of coca planted for departments with 3% or more area for Past Cocaine Price, crop production for Past Output Price, GDP in agriculture for Temperature, Rainfall, Labor, Livestock and Trend. Standard errors in brackets are computed with the delta method (Papke and Wooldridge [61]).
[a] Equation (9). [b] Equation (9) restricted by $\alpha_{ik} = \gamma_k = 0$ for all *i* and *k*.

The IDP productivity elasticity indicates that a 1% increase in IDP per 100,000 inhabitants would produce a 0.0436% downward shift of the production function. A 1% increase in war-related casualties would shift the production function down by 0.014% ⑪, while a 1% increase in past cocaine price would shift it down by 0.23%.

The technology-changing variables related to weather indicate that a 1% increase in the mean annual temperature would lower licit Colombian agriculture yield by approximately 1.51%. A 1% increase in the yearly mean precipitation would produce an increase in Colombian agricultural yield of about 0.29%. The productivity elasticity for past output price indicates that a 1% increase in the previous three-years average output price would cause a 0.41% upward shift of the Colombian agricultural production function. This price impact implies that a boom in agricultural commodity prices like that in the 2000–2007 period or the first five years of the 2010s created incentives to invest in Colombia's agriculture. These incentives would promote the innovation and adoption of new production techniques, and therefore the price regime during the boom would positively affect the technology relevant to subsequent periods.

The lower panel in column two of Table 3 displays the average production elasticities for traditional inputs. The average production elasticity for labor is 0.47 and for livestock is 0.33, both statistically significant (implying an average land elasticity of 0.20 (1.00 – 0.47 – 0.33)). The trend coefficient indicates that the average rate of exogenous technical change in the Colombian agricultural sector shifts the production function about 1% per year.

The last column of Table 3 shows the estimates of a conventional Cobb-Douglas production function. From this model, the elasticity of production for labor is 0.73 and for livestock is about 0.12 (implying an average land elasticity of 0.15). The estimated annual exogenous technical change from this model is about 0.8%. However, an F-test rejects this nested model in favor of the full model reported above.

Some multicountry studies have estimated production elasticities that can be compared to those estimated here. These use different methods and levels of aggregation. Evenson and Fuglie [62] and Trindade and Fulginiti [63] estimate labor production elasticities for a set of countries to range from 0.14 to 0.46 compared to our 0.47. In studies for Colombian agriculture estimates of labor production elasticity range from –1.29 to 2.01. Jiménez *et al.* [64] estimates range from 0.07 to 0.44; Ramoni-Perazzi and Orlandoni-Merli [65] estimates average 0.85 (–1.29 in Caquetá to 2.01 in Sucre). González and López [66] estimate off-farm and farm family labor production elasticities of 0.30 and 0.31, respectively.

The average livestock production elasticity estimated here, 0.33, is within the range established by previous studies. The average production elasticity for South American countries by Trindade and Fulginiti [63] is 0.55; in Bharati and Fulginiti [67], it is 0.24; and in Ev enson and Fuglie [62], it is 0.14–0.25. The study for Colombian agriculture by Jiménez *et al.* [64] estimate a livestock production elasticity of 0.93.

Past output prices have a positive impact on licit agricultural productivity, while past cocaine prices have a negative one. These results are as expected, because increases in prices of licit agricultural products would stimulate innovations and investments to increase the productivity of licit agriculture while increases in price of cocaine would stimulate innovations and investments to increase the productivity of illicit agriculture that competes with licit agriculture for resources [28,48,68,69]. The productivity elasticity for past output prices is about 0.41, as compared to Fulginiti and Perrin [32] who report an average past-price productivity elasticity of 0.13 for a group of 18 countries in the period 1961-1984, but only 0.028 for Colombia. Mundlak *et al.* [33] compute a past-price productivity elasticity of 0.2 for 30 developed and developing countries in the years 1972–2000. The productivity elasticity estimated here is slightly more than double that of Mundlak *et al.* [33] and is significantly larger than that of Fulginiti and Perrin [32]. However, those studies conducted cross-country analysis and such aggregated data generally produces lower elasticity estimates, as does controlling for unit-level fixed effects in panel data analysis [70].

