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Examining spatially varying relationships between coca crops and associated factors in Colombia, using geographically weight regression

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A B S T R A C T

This article addresses the expansion of illicit crops (coca) and the associated socio-institutional and geographical drivers in Colombia between 2001 and 2008. The analysis is based on a Geographically Weighted Regression (GWR) models and shows that the relationships between the analyzed variables and the coca crops are not constant over space. Similarly, it is demonstrated that the factors commonly associated with the expansion of coca crops are not constant with respect to time, as changes can be seen between the years of the study (2001 and 2008). The article finds that the models that include the local reality offer the best way of understanding the factors associated with the expansion of illicit coca crops in Colombia, a fundamental step in the formulation of effective policies in the reduction of crops for illicit use (coca).

Introduction

The economic benefits generated by the illegal trafficking of natural resources create an incentive for illegal armed groups to take advantage of the adverse social, economic and institutional conditions that exist in some countries such as the Republic of Congo (coltan), Sierra Leone (diamonds) and Colombia (coca to produce cocaine). Most instances involving natural resources and violent conflicts are found in developing countries and particularly in areas with vulnerable populations, typically with a combination of illegal armed groups and weak government presence (Le Billon, 2001).

Coca is a traditional crop in many Andean countries (Matteucci & Morello, 2003; Timothy, 1981). However, since the 1970s, the production of coca has been increasingly focused on the manufacture of cocaine because of increased demand, principally from the United States and Europe (Guridi, 2002). In the last few decades, Colombia, Peru and Bolivia have been responsible for the bulk of coca leaf production. Peru was the principal producer of the coca leaf until 1997, when Colombia became the world's number one producer (UNODC, 2008).

In the literature, various factors have been identified as being linked to illicit crops, including the forced displacement of populations and violence (Díaz & Sánchez, 2004; Garcés, 2005; Vargas, 2005), poverty (Dion & Russler, 2008), corruption (Molano, 2004), land tenure (Fajardo, 2002, 2004), an abundance of land and inaccessible forests (Álvarez, 2003; Dávalos, Bejarano, & Correa, 2009; Dávalos et al., 2011), an absence of the state (Kalmanovitz & López, 2005; Molano, 2004; UNDP, 2003) and the institutional weaknesses of Colombian society (Thoumi, 2005a, 2005b, 2005c). Illegal armed groups take advantage of the absence of the state, creating their own rules (Rangel, 2000). Although it has been argued that violence and armed conflict in Colombia are factors that aid in the conservation of forests (Dávalos, 2001) and that isolation from traditional markets, low road density and therefore low accessibility have facilitated environmental protection (Ali, Benjaminsen, Hammad, & Dick, 2005; Chomitz & Gray, 1996; Rincon, Romero, Bernal, Rodriguez, & Rodriguez, 2006), these assumptions have changed with the expansion of drug trafficking. Inaccessibility and violence are no longer obstacles, but rather combine to facilitate the degradation of forests due to the illegal use of coca crops for cocaine production (Díaz & Sánchez, 2004; Jaramillo, Mora, & Cubides, 1989; Posada, 2009; Sánchez, 2007; Sánchez, Díaz, & Formisano, 2003).

This study examined the relationships between the expansion of illicit crops and several of the factors mentioned as drivers of this behavior in the literature. The study emphasizes the importance of local heterogeneity—a topic that has been largely overlooked in the

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literature on illicit crops. Specifically, answers are sought to the following questions:

> Can models that incorporate local realities enable an improved understanding of the factors associated with the expansion of coca crops in Colombia?
> Is it possible to make generalizations regarding the factors associated with the expansion of coca crops that are applicable to the entire country?
> Are the types of relationships between illicit crops and the associated factors the same on the global and local levels? Are the relationships constant with respect to space (i.e., stationary)?
> Are the factors commonly associated with the expansion of illicit crops constant over time?

The aim of the examination of the issues above is to achieve an improved understanding of the factors associated with the expansion of illicit crops in Colombia between 2001 and 2008 by taking the local reality into account. The paper aims to show that the factors associated with the expansion of illicit coca crops have changed geographically during the last decade and therefore demand new policies that integrate local realities rather than more general ones.

Modeling the related factors to coca crops

Previous studies (Dávalos et al., 2011; Dion & Russler, 2008) aimed to define the relationship between coca crops and social, institutional and biophysical factors using global regression analysis. In this study, a “global” analysis refers to an analysis on a national scale without accounting for regional characteristics. Previous studies presented the results as average values, assuming that the relationship does not change over space or time. However, this assumption is not necessarily true. Models testing the influences of related factors on coca crops reveal relationships on a global scale between coca crops and factors such as violence, poverty, accessibility (distance to rivers and roads), aerial fumigation and deforestation (Dávalos et al., 2011; Díaz & Sánchez, 2004; Dion & Russler, 2008; Moreno-Sanchez, Kraybill, & Thompson, 2003). Dávalos et al. (2011) applied logistic regression models to determine how coca crops increase the risk of deforestation and how so-called protected areas minimize this risk. However, as that study was detailed in its scope, socioeconomic and institutional information, which are typically used at a more aggregated scale, were not included. Moreover, those authors do not consider the spatial or temporal variation in the variables.

A study on Columbia was conducted by (Dion & Russler, 2008) to explain the persistence of coca crops in Colombia over the last decade, but their analysis focused on global models and assumed that there would be no changes in the global parameters (Díaz & Sánchez, 2004) better determined the spatial relationship and enhanced understanding of the different processes at both local and municipal scales, although their primary focus was the relationship between coca crops and armed conflict.

Interestingly, thus far, no modeling or correlation analysis of coca crops has considered the possible non-stationarity of the analyzed variables, nor has such an analysis included indicators that compare the significance of accessibility, violence and institutional factors (a weak or absent state) over more than a single time period. The Geographically Weighted Regression – GWR (Fotheringham, Brunsdon, & Charlton, 2002) was recently developed to explore spatially varying relationships and has been employed in different areas such as studies of reforestation (Clement, Orange, Williams, Mulley, & Epprecht, 2009), environmental justice (Gilbert & Chakraborty, 2011), freshwater acidification (Harris, Fotheringham, & Juggins, 2010), land use and water quality (Tu & Xia, 2008), wealth and land cover (Ogneva-Himmelberger, Pearsall, & Rakshit, 2009) and deforestation (Pineda Jaimes, Bosque Sendra, Gómez Delgado, & Franco Plata, 2010).

In this study, we applied GWR methods to examine and compare the spatially varying relationships between coca area percentages on a municipal scale and socio-institutional factors and geographical characteristics, such as road density and forest area. GWR is a widely used method for this type of study, in which the local aspects of an area are considered with the aim of improving the understanding of the actual situation, beyond the global and general models (Clement et al., 2009; Gao & Li, 2011). Additionally, this study is the first to apply GWR in examining the impact of socio-institutional and physical variables on the presence of illicit crops over two time periods.

