Department of Economics- FEA/USP

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JÚLIA GALLEGO ZIERO UHR, ANDRÉ LUIS SQUARIZE CHAGAS, DANIEL DE ABREU PEREIRA UHR, RENAN PORN PERES

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A study on environmental infractions for Brazilian municipalities: a spatial dynamic panel approach

Júlia Gallego Ziero Uhr (zierouhr@gmail.com)

André Luis Squarize Chagas (achagas@usp.br)

Daniel de Abreu Pereira Uhr (daniel.uhr@gmail.com)

Renan Porn Peres (renanpperes@gmail.com)

Research Group: NEREUS

Abstract: This paper presents novel evidence for environmental offenses in Brazil. IBAMA's strategy to deter violations is based on large operations and on decapitalizing offenders to signal its will to monitor and enforce the law. We want to answer the following questions: Do the sanctions applied by IBAMA, especially sanction charges, deter actual and potential offenders? Are there any spatial or temporal patterns affecting violations? We use data on offenses against flora and applied fines for Brazilian municipalities between 1998-2015. We contribute to the existing research by providing evidence for Brazil and by incorporating spatial controls in a dynamic panel approach to explain infractions against the environment. We develop and apply a Spatial LIML estimator that accounts for the endogeneity of sanction charges to estimate our panel models. Results show that there is a *pedagogic deterrent effect* associated with applied fine values. Sanction charges are important to discourage new offenses.

Keywords: Environment; Violations; Deterrence; Pedagogic effect; Brazil.

JEL Codes: K32; K42; C23; C55

1. Introduction

Brazil is a continental country, therefore monitoring and enforcing are enormous challenges when it comes to environmental crimes. The Environmental Crimes Law (ECL), published in 1998, is a milestone in defense of the environment. It introduced the punishment system with specific sanctions for the offenders. Along with Federal Decree No. 6.514, published in 2008, they define environmental violations and possible penalties to criminals. The Brazilian Institute for the Environment and Renewable Natural Resources (IBAMA) is responsible for monitoring infractions and has the power to apply administrative sanctions. Since its creation, the institute's line of action has been guided by a national and worldwide concern: deforestation and other aggressions against Brazilian flora. IBAMA's annual management reports show not only the significance of technological advances in monitoring deforestation and other offenses but also the relevant role of sanctioning for deterring environmental crimes. For example, the reports mention the importance of on-site enforcement actions to the *continuous deterrence* of illegal practices and that IBAMA acts more effectively in emblematic perpetrators to deter other *potential offenders* (IBAMA 2008, 2009, 2010). A news report on the institute's website[1] says that "the strategy of operations focuses on large actions with a *pedagogic deterrent effect*, based on the decapitalization of offenders."

Is there data support for the claim that sanctioning transgressors change the future behavior of actual and potential offenders that are observing IBAMA's actions? Is there a spatial pattern in the distribution of violations? Is there a temporal pattern? If so, how do these patterns affect violations? To answer those questions, we use data on violations against flora[2] and applied fines (values), recorded by IBAMA, for all Brazilian municipalities[3] between 1998 and 2015[4]. Sanction charges have a significant role in Brazilian legislation since fines are applied individually or cumulatively to other sanctions, therefore being applied to all environmental violations[5]. It's important to note that the assembled dataset provides the resources for a broad study of environmental infractions and applied penalties at the municipal level, nationwide, and for future papers evaluating other relating aspects. No such study has been undertaken so far. We also contribute to the existing literature by incorporating spatial controls in a dynamic panel approach to explain infractions against the environment.

We apply a Spatial LIML Estimator that accounts for the potential endogeneity of sanction charges to estimate our models. Fine magnitudes are instrumented using variables suggested by the ECL as extenuating conditions for the penalty gradation: low income and low levels of education. We are interested in finding the direct (or specific) and indirect (spillover) effects to access IBAMA's claim that there *is pedagogic deterrent effect* in monitoring and enforcement actions affecting actual and potential offenders. Our main finding is that there is a *pedagogic deterrent effect* associated with fine values. Sanction charges imposed in the municipality of the infraction and in the neighborhood, are important to discourage new offenses. For the long run, fines above 33.7 thousand applied in one municipality are already sufficient to deter violations in the same municipality. Considering the indirect effects

[1] Available at <https://uc.socioambiental.org/noticia/acoes-de-fiscalizacao-do-IBAMA-e-de-parceiros-levam-a-queda-historica-de-desmatamento>

[2] Brazilian legislation defines various categories of environmental infractions (flora, fauna, pollution, etc.). We decided to work only with flora for two main reasons: it has the highest number of registered offenses, and it is highly related to deforestation, which is a major concern in Brazil. However, they are not limited to cases of deforestation, but also deal with situations such as trading or transporting chainsaws, coal, and other minerals without a license, make use of fire or cause fire in rural or forested area, manufacture, sell or release balloons that may cause fire in urban or rural areas, commercialize or maintain ornamental plants without a license.