Regarding the negative productivity elasticity of cocaine price, there is both intuitive and quantitative evidence that illicit activity such as coca cultivation occurs in regions where the rule of law is weak and that it in-

⑪ The magnitude of the estimated productivity elasticities for the variables representing violence shocks (i.e., IDP and casualties) are relatively small because the regressions control for crucial factors that could affect both productivity and violence. Some of these factors include the weather and income shocks that may explain changes in violence through mechanisms related to the changes in the economic incentives to invest in the agricultural sector. Once the regressions include some of these factors, the estimations mitigate endogeneity concerns. Therefore, the estimated productivity effects may be attributed mainly to variations in the violence and not those other factors affecting the Colombian agricultural sector. Moreover, the productivity effects of violence shocks estimated here represent permanent changes in agricultural productivity or shifts of the production function of Colombia's agriculture.

creases the duration of civil conflicts [48,69,71,72]. Angrist and Kugler [48] provide empirical evidence on this issue from a quasi-experimental research design that studies the impact of demand shocks for illicit products on rural economic conditions and civil conflict. Their study examines the consequences of an exogenous upsurge in coca prices and cultivation in Colombia. The authors found that the rural areas that saw accelerated coca production became considerably more violent. This link is evidence that the financial opportunities that coca provides and the rent-seeking by combatants drive the economic gains from coca to the detriment of main licit productive activities in rural areas.

The productivity elasticities for the annual mean temperature are negative everywhere, which implies an adverse effect on agricultural productivity in the 26 departments. The elasticities of productivity concerning annual rainfall show positive effects across the departments. These results are consistent with those in Lachaud *et al.* [73] who assess the agricultural productivity in Latin America in the presence of weather shocks. First, they point out that a gap in the agricultural productivity literature is the omission of climatic variables as regressors in the models used to estimate Total Factor Productivity (TFP). Second, the authors developed climate-adjusted TFP measures for Latin America and assess the impact of climatic variability on TFP using a stochastic production frontier. They find that adverse weather shocks harm productivity with an average reduction in output across the region ranging between 0.02%–22.7% over the period 2000–2012 relative to 1961–1999. The present study also accounts for climatic effects in analyzing Colombian agriculture. Our results show that an increase in temperature or a decrease in precipitation would reduce the productivity of Colombian agriculture.

Table 4 shows how the estimates of productivity and production *elasticities* have changed over the period 1995–2017. None of the productivity elasticities of the technology-changing variables have changed appreciably. However, the production elasticity for labor increased from about 0.4 to about 0.5, while livestock production elasticity rose from around 0.2 to nearly 0.5. The annual average rate of exogenous technical change varies slightly between 0.8% and 1.2%, virtually identical to the range of estimates of 0.8–1.3% by Jiménez *et al.* [64] for 1975–2013 in Colombia ⑫.

⑫ We computed elasticities for each observation in the sample and in addition to the yearly averages across departments we also are able to compute averages per department (not presented in the text). We note that agricultural productivity of all 26 departments has been negatively affected by the internal displacement of people due to violence from the armed rural conflict. The departments with the highest IDP productivity elasticities are La Guajira, Meta, Casanare, Arauca, Cauca, Norte de Santander, Huila, Putumayo, Caquetá, Tolima, Santander, Bolívar, Nariño, and Valle del Cauca. Consistent with this, *Defensoría del Pueblo* [74] pointed out that 40% of the Colombian IDPs come from the departments of Nariño, Cauca, Chocó, and Valle del Cauca. This is also consistent with the fact that at most 70% (18 of the 26 departments) of the productivity elasticities for casualties indicate a downward shift of the production function, the most sensitive being La Guajira, Cauca, Nariño, Putumayo, Huila, Norte de Santander, Risaralda, Valle del Cauca, Tolima, Meta, Quindío, Caldas, Bolívar, Santander, Chocó, and Antioquia. These findings are also consistent with reports (see, e.g., Gallego [75]) showing that the departments with more than 46% armed conflict victims in Colombia are Cauca, Antioquia, Nariño, Chocó, Bolívar, and Caldas. These are also departments where the highest number of murders of social leaders and former guerrillas have occurred (Gallego [75]).

Table 4. Average Annual Productivity and Production Elasticities and Exogenous Technical Change for Colombian Agriculture for 26 Departments, 1995–2017 (Simple Average).