Study area

Colombia covers an area of 2,070,408 km^2, of which 1,141,748 km^2 correspond to terrestrial territory and the remaining 928,660 km^2 to maritime territory. Colombia is located in the northwestern corner of South America and consists of five continental natural regions (Map 1): the Andean (AN) region, Caribbean (CA) region, Pacific (PA) region, Orinoquia (OR) region and Amazon (AM) region. The country is divided into 32 departments and 1101 municipalities, of which 23 departments (72%) and 274 municipalities (25%) reported the presence of coca crops for at least one year during the period 2001–2008. Colombia is responsible for over 50% of the global production of coca for cocaine production (UNODC, 2006a). The region with the highest average area and production of coca at the beginning of the study period (2001) is the Amazon region, principally in the departments of Putumayo, Meta and Guaviare. However, in the following years, coca cultivation spread to the Pacific region and the north of Colombia (UNODC, 2006, 2009).

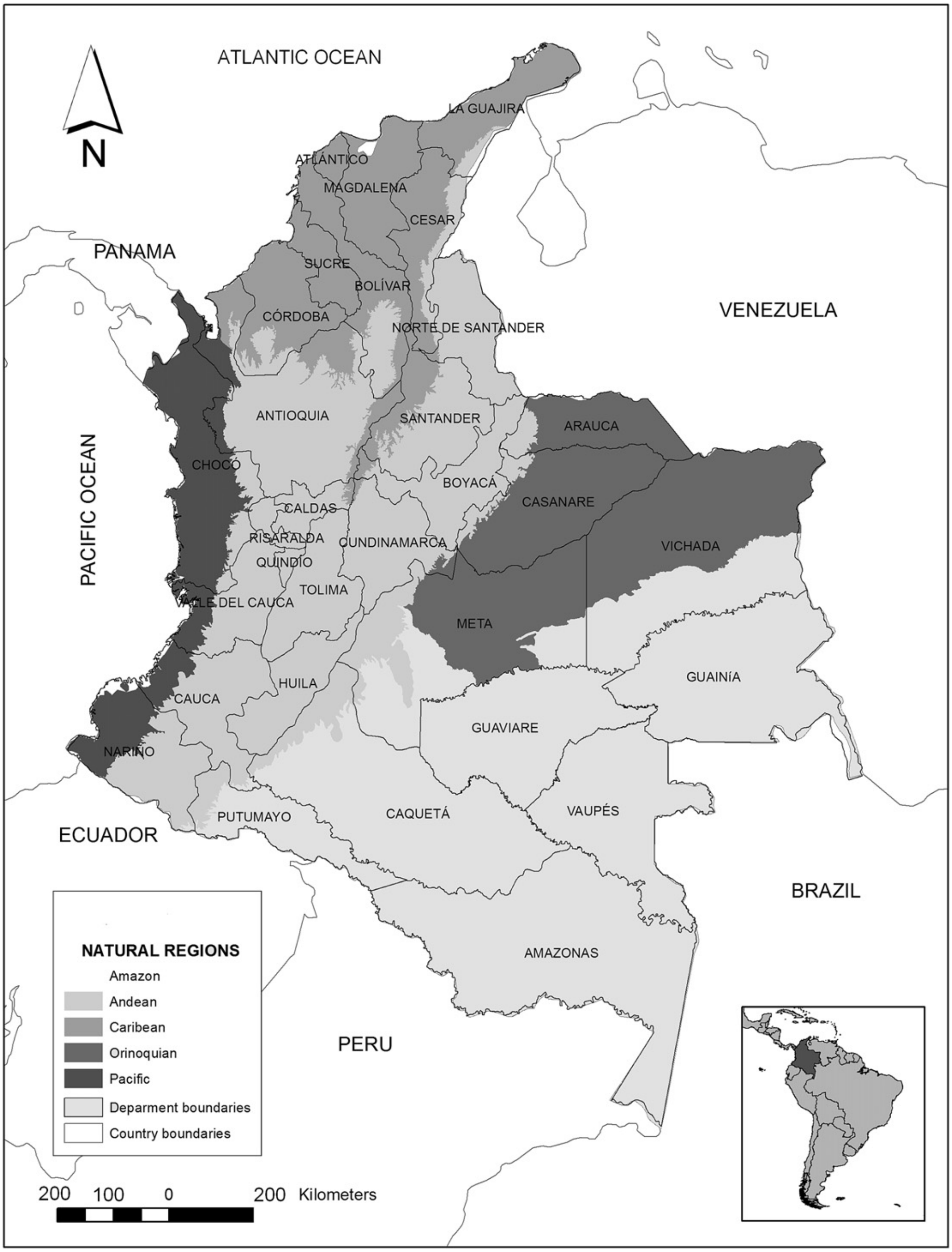
Methodology

The Geographically Weighted Regression (GWR) model is an extension of the Ordinary Least Squares (OLS) regression model that allows spatial (local rather than global) parameters to be estimated (Fotheringham et al., 2002; Fotheringham, Charlton, & Brunsdon, 2001). OLS models lead to generalized relationships that are not applicable to the entire territory, while they do not allow for the consideration of the local characteristics of certain areas. This issue becomes an obstacle for the analysis of issues such as the expansion of illicit crops, which is a topic that requires a better understanding of local realities. GWR follows a local statistics approach, introducing a set of local parameter estimates that demonstrate how a relationship varies across space. Subsequently, the spatial patterns of the local variables are assessed to provide an improved understanding of hidden possible causes of the patterns observed (Brunsdon, Fotheringham, & Charlton, 2002). A global regression (OLS) is expressed as follows:

$$Y_i = \beta_0 + \sum_k \beta_k \chi_{ik} + \varepsilon_i \tag{1}$$

where Y_i is the dependent variable at location i, β_0 is the intercept, χ_{ik} is the value for the kth independent variable at location i, β_k is the parameter estimate for the independent variable k and ε_i is the error term at location i.

GWR generates a separate regression equation for each observation and provides a method to assess the degree of spatial non-



Map 1. Departments and continental natural regions of Colombia.

stationarity in the relationship between the dependent and independent variables. It generates a local regression equation for each observation, which is expressed as:

$$Y_i = \beta_0(\mu_i, \nu_i) + \sum_k \beta_k(\mu_i \nu_i)\chi_{ik} + \varepsilon_i \quad (2)$$

where (μ_i, ν_i) are the coordinates at location i.

GWR is calibrated by weighting all observations around a sample point using a distance decay function (Tu & Xia, 2008), which assumes that data observed near point i have a greater influence on the estimated values of β_k than data located farther from j (Fotheringham et al., 2001).