[3] There are currently 5,564 municipalities in Brazil.

[4] Our data set initiated in 1998, the same year of the publication of the Brazilian Environmental Crimes Law.

[5] In Brazil, as for other countries, administrative penalties such as fines are far more common than civil or criminal prosecutions (Alm and Shimschak, 2014). However, we are working on separating the administrative offenses that are also prosecuted as environmental crimes to see the impact of the possibility of incarceration and other heavier penalties on violations.

(spillovers), the necessary fine values applied in the municipality and in the neighboring localities is of 22.6 thousand (general deterrence).

The research on regulation enforcement is well established. The theoretical foundation proposed by Becker (1968), and later generalized by Posner (1997), was applied by Russell et al. (1986) to pollution control. The first empirical studies focused on the available mechanisms of monitoring and enforcement to regulatory agencies (Magat and Viscusi, 1990; Laplante and Rilstone, 1996; Gray and Deily, 1996; Nadeau, 1997; Helland, 1998; Sigman, 1998; Viladrich-Grau and Groves, 1997). The literature advances in the study of the deterrent effects of sanctions and monitoring on formal and informal perspectives (Afsah et al., 1996, Dasgupta et al., 2000; Stafford, 2002; Stafford, 2003; Anton et al., 2004; Shimshack and Ward, 2005; Shimshack and Ward, 2008; Rousseau, 2008). Gray and Shadbegian (2007) use spatial analysis to study regulatory compliance. The authors find that compliance is positively spatially correlated, showing that regulatory activity has effects over inspected and neighboring plants in the same state. Almer and Goeschl (2010) studied the deterrent effect of criminal prosecution over environmental crimes in Germany. They find that public trials have a greater effect on the offense rate than the likelihood of conviction and the magnitude of fines. Gray and Shimshack (2011) review the empirical literature showing that there is sufficient evidence demonstrating how monitoring and enforcement generate not only specific deterrence at the targeted plant, but also substantial spillover effects (general deterrence) by reducing future violations at other firms. More recently, Earnhart and Friesen (2013), Aklin et al. (2014) and Sjöberg (2016) add other important aspects to the analysis: experiential deterrence, corruption as a cause of poor law, the role of local governments in the application of environmental laws.

Brazil has a recent and growing literature on the subject. De Oliveira (2002) discusses the importance of decentralization to implement environmental policies (mainly the creation of protected areas) presenting a case study for the state of Bahia. Assunção et al. (2013) evaluate the impact of monitoring and enforcement actions by IBAMA on Amazon deforestation. The authors use the number of fines as a proxy for command and control. They conclude that IBAMA had a major role in deterring deforestation: observed deforestation between 2007 and 2011 would have been 73% bigger in the absence of fines. Uhr and Uhr (2014) use data on environmental infractions against flora, but their dataset is for Brazilian states. Using fines as a proxy for regulators willingness to enforce the law, they find that sanction charges have a substantial deterrent effect over environmental violations: a value increase produces a specific effect, reducing infractions on the state in which it was applied, and a spillover effect, reducing offenses in neighboring states. Da Silva and Bernard (2016) argue that the Brazilian system for enforcing the environmental law is inefficient. Using data for wildlife infractions and payment of fines in the state of Pernambuco, they show that over a period of twelve years only 1% of fines were paid.

The remainder of this paper is organized as follows. We present the Brazilian environmental legislation, the monitoring procedure, and the enforcement process in the next section. Data and descriptive statistics are discussed in section three. Section four describes the applied methodology (Spatial LIML estimator) and the regression equation. Empirical results are discussed in section five. Final thoughts are presented under "Conclusions."

2. Brazilian Environmental Regulation[6]

2.1. Brazilian environmental legislation on environmental infractions

[6] A summary of the laws, decrees, and regulations commented in this section is available in Table IV, attached to the end of the paper. This section is based on Federal Legislation, so the same laws apply to all municipalities. For a historical overview of the Brazilian environmental legislation, we recommend reading Drummond and Barros-Platiau (2006).