	Productivity elasticity for						**Production elasticity for**		**Trend**
Year	**IDP (φ_1)**	**Casualties (φ_2)**	**Past Cocaine Price (φ_3)**	**Temperature (φ_4)**	**Rainfall (φ_5)**	**Past Output Price (φ_6)**	**Labor ($\ln x_1$)**	**Livestock ($\ln x_1$)**	**(τ)**
1995	–0.035	–0.006	–0.655	–1.525	0.259	0.399			0.011
	[0.016]	[0.022]	[0.125]***	[0.211]***	[0.069]*	[0.122]**			[0.005]
1996	–0.040	–0.011	–0.615	–1.577	0.233	0.419			0.010
	[0.019]	[0.025]	[0.140]*	[0.234]***	[0.076]*	[0.136]**			[0.006]
1997	–0.054	–0.027	–0.514	–1.696	0.184	0.453	0.416	0.200	0.008
	[0.024]	[0.029]	[0.157]	[0.265]***	[0.084]	[0.154]**	[0.065]***	[0.127]	[0.006]
1998	–0.043	–0.015	–0.594	–1.596	0.230	0.418	0.471	0.278	0.010
	[0.019]	[0.024]	[0.132]**	[0.232]***	[0.074]*	[0.134]*	[0.059]***	[0.120]	[0.005]
1999	–0.034	–0.006	–0.660	–1.507	0.277	0.381	0.523	0.340	0.012
	[0.019]*	[0.025]	[0.144]***	[0.240]**	[0.078]*	[0.142]*	[0.059]***	[0.112]*	[0.006]

Table 4 continued

	Productivity elasticity for						Production elasticity for		Trend
Year	**IDP (φ_1)**	**Casualties (φ_2)**	**Past Cocaine Price (φ_3)**	**Temperature (φ_4)**	**Rainfall (φ_5)**	**Past Output Price (φ_6)**	**Labor ($\ln x_1$)**	**Livestock ($\ln x_1$)**	**(τ)**
2000	–0.043	–0.014	–0.593	–1.607	0.217	0.432	0.521	0.344	0.009
	[0.018]*	[0.023]	[0.119]***	[0.221]***	[0.070]*	[0.124]**	[0.057]***	[0.109]	[0.005]
2001	–0.039	–0.009	–0.627	–1.567	0.232	0.421	0.479	0.323	0.010
	[0.021]	[0.027]	[0.148]**	[0.248]**	[0.080]*	[0.145]*	[0.057]***	[0.105]	[0.006]
2002	–0.040	–0.010	–0.620	–1.576	0.229	0.424	0.488	0.377	0.010
	[0.018]	[0.024]	[0.140]**	[0.231]***	[0.076]**	[0.136]*	[0.059]***	[0.104]	[0.005]
2003	–0.043	–0.013	–0.600	–1.603	0.214	0.436	0.503	0.395	0.009
	[0.018]	[0.023]	[0.127]**	[0.225]***	[0.073]**	[0.129]**	[0.057]***	[0.110]*	[0.005]
2004	–0.042	–0.012	–0.605	–1.600	0.212	0.439	0.479	0.354	0.009
	[0.017]*	[0.022]	[0.122]**	[0.219]***	[0.071]*	[0.124]**	[0.056]***	[0.112]	[0.005]
2005	–0.041	–0.009	–0.615	–1.593	0.210	0.442	0.476	0.408	0.009
	[0.017]*	[0.023]	[0.122]***	[0.218]***	[0.070]**	[0.124]**	[0.051]***	[0.106]*	[0.005]*
2006	–0.039	–0.008	–0.627	–1.570	0.227	0.427	0.477	0.415	0.010
	[0.016]*	[0.022]	[0.122]**	[0.216]***	[0.070]**	[0.124]**	[0.049]***	[0.105]*	[0.005]*
2007	–0.039	–0.008	–0.628	–1.571	0.227	0.427	0.483	0.408	0.010
	[0.016]*	[0.022]	[0.120]***	[0.212]***	[0.069]**	[0.121]**	[0.049]***	[0.112]*	[0.005]*
2008	–0.040	–0.010	–0.622	–1.574	0.228	0.425	0.531	0.462	0.010
	[0.016]*	[0.022]	[0.117]**	[0.211]***	[0.068]**	[0.119]**	[0.050]***	[0.120]*	[0.005]
2009	–0.037	–0.008	–0.638	–1.549	0.245	0.410	0.522	0.437	0.011
	[0.016]*	[0.022]	[0.121]***	[0.212]***	[0.069]*	[0.121]**	[0.051]***	[0.110]*	[0.005]
2010	–0.036	–0.008	–0.645	–1.533	0.259	0.397	0.559	0.490	0.011
	[0.016]*	[0.021]	[0.118]***	[0.211]***	[0.068]*	[0.119]**	[0.049]***	[0.109]**	[0.005]
2011	–0.037	–0.010	–0.635	–1.539	0.262	0.392	0.539	0.463	0.011
	[0.015]*	[0.020]	[0.117]**	[0.208]***	[0.067]*	[0.119]*	[0.048]***	[0.117]*	[0.005]
2012	–0.042	–0.015	–0.602	–1.581	0.242	0.408	0.532	0.441	0.010
	[0.017]**	[0.022]	[0.116]**	[0.213]***	[0.068]*	[0.120]**	[0.052]***	[0.120]*	[0.005]
2013	–0.041	–0.015	–0.602	–1.580	0.243	0.406	0.591	0.497	0.010
	[0.017]*	[0.022]	[0.113]***	[0.212]***	[0.067]*	[0.118]*	[0.058]***	[0.124]*	[0.005]
2014	–0.041	–0.014	–0.608	–1.569	0.251	0.399	0.522	0.460	0.010
	[0.016]*	[0.021]	[0.118]**	[0.213]***	[0.068]**	[0.121]*	[0.058]***	[0.125]*	[0.005]
2015	–0.043	–0.017	–0.590	–1.591	0.243	0.405	0.557	0.472	0.010
	[0.018]*	[0.022]	[0.119]**	[0.219]***	[0.069]**	[0.123]*	[0.059]***	[0.134]*	[0.005]
2016	–0.043	–0.018	–0.589	–1.588	0.247	0.400	0.641	0.558	0.010
	[0.017]*	[0.022]	[0.117]**	[0.217]***	[0.069]*	[0.122]*	[0.057]***	[0.143]**	[0.005]
2017	–0.045	–0.020	–0.573	–1.612	0.232	0.413	0.511	0.350	0.010
	[0.019]*	[0.024]	[0.122]**	[0.230]***	[0.072]*	[0.128]**	[0.066]***	[0.179]	[0.005]