Following (Fotheringham et al., 2002), the weighting function selected is Gaussian:

$$\omega_{ij} = \exp\left[-1/2\left(d_{ij}/b\right)^2\right] \quad (3)$$

where d_{ij} expresses the distance between points i and j, and b is the kernel bandwidth (Fotheringham et al., 2002). A fixed kernel has a constant bandwidth across space, while an adaptive kernel can adapt the sizes of bandwidths to variations in data density, such that bandwidths are larger in locations where the data are sparse and smaller where the data are denser (Clement et al., 2009; Tu & Xia, 2008). Both fixed and adaptive kernel bandwidths can be selected in the GWR 3.0.1 software program developed by Fotheringham. We employ an adaptive kernel bandwidth in this study because the sample density varies across the study area. The optimal bandwidth was determined by minimizing the Akaike Information Criterion (AIC) as described in (Fotheringham et al., 2002).

The significance of the spatial variability in the local parameter estimates (the stationarity test) was evaluated using a Monte Carlo simulation (Fotheringham et al., 2002). As an indication of the extent of the variability in the local parameter estimates, we followed the method proposed by Charlton, Fotheringham, and Brunsdon (2006): The authors calculated a five-number summary of these parameters: the median, upper and lower quartiles, and the minimum and maximum values of the data; this approach was helpful in obtaining a proxy for the degree of spatial non-stationarity in a relationship by comparing the range of the local parameter estimates with a confidence interval around the global estimate of the equivalent parameter. In this test, the range of values for the local estimates between the lower- and upper-quartiles can be compared with a range of values of ±one standard deviation (S.D.) of the global estimate. If the range of the local estimates within the interquartile ranges are greater than a limit of two S.D. of the global mean, this suggests that the relationship might be non-stationary (Charlton et al., 2006).

All of these tests were performed using GWR 3.0.1 software developed by Fotheringham (Charlton et al., 2006; Charlton & Fotheringham, 2009; Fotheringham et al., 2002). The outputs of the GWR software include a parameter estimate, a t-value, and the goodness-of-fit for each municipality. All of these results were spatially displayed in a Geographical Information System environment, thus allowing a visual interpretation of the results.

The data

Information on the major drivers of the expansion of coca crops in Colombia was gathered from the relevant literature. This information included socio-institutional factors, for example violence and the absence of the state, and geographical and biophysical characteristics such as accessibility and the percentage area of forest cover. Only official information available at the municipal level and for the entire country during the study period (2001–2008) was used. Table 1 describes the variables selected, their sources and the years for which data are available. The information is on the municipality level.

The index of municipal development (DNP, 2002) and the presence of illegal armed groups were selected to indicate the absence/weakness of the state at the municipal level. The latter was estimated via two indicators: the rate of murders committed by illegal armed groups and the forced displacement of individuals.

The geographical and biophysical indicators are represented by the primary road density and the percentage of municipal territory located in a primary forest area. Spatial and alphanumeric information on coca crops was obtained from the Integrated System of Monitoring of Illicit crops of the United Nations on Drugs and Crime (SIMCI in Spanish). The unit of study is the municipality, and the dependent variable in the analysis is the percentage of area under coca cultivation (Percentage Coca Area – PCA). Due to the variations in the size of the municipalities, the percentage was considered to be the best option. In the results, the "coca area" refers to municipalities where coca was present during the study period.

When information was unavailable for a variable in a given year, data from the nearest year were used. In cases where data on a variable were only available for a single year, this information was used for both periods and only one variable was used: primary road density (PRD). This assumption may bias the results for the PRD variable; however, consultations with experts indicated that although the density has changed over time, the regional trends have remained, which may minimize this potential bias. However, we are aware that the accuracy of this result is limited.

Results

The results of the performance assessment of the GWR for 2001 are summarized in Table 2. The results of the R squared and adjusted R squared parameters were 0.93 and 0.91 respectively, showing an appropriate adjustment of the model. Para el 2008, the values of the R squared and the Adjusted R squared decreased to 0.654 and 0.625 respectively, without changing the performance of the model.

The specific results are divided into two sections: 1) GWR models: stationarity test (2001 and 2008) and 2) significance analysis of the GWR model for 2001–2008.

GWR models: stationarity test (2001 and 2008)

We employed two tests to determine the stationarity or non-stationarity of the local variables estimated in the GWR models. This first is an informal test, based on the methods documented by (Charlton et al., 2006). This test determines whether the range of the local estimates within the interquartile ranges exceeds the limits by more than two S.D. of the global mean (OLS model); this result indicates that the relationship may be non-stationary. Table 3 presents the results of the stationarity test for the year 2001. These results indicate that the interquartile range of the local estimates is far smaller than two S.D. of the global estimate (OLS model), indicating a stationary relationship among the parameters.

For 2008, the results indicate that the interquartile range of the local estimates is greater than two S.D. for all variables (except the density of roads variable), suggesting that the relationships may be non-stationary (Table 4). This result indicates a difference from the 2001 estimates, in which stationary relationships were observed among all variables.

The second test is a Monte Carlo test to assess whether spatial variation in the relationship between each independent variable and the dependent variable is statistically significant across the study region. The results of these tests (Table 4) indicate that the spatial variation in our local parameter is not significant. The results of the Monte Carlo test for 2001 (Table 5) confirm the results found previously.

The results of the Monte Carlo test for 2008 indicate that there is significant spatial variation in the local parameter estimates for all variables, except for displacement, as reported in the second column of Table 4. This result complements the results found previously and confirms the change from 2001 (in which a stationary relationship was found) to 2008, where no stationarity was observed.

Significance analysis of the GWR model 2001–2008

Here, we present an analysis of significance of the variables included in the model for the two years of the study (2001 and 2008), beginning with the percentage of primary forest area (PPF) within a municipality variable, followed by the analysis of primary roads density (PRD), forced displacement of population (FDP), murder rate by illegal armed groups (MR) and, finally, the index of municipal development (IMD). The statistical results make it possible to identify the regional differences in the variables influencing the cultivation of coca. Differences were found between the Amazon, Pacific, Caribbean and Andean regions. Additionally, significant differences were found between the two years studied. In the following maps, the percentage of coca area (PCA) is depicted

Table 1
Variables included in the OLS and GWR models.

Variable	Acronym	Variable name	Year	Source of data	Unit	Additional explanation
Var *X*	PCA	Percentage of area under coca cultivation	2001–2008	Coca maps (shape) – Integrated Illicit Crops Monitoring System (SIMCI: Spanish acronym for "Sistema Inte grado de Cultivos Ilicitos")	Percentage	Percentage of hectares of cultivated coca in comparison to the total area of the municipality.
Var *Y*	PRD	Primary roads density	2005	Road map (shape) – Geographic Institute Agustín Codazzi – Estimation by the authors	Mts/roads/ha	Meters of primary roads per hectare.
	FDP	Forced displacement of population – expulsion	2001–2008	Presidency of the Republic of Colombia – Presidential Agency for Social Action and International Cooperation	Number of displaced people	Number of forced displaced people by violence and conflict. This information is taken from the National System of Integral attention of Displaced People ("Sistema Nacional de Atención Integral a la Población Desplazada")
	IMD	Index of municipal development	2001–2008	National Planning Department of Colombia (DNP – Spanish acronym for "Departamento Nacional de Planeación") – Dirección de Desarrollo Territorial Sostenible DDTS	Index from 0 to 100 (where 0 means low municipal development)	Synthetically measuring the performance of municipalities in social and financial variables. The variables taken are: % of population in header, % of households with water supply, % of households with sewage, % households with energy services, % of people without NBI 2005 per head, % of people without NBI 2005 (rest), % alphabetics, % school attendance, tax revenues per capita (current $), municipal public investment per capita (current $), % of non-reliance on transfers
	MR	Murder rate by illegal armed groups (used as proxy to presence of illegal armed groups),	2001–2008	Colombian National Police – Estimation by the Authors	Number of homicides per 100.000 inhabitants	Number of homicides per 100,000 inhabitants committed by illegal armed groups (FARC, AUC, ELN). Homicides committed by common crime are not taken into account.
	PPF	Percentage of primary forest area	2000	Colombia Ecosystem map (shape) – Institute of Hydrology, Meteorology and Environmental Studies of Colombia (IDEAM: Instituto de Hidrología, Meteorología y Estudios Ambientales de Colombia) – Estimation by the author	Percentage	Hectares of primary forest as percentage of the total area of the municipality.

for each study year (2001 and 2008) in addition to the associated parameter variables that were significant in both 2001 and 2008.

PPF: For 2001, PPF was found to have a significant and inverse relationship with PCA in some municipalities in the Amazon region (southern departments of the country, such as Putumayo and Caqueta). For 2008, this relationship changes in two ways: a) it is no longer significant in Putumayo and Caqueta, and b) it becomes positive and significant in some municipalities of the Pacific and Caribbean regions (see Map 2). The reason for this behavior is that in 2001, Putumayo exhibited high levels of forest transformation and had the greatest presence of coca among the departments (showing an inverse relationship); however, by 2008, the coca crops had been displaced to other areas characterized by low levels of transformation (high levels of natural forest cover) in the Pacific region (hence the positive relationship).

PRD: In 2001, PRD had an inverse and significant relationship with PCA in some municipalities of the Amazon region (Putumayo and Caqueta departments), which is similar to the findings for PPF. Additionally, PRD was inverse and significant in some municipalities in the Pacific region (some municipalities of the Nariño department). In the Caribbean region and the north of the Andean region, PRD only became significant in some municipalities in the department of Antioquia. In 2008, this variable continued to exhibit an inverse relationship while becoming more negative and significant in other municipalities in the Pacific region and the north of the Andean region and remaining significant in the municipalities in the Amazon region. The analysis indicates that road density was an important indicator in both periods, but primarily in the south of

Table 2
Performance assessment of the OLS and GWR models (2001 and 2008).

Year	2001		2008	
Diagnostic information	OLS	GWR	OLS	GWR
Akaike Information Criterion – AIC	1,757, 552,060	−505,018, 207	−1,165,804, 900	−1,853,635, 868
R-square	0.067524	0.935338	0.243399	0.654029
Adjusted R-square	0.062392	0.915425	0.239234	0.625282

Table 3
Results of the stationarity test for OLS and GWR for 2001.

2001	OLS model		GWR model			
Variable	S.D.	2*S.D.	Lw quartile	Up quartile	Range GWR	Range GWR − 2*S.D.
PPF	0.00085	0.00169	0	0.00027	0.00027	−0.00143
PRD	0.01325	0.02651	−0.00029	0	0.00029	−0.02622
FDP	0.00002	0.00004	0	0	0	−0.00003
MR	0.00496	0.00991	0	0.0007	0.0007	−0.00921
IMD	0.00183	0.00367	−0.00017	0	0.00017	−0.0035

Table 4
Results of the stationarity test for OLS and GWR for 2008.

2008	OLS model		GWR Model			
Variables	S.D.	2*S.D.	Lw quartile	Up quartile	Range GWR	Range GWR − 2*S.D.
PPF	0.00022962	0.00045924	0.000015	0.001807	0.001792	0.001332757
PRD	0.00350462	0.00700924	−0.006472	0.000057	0.006529	−0.000480237
FDP	7.73E−06	1.55E−05	0.000005	0.000075	0.00007	5.45E−05
MR	0.00363265	0.0072653	−0.000069	0.03378	0.033849	0.026583702
IMD	0.00038969	0.00077937	−0.001517	−0.000066	0.001451	0.000671626

Table 5
Tests based on the Monte Carlo significance test procedure (2001 and 2008).