Notes: The elasticities are simple average of all departmental elasticities for each year. Standard errors in brackets are computed with the delta method (Papke and Wooldridge [61]).

*** Significant at the 1 percent level. ** Significant at the 5 percent level. * Significant at the 10 percent level.

6. The Estimated Cost of Violence on Productivity Level

One of our main results is the estimate of the economic costs imposed by the armed conflict in terms of agricultural productivity loss. To evaluate this loss, we first calculated productivity elasticities for each department for each year. We then computed the corresponding measure of productivity loss by multiplying this elasticity by the percentage change in the technology-changing variables of interest.

$$Productivity\ Cost_{kdt} = \varphi_{kdt} \times \%\Delta v_{kdt} \tag{11}$$

where φ_{kdt} is the elasticity of productivity for technology-changing variable v_k in department d in year t; $\%\Delta v_{kdt}$ is the percentage change in a technology-changing variable between the observed value and 0 (a decrease of 100%). Note that this is a change in productivity level rather than in productivity growth.

Table 5 shows the average estimated impacts of violence from armed conflict (IDP and casualties) on the productivity level. For Antioquia, for example, the estimate of the average impact of IDP was to decrease the level of productivity by 2.7%, while casualties decreased the level of productivity by 0.6%, for a total productivity level cost of violence of 3.3%. We observe that IDP and casualties together are associated with more than a 5% decrease of agricultural GDP in 13 departments (Arauca, Caquetá, Casanare, Cauca, Huila, La Guajira, Meta, Norte de Santander, Nariño, Putumayo, Risaralda, Tolima and Valle del Cauca). In the rest of the departments the decrease in GDP would have been between 1% and 5%. Some of these are big agricultural producers (i.e., Antioquia, Cordoba, Meta, Cundinamarca, Guajira, Putumayo, and Casanare) so this implies a sizable decrease in Colombian agricultural GDP. On average, during the 1995–2017 period, the decrease in agricultural GDP associated with IDP and casualties amounted to $1.046 million dollars (2005 U.S. dollars) per year.

Table 5. Impact of Violence on Agricultural Productivity Level, Average Per Department in Colombia for the 1995–2017 Period (Fractional Change in the Level of ag GDP).