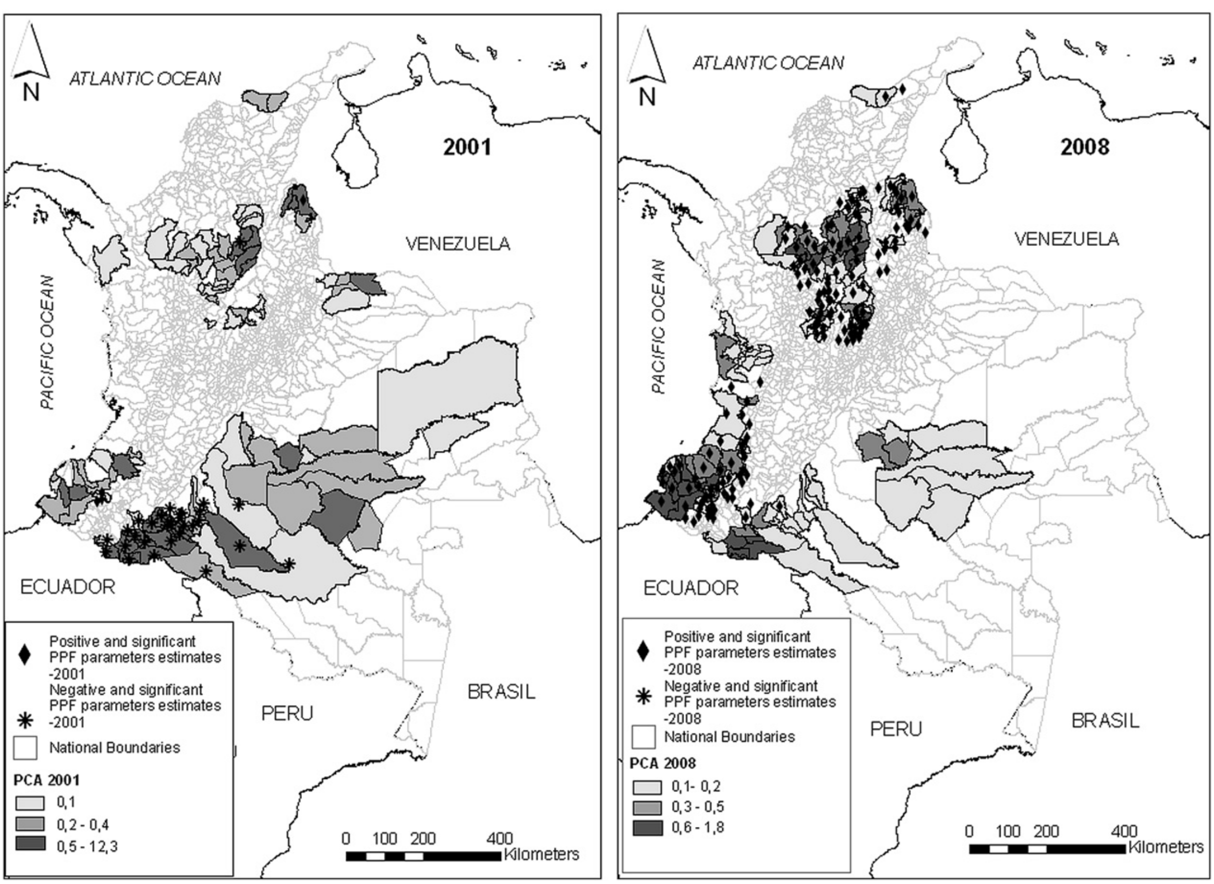
Parameter	*P*-value 2001	*P*-value 2008
Intercept	0.65000 n/s	0.00000***
PPF	0.85000 n/s	0.01000**
PRD	0.27000 n/s	0.00000***
FDP	0.88000 n/s	0.39000 n/s
MR	0.99000 n/s	0.04000*
IMD	0.99000 n/s	0.00000***

***Significant at .1% level; **significant at 1% level; *significant at 5% level.
n/s = Not significant.

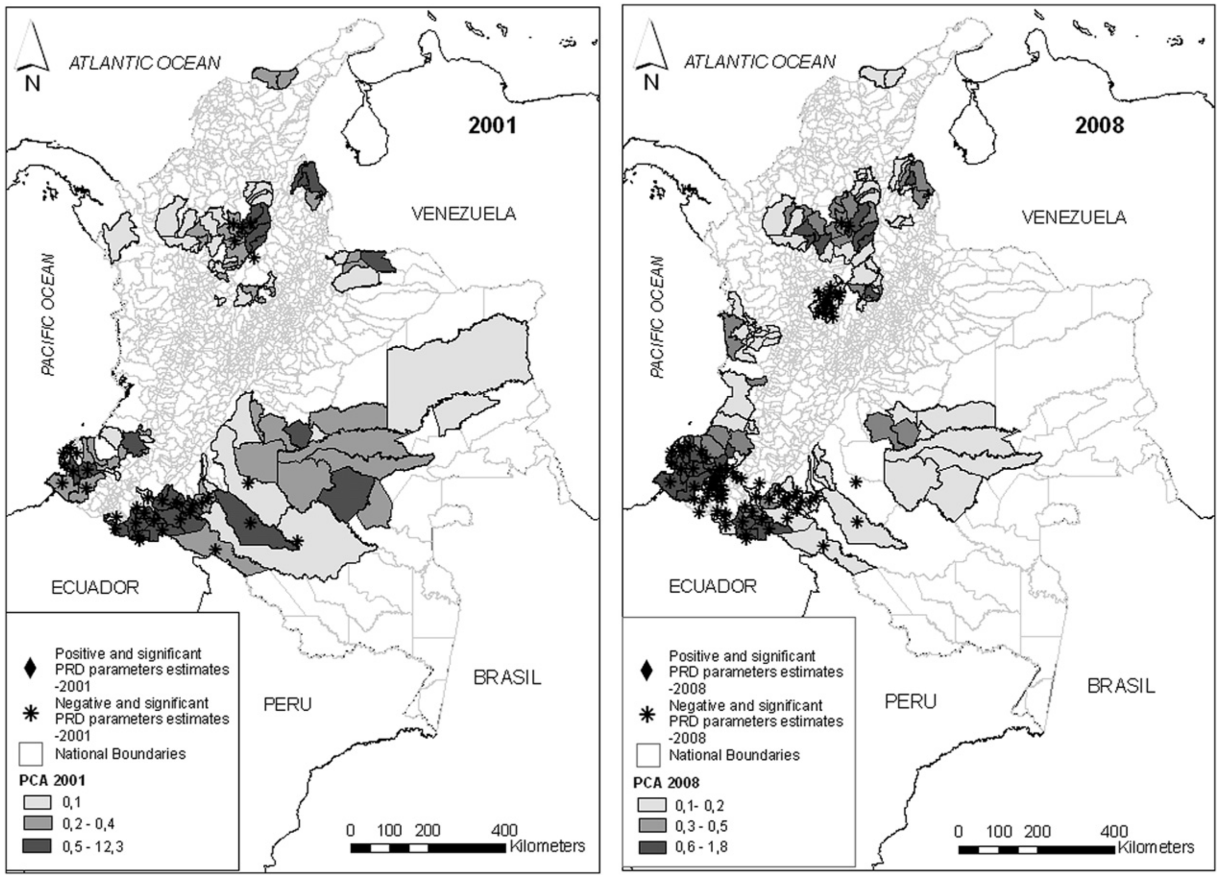
the country (Pacific and Amazon region), as this variable is almost never significant in the north of the country (Map 3).

FDP: For 2001, FDP was found to have a significant and positive relationship with PCA in some municipalities of the Amazon region (southern departments of the country, such as Putumayo and Caqueta). In 2008, the relationship became significant in the Nariño department and many other coca-growing municipalities in the Pacific region, the Caribbean region and the north of the Andean region (see Map 4).

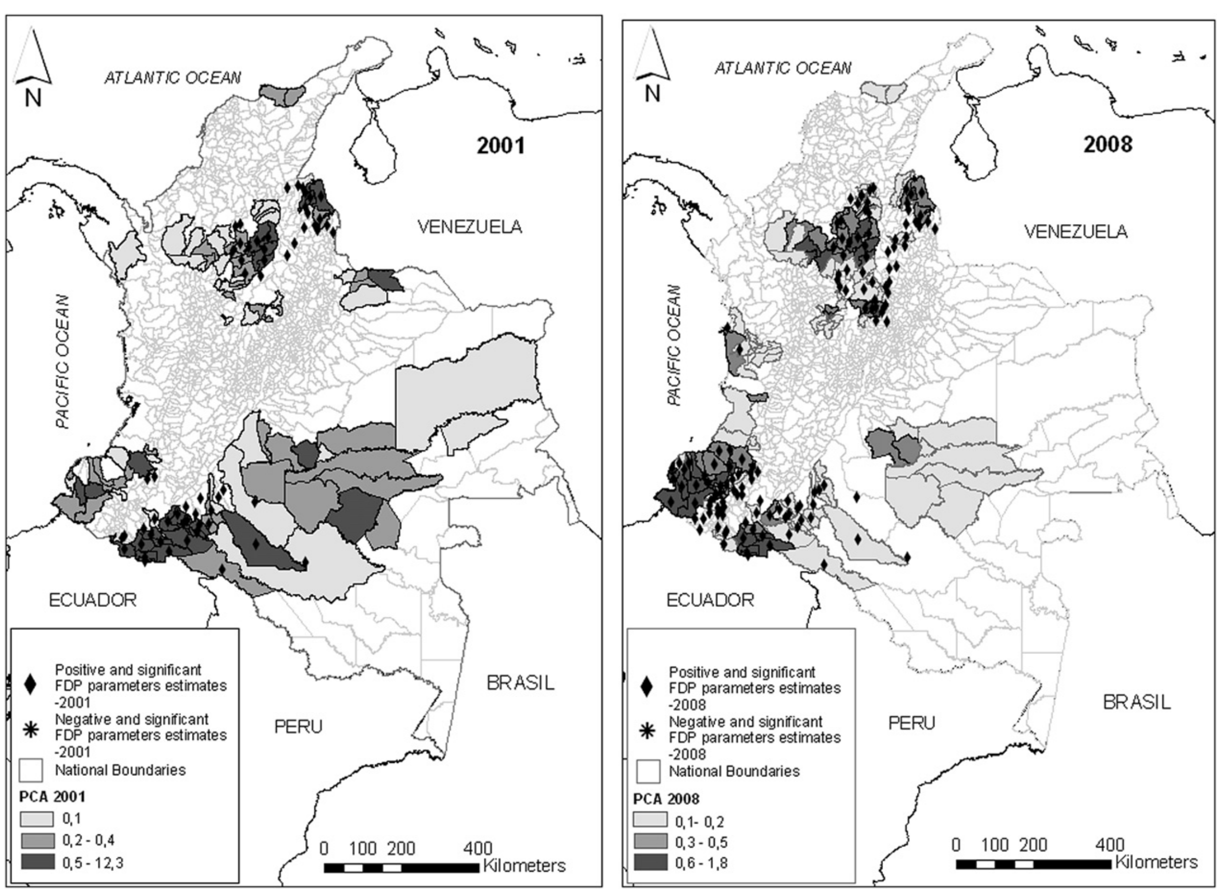
MR: In 2001, the murder rate by illegal armed groups variable had a positive relationship with PCA in the Amazon region and the



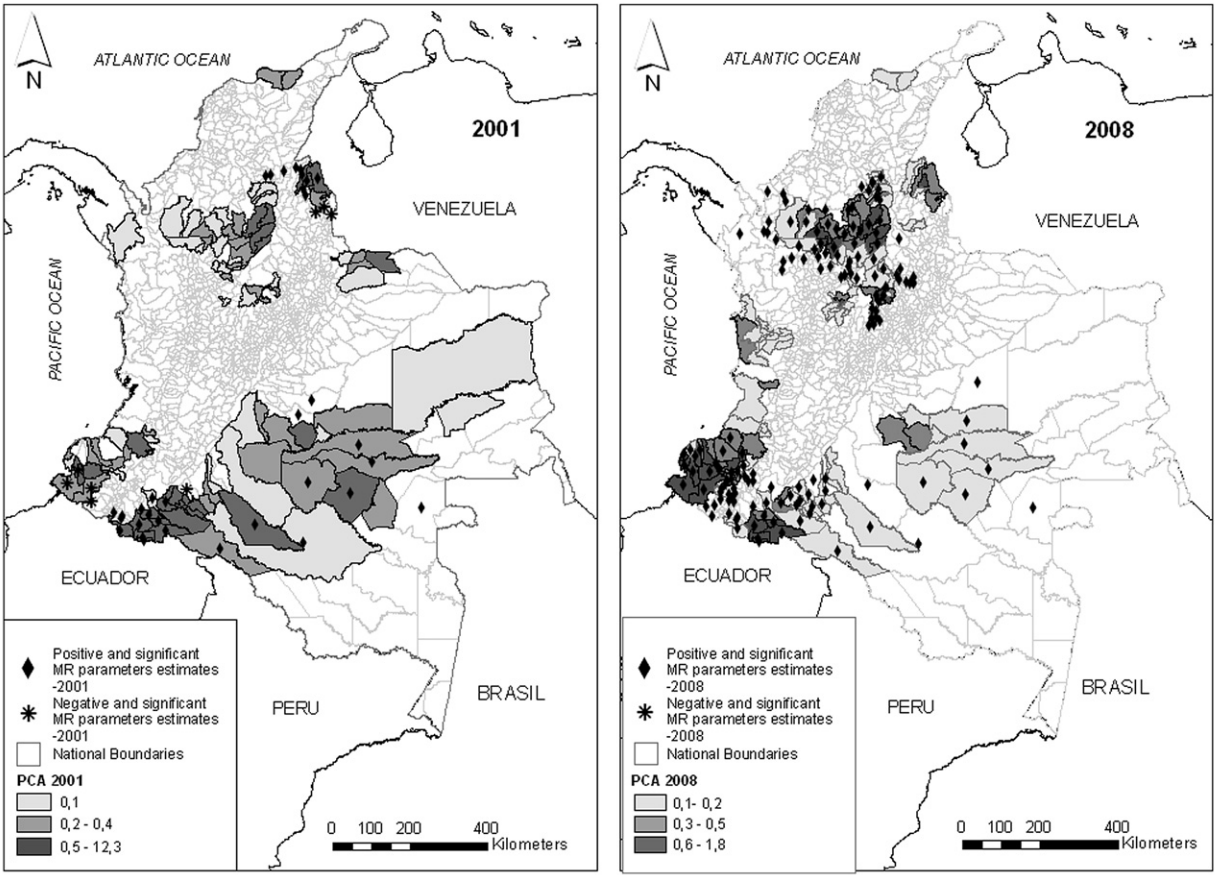
Map 2. GWR model/significant PPF parameter estimates vs PCA (2001–2008).