Department	IDP	Casualties	Cocaine price
Antioquia	−0.027	−0.006	−0.693
	[0.013]**	[0.017]	[0.133]**
Arauca	−0.076	0.015	
	[0.033]**	[0.053]	
Atlántico	−0.017	0.005	
	[0.012]	[0.016]	
Bolívar	−0.036	−0.009	−0.642
	[0.012]***	[0.015]	[0.092]***
Boyacá	−0.018	0.003	
	[0.010]**	[0.014]	
Caldas	−0.026	−0.01	
	[0.010]*	[0.012]	
Caquetá	−0.053	0.003	−0.581
	[0.020]**	[0.031]	[0.112]**
Casanare	−0.079	−0.002	
	[0.030]**	[0.045]	
Cauca	−0.063	−0.057	−0.404
	[0.029]**	[0.033]*	[0.136]**
Cesar	−0.029	0.016	
	[0.018]	[0.028]	
Chocó	−0.014	−0.007	
	[0.010]	[0.014]	

Table 5 continued

Department	IDP	Casualties	Cocaine price
Córdoba	–0.001	0.026	
	[0.016]	[0.024]	
Cundinamarca	–0.02	–0.002	
	[0.008]*	[0.011]	
La Guajira	–0.094	–0.062	
	[0.034]***	[0.037]	
Huila	–0.057	–0.034	
	[0.020]***	[0.021]	
Magdalena	–0.028	0.007	
	[0.013]*	[0.021]	
Meta	–0.087	–0.016	–0.360
	[0.027]***	[0.038]	[0.154]*
Nariño	–0.035	–0.04	–0.585
	[0.021]*	[0.025]	[0.110]***
N. Santander	–0.06	–0.032	–0.472
	[0.020]***	[0.022]	[0.100]**
Putumayo	–0.056	–0.04	–0.474
	[0.021]***	[0.023]*	[0.100]***
Quindío	–0.027	–0.014	
	[0.010]*	[0.012]	
Risaralda	–0.026	–0.029	
	[0.015]*	[0.018]*	
Santander	–0.037	–0.007	
	[0.012]***	[0.017]	
Sucre	–0.012	0.016	
	[0.013]	[0.020]	
Tolima	–0.049	–0.022	
	[0.015]***	[0.018]	
V. del Cauca	–0.031	–0.022	
	[0.013]**	[0.014]	

Notes: The percentage change in IDP and casualties is calculated by taking the relative difference between 0 and each department level for the given year (a decrease of 100%); this is then multiplied by the productivity elasticity for each department for each year to obtain the fractional change in GDP due to IDP and Casualties. This is then averaged by department. For the Cocaine price column only departments with more than 3% area of cocaine production are included. Standard errors in brackets are computed with the delta method (Papke and Wooldridge [61]).

*** Significant at the 1 percent level. ** Significant at the 5 percent level. * Significant at the 10 percent level.

It is also interesting to note the negative impact of cocaine price, as an incentive for coca production, on licit agricultural productivity. Several departments comprise 93% of the coca area in the period of analysis: Putumayo (21%), Nariño (20%), Caquetá (16%), Meta (10%), Norte Santander (8%), Cauca (6%), Antioquia (6%), and Bolivar (4%). For Putumayo for example the estimate of the average impact was to decrease productivity by 47%. A 100% reduction in the price of cocaine implies, approximately, a 23% increase in licit agricultural productivity for Colombia.

Elimination of both, conflict and incentives derived from illicit agriculture in Colombia, would have implied an average increase in Colombian agricultural GDP of approximately 29% during 1995–2017.

7. Conclusions

The central issue addressed by this study is whether violence and incentives for coca production are significantly associated with the productivity of the licit agricultural sector in Colombia. For this, we hypothesize that these variables affect the production structure of the sector impacting the adoption of new technology and therefore productivity of the sector. We use a variable coefficients department-level production function in which the Colombian agricultural production structure is permanently affected by state or technology changing variables inducing shifts of the production function. In this approach the change in production structure is captured by production elasticities that are a function of the technology changing variables and productivity elasticities that indicate permanent shifts of the production function due to these variables. The state/technology changing variables considered are internally displaced people and casualties due to armed violence, the incentives for coca production, and weather variables.

We find that elimination of armed conflict-related internally displaced people and casualties would have implied an increase in the level of productivity in Colombian agriculture of around 4.4% and 1.4%, respectively. We also find that if the price of cocaine were to fall to zero (i.e., no incentive for illicit agriculture), the level of agricultural productivity would have been, on average, 23% higher.