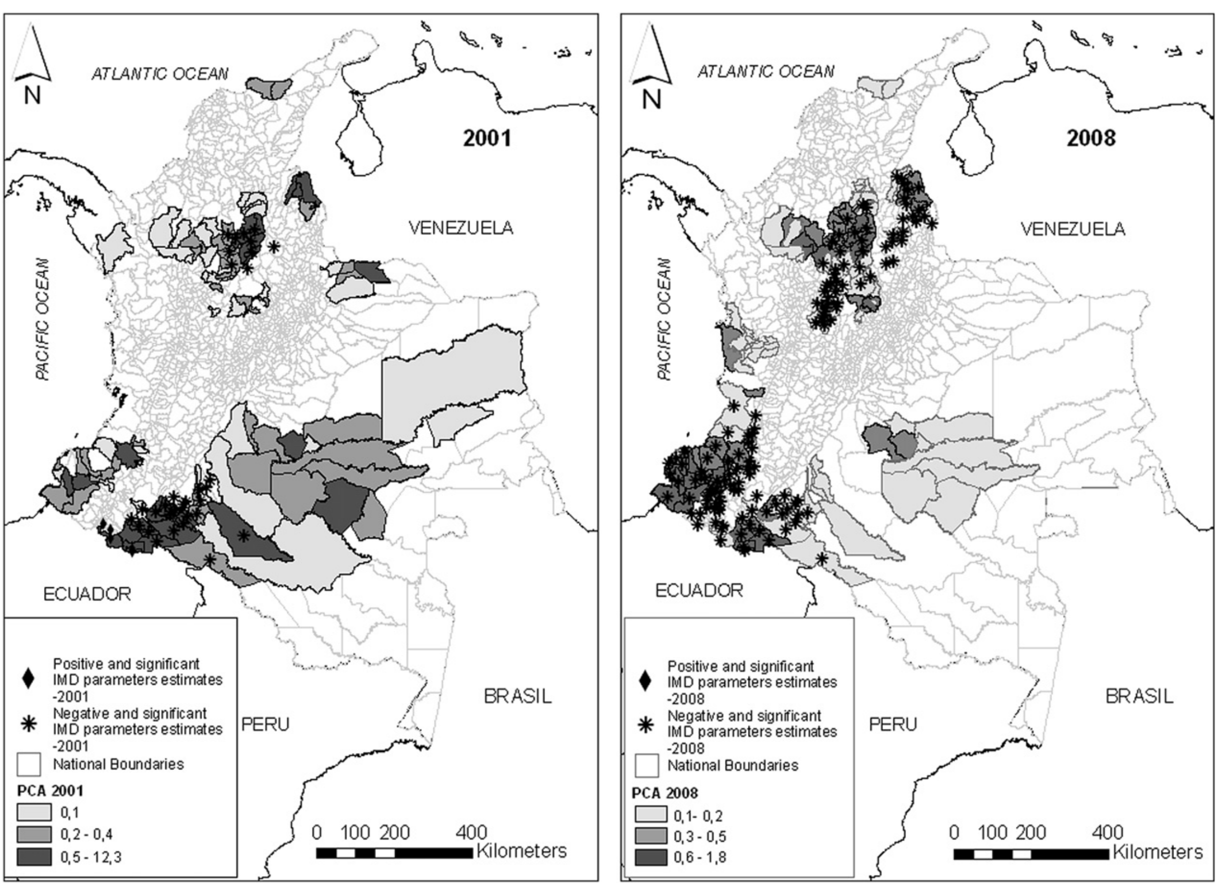
Map 3. GWR model/significant PRD parameter estimates vs PCA (2001–2008).



Map 4. GWR model/significant FDP parameter estimates vs PCA (2001–2008).



Map 5. GWR model/significant MR parameter estimates vs PCA (2001–2008).



Map 6. GWR model – significant IMD parameter estimates vs PCA (2001–2008).

Table 6
GWR model – significant relationships with PCA by region (2001–2008).

Acronym	Variable name	2001 (Significative relation with PCA by region)	2008 (Significative relations with PCA by region)
PRD	Primary roads density	Inverse relation in: south-central of the country (Putumayo and Caqueta)/southwest (Nariño and Cauca)/ North (a few municipalities in Bolivar)	Inverse relation in: south-central of the country (Putumayo and Caqueta)/southwest (Nariño and Cauca)/Norh (a few municipalities in Antioquia)
FDP	Forced displacement of population – expulsion	Positive relation in: south-central of the country (Putumayo and Caqueta)/North (Bolivar and Santander)	Positive relation in: south-central of the country (Putumayo and Caqueta)/southwest (Nariño and Cauca)/North (Bolivar and Santander)
IMD	Index of municipal development	Inverse relation in: south-central of the country (Putumayo and Caqueta)/North (Antioquia and Bolivar)	Inverse relation in: south-central of the country (Putumayo and Caqueta)/southwest (Nariño and Cauca)/North (Antioquia, Bolivar and Santander)
MR	Murder rate by illegal armed groups (used as proxy to presence of illegal armed groups),	Positive relation in: south-central of the country (Putumayo and Caqueta)/Southwest (a few municipalities in Nariño)/North (North of Santander)	Positive relation in: south-central of the country (Putumayo and Caqueta)/southwest (Nariño and Cauca)/North (Cordoba, Bolivar, Antioquia)
PPF	Percentage of the municipal territory in primary forest area (2000)	Inverse relation in: south-central of the country (Putumayo and Caqueta)	Inverse relation in: Southwest (Nariño and Cauca)/North (Cordoba, Antioquia, Norte de Santander and Bolivar)

north of the Andean region and was the only significant variable for 2001 in the municipalities in the de Meta and Guaviare departments (north of the Amazon region). For 2008, this positive significance included more areas of the country (the Pacific, Andean and Amazon regions). MR was a significant variable in most regions of the country in 2008 (Map 5).

IMD: The municipal development index was found to have an inverse and significant relationship with the dependent variable in both time periods. In 2001, this index was mainly significant in municipalities of the Amazon and the north of the Andean region; by 2008, there had been an expansion to the Pacific region (mainly in the south) and the Caribbean regions. This index shows a consistent pattern of significance with the municipalities with the highest percentages of coca area (see Map 6).

By performing an integrated analysis of the maps of significance for each variable described previously, it was observed that for 2001 all variables were significant in only the southwestern Amazon (Putumayo). This is not true for the other regions, as their estimated values significance was different according to the variable. By 2008 all the analyzed variables retain their significance in the department of Putumayo, but also prove to be significant in the rest of the south pacific region, such as the department of Nariño.

Maps 2–6 are summarized in Table 6. The analysis of the data suggests that in 2001, the percentage of forest area, forced displacement, homicides by illegal armed groups and municipal development were significant in Amazon region (Putumayo and Caqueta in particular) but not in the Pacific region (Nariño and Cauca). By contrast, road density was significant both in the Amazon and Pacific regions, e.g., Putumayo, Caqueta, Nariño and Cauca. In 2008, these significant relationships had expanded in both the Amazon and Pacific regions.