Other interesting findings are those related to weather. We estimate that the marginal impacts of weather on agricultural yields in Colombia are important. A 1% increase in temperatures is related to a 1.51% decrease in yields, while a 1% increase in rainfall relates to an increase in yields of 0.29%. The average annual rate of exogenous and unexplained technical change is approximately 1%. These departmental averages hide considerable heterogeneity across departments.

The productivity effects calculated here are useful for examining the economics of Colombian agriculture because the technology-changing variables we consider reflect some of the main events that affected the sector [13] during 1995–2017. These have consisted primarily of armed conflict, drug traffic and illicit crop production.

In some sense we have estimated the tradeoff between licit and illicit agriculture in Colombia: without violence and the related coca production, the level of productivity of licit agriculture would have been 29% higher during the 1995–2017 period.

⑬ See Appendix A in Jiménez *et al.* [64] for a detailed list of the most remarkable events about Colombia's agriculture during 1975-2013, and Chapter 8 (about Colombia) of the series of annual reports on Agricultural Policy Monitoring and Evaluation for 2015-2018, OECD [76].

Author Contributions

Wilman Iglesias Pinedo developed the data sets, wrote the statistical code, estimated parameters and calculated elasticities, and shared the interpretation of the results. Lilyan E. Fulginiti contributed to the conceptualization of the research and the development of the model, to the interpretation of results of the estimation, to obtaining productivity impacts, shared the writing of the manuscript and reviewed it critically. Richard K. Perrin contributed to the conceptualization of the research and the development of the model, to the interpretation of results of the estimation, shared the writing of the manuscript and reviewed it critically.

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Data Availability

We will upload the data set to the University of Nebraska Digital Commons once paper is accepted.

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Appendix

Sensitivity Analysis of the Baseline Estimates from the Structural Model

Table A. 1 shows estimated productivity and production elasticities using alternative econometric specifications. This is done to check for robustness of the model chosen for the analysis. Column (1) replicates our baseline estimates of equation (4). Column (2) includes a control for farm size (or average APU size) defined here as the total number of hectares covered by the UPAs divided by the total number of UPAs. In column (3), the error term u_{0dt} of equation (4) is clustered at the regional level to account for possible serial correlation across departments over time. Column (4) includes a fixed effect for 26 departments. Column (5) is pooled OLS.

Table A.1- Productivity and Production Elasticities with Some Alternative Specifications

	(1)	(2)	(3)	(4)	(5)
Productivity elasticity for					
IDP (φ_1)	-0.0408	-0.0407	-0.0408	-0.0433	-0.0437
	[0.0176]*	[0.0177]*	[0.0161]*	[0.0175]*	[0.0174]*
Casualties (φ_2)	-0.0123	-0.0123	-0.0123	-0.0157	-0.0178
	[0.0230]	[0.0231]	[0.0244]	[0.0224]	[0.0222]
Past Coca Price (φ_3)	-0.2331	-0.2330	-0.2331	-0.2107	-0.2042
	[0.0478]**	[0.0481]**	[0.0478]**	[0.0444]**	[0.0430]**
Temperature (φ_4)	-1.5784	-1.5586	-1.5784	-1.5204	-1.5338
	[0.2224]***	[0.2483]***	[0.1812]***	[0.2195]***	[0.2189]***
Rainfall (φ_5)	0.2349	0.2367	0.2349	0.2132	0.2067
	[0.0716]*	[0.07276]*	[0.06149]*	[0.0696]*	[0.0699]*
Past Output Price (φ_6)	0.4161	0.4153	0.4161	0.4341	0.4297
	[0.1272]**	[0.1280]**	[0.1101]**	[0.1265]**	[0.1256]**
Technical Change (τ)	0.0100	0.0102	0.0100	0.0104	0.0103
	[0.0051]	[0.0052]	[0.0049]	[0.0050]	[0.0059]
Production elasticity for					
Labor ($\ln x_1$)	0.5153	0.5118	0.5153	0.5343	0.5040
	[0.0556]***	[0.0598]***	[0.0506]***	[0.0564]***	[0.0567]***
Livestock ($\ln x_2$)	0.4034	0.4025	0.4034	0.4684	0.4823
	[0.1192]*	[0.1201]*	[0.0813]*	[0.1183]**	[0.1175]**

Notes: These are average elasticities. Standard errors in brackets are computed using the delta method (Papke and Wooldridge 2005). *** Significant at the 1 percent level. ** Significant at the 5 percent level. * Significant at the 10 percent level.