In the north of the country, the significance was more heterogeneous: in 2001, the municipal development index and forced displacement were significant in the departments of Antioquia and Bolivar and expanded to other municipalities in the north in 2008. The percentage of forest area variable was only significant in 2008 in the northern area. Road density was not generally significant in the north of the country (only in some municipalities). The homicides variable was not generally significant in 2001 in the north; only the North of Santander department showed a significant result. Nevertheless, in 2008, this variable was significant in several municipalities in the north, including the northwest (Antioquia, Cordoba, Bolivar and even Chocó).

For the department of Nariño, which had the highest growth in coca cultivation between 2001 and 2008, road density and homicides by illegal armed groups were the only significant variables in 2001. However, due to the expansion of coca crops toward this department during the 2000s, all of the other variables became significant in 2008.

Discussion

An important factor is the stationarity of the parameters. Stationarity was observed in the 2001 models, indicating that the local situation was similar to the global situation. However, by 2008, none of the relationships exhibited stationarity. The change from stationarity to non-stationarity between 2001 and 2008 can be explained as follows. At the beginning of the decade, and in previous periods, coca was concentrated in particular areas in the Amazon, particularly in the department of Putumayo (Aiken & Leigh, 1986). This concentration had long remained nearly unchanged, and hence the local situation coincided with the national reality. However, from 2000 to 2008, due to the extreme policy of spraying coca in the Amazon areas and especially in Putumayo, there was a displacement of illicit crops to different parts of the country, especially toward the Pacific and previously unaffected municipalities in the north. The changes generated new local realities, as the expansion of coca cultivation moved into new municipalities with similarly favorable conditions, such as low accessibility and high forest cover in the case of the south.

In 2002, there was only a significant and inverse relationship between forests and coca in the Amazon region (Putumayo department), while in 2008 a significant and positive relationship was found for almost all areas engaged in coca production. This change between 2001 and 2008 is interesting and merits discussion. Although abundant forest cover is initially an incentive for the expansion of coca crops, once the crops are established, they begin to exert substantial pressure on the forest. At the end of the 1990s, Putumayo represented approximately 40% of the total area under coca in Colombia (58,000 ha); in 2000, this figure had increased to 66,000 (UNODC, 2003), which is the reason for the considerable decline in forest cover by the year 2001. Therefore, an inverse relationship between forest and coca was found for this department in 2001. However, due to a fumigation policy that targeted Putumayo, illicit crops moved to other areas, and the areas affected by this expansion coincided with areas of high forest cover. Therefore, a direct relationship is observed between a high percentage of forest cover and coca area in 2008, while this relationship diminished significantly in Putumayo.

The municipal development indicator could be considered to be a key factor in explaining the presence of illicit crops, as it was found to be significant regardless of the region or year (see Map 6). Therefore, in the coca regions, which are characterized by low levels of this indicator, we are more likely to observe the emergence of and control by illegal armed groups and thus violence and displacement—variables which were found to be significant in 2008 (see Map 5). Low levels of IMD and the increase in the territory controlled by illegal armed groups (high levels of MR) caused the expansion and movement of illicit crops.

Violence and low road density, which could be considered indicators of forest conservation (Álvarez, 2001; Rincon et al., 2006), are ultimately factors that encourage the expansion of illicit crops and thus deforestation (see Maps 3 and 5). Therefore, a weak and absent state is considered to be an important factor in social conflicts that involve the control of natural resources (forest and rivers) for the expansion of illicit crops. Significant expansions of the analyzed variables can be observed throughout the country between 2001 and 2008: in 2001, only a few variables were significant and only for particular regions, mainly in the south. Factors such as poor accessibility, violence (murder by illegal armed groups), displacement, and lower municipal development were demonstrated to have greater explanatory power in the country in 2008.

Conclusions

This study examined the relationships between the expansion of coca crops and some of the social, institutional and biophysical factors identified in the literature, with a focus on local aspects.

Models that include local characteristics allow for an improved understanding of the factors associated with the expansion of illicit (coca) crops in Colombia. This study examined the relationships between the percentages of given areas under coca cultivation, with institutional and biophysical factors using GWR models. For Colombia, these results demonstrate the importance of considering the country's regional heterogeneity. This method of analysis allows for improved approximations of reality through the improved incorporation and understanding of specific local relationships.

The factors that are commonly associated with the expansion of coca crops cannot be generalized across the entire country. The relationships between coca crops and the associated factors that exist on global and local levels differ. In other words, the relationships are not constant across space (they are not stationary). Although stationarity was found in 2001, it had been replaced by non-stationarity by 2008. The local reality changed between 2001 and 2008: in 2001 the crops were concentrated in a few areas, and the global reality was similar to the local analysis as a result (stationarity). By 2008, the expansion of coca to other regions had led to the creation of multiple situations with differing characteristics, demonstrating how coca crops were associated with different features according to the region where they were located. Consequently, non-stationarity was observed, indicating that a global analysis could not reflect the complex local reality in 2008. The importance of using models that include the local reality becomes evident in our research. Only through the use of GWR models is it possible to analyze and understand the particular realities that must be taken into account to develop proper policy; failing to do so can lead to serious mistakes. General and OLS models generally identify global factors for an entire country, but many of these factors are not significant in all regions and may change over time. The GWR model revealed significant relationships between coca crops and the majority of the analyzed variables in both periods (2001 and 2008) and for specific variables and zones. This result is important with respect to drug policy, as it implies that specific local realities should be considered rather than applying general policies for the country as a whole.

The statistical results allow for the identification of regional differences in the variables influencing the cultivation of coca. Differences were found between the Amazon, Pacific, Caribbean and Andean regions. Additionally, significant differences were found with respect to the period being studied. For example, in the Pacific region (specifically the department of Nariño), which had the highest growth in coca cultivation between 2001 and 2008, road density and homicides by illegal armed groups were the only significant variables in 2001. However, with the expansion of coca in this department, all other variables had become significant by 2008. In general, we can state that the influence of biophysical, social, economic and institutional variables on coca cultivation in Colombia have changed over time.

GWR provided a valuable new exploratory methodology in identifying the most prominent drivers of coca crop expansion and assessing the heterogeneity of their impacts on a local scale. Local models provide a much better explanation for the existence of coca crops than the averages identified by global models. The results lead to the conclusion that drug policy must be tailored according to local realities rather than, as is currently the case, a general policy that exists for the entire country (Isacson & Poe, 2009; Rodriguez, 2009). Therefore, we argue that locally sensitive policies can be far more efficient than generalized initiatives.

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