Law No. 9.605/98, known as the "Environmental Crimes Law" (ECL), is considered the most significant political and legal advance in defense of Brazilian environmental resources, adding to other relevant legislation on environmental liability (Federal Constitution, Laws No. 4.771/65, 6.938/81, 7.735/89, 9.433/97, among others). Despite the name, the law is not restricted to establishing sanctions against environmental crimes but also addresses administrative offenses against the environment. The norm inaugurates the punishment system with specific penalties for the offenders and guides monitoring actions through different categories of environmental crimes.

In its 70th article, the ECL defines the concept of "administrative environmental infraction" as "*any act or omission that violates the legal rules of use, enjoyment, promotion, protection, and recovery of the environment*", this being a rather broad concept. Also, the law establishes in general terms the administrative procedure for investigating offenses and the applicable sanctions. The Federal Decrees No. 6.514/08 and No 6.686/08 regulate the types of environmental infractions and administrative penalties applicable to each particular case. The Decree No. 6.514/08 also deals with the federal regulatory process for investigating these violations in a more accurate way then the ECL.

The Federal Decree No. 6.514/08 has replaced Decree No. 3.179/99. The difference lies in the aggravation of the penalties imposed; the inclusion of aggravating circumstances such as repeated infringement by the offender in a shorter period than five years; the exclusion of a conduct adjustment term that could replace the payment of a fine; and the addition of new potentially harmful acts to the environment. Also, the Decree reduced the number of possible appeals, from four to two judging instances. The Decree No. 6.686/08 does not revoke the previous one, but changes and adds new legal devices, making the regulation more comprehensive and rigid.

The following categories of administrative violations against the environment are defined by the law: offenses against flora; fauna; relating to pollution; and other environmental infractions. Federal Decree No. 6.514/08 contains twenty articles defining administrative offenses against flora, such as: Destroying or damaging forests or other forms of natural vegetation in area considered as "permanent preservation site" without permission of the competent agency; Cut trees in permanent conservation area or whose species are specially protected without authorization; Cause direct or indirect damage to protected areas; Cause fire in woods or forest; Cut or turn hardwood into charcoal; Prevent or hinder the natural regeneration of forests or other forms of native vegetation in protected areas; Clearing forests or other native formations, outside the legal reserve, without authorization of the competent authority; Commercialize chainsaws without a license.

The legislation describes ten different administrative sanctions, such as warning; fine imposition; apprehension of products and by-products or any equipment; activities embargo and the restriction of civil rights. The inspection agent, when communicating the infraction, also indicates the appropriate sanctions to the transgressor. Is important to stress that fines can be issued with (cumulative penalties) or without other sanctions, therefore being applied to all infractions in every case. The values range from fifty to fifty million Reais (local currency), respecting the relevant unit of measurement for different types of infractions, maximum and minimum values as defined by the law for each violation, the severity of the offense, potential impacts on the health of neighboring populations, and the identification of the offender's economic capacity and level of education. At the time of the final judgment, after the legal process, the fine can be increased or lessened by 50% depending on aggravating or mitigating circumstances predicted by Decrees No. 6.514/08 and No. 6.686/08 and IBAMA normative instructions IN No. 08/03, IN No. 14/09 and IN No. 10/12.

2.2. The administrative process for monitoring and enforcement of environmental violations

2.2.1. Who's responsible?

IBAMA was created in 1989 by Federal Law No. 7.735. It's linked to the Ministry of Environment (MMA), integrating the National Environmental System (SISNAMA). The institute is responsible for exercising the power of environmental police, performing actions related to surveillance, environmental monitoring, and control, exercising the role of judging authority and the application of administrative sanctions (Law No. 11.516/07, IN offenses No. 10/12). Also, the agency can propose and edit environmental quality norms and standards and establish criteria for managing the use of natural resources through the country. To achieve its objectives, the Institute works in conjunction with other agencies and entities of public administration that are members of SISNAMA, in federal, state and municipal levels.

2.2.2. Monitoring Actions

IBAMA has units in all 27 Brazilian states and the Federal District. Until the 1990s investigation activities were carried out according to complaints and were focused on emergencies such as fires and deforestation, mainly in the Amazon and Pantanal regions. Nowadays, inspections are planned in advance and directed by the use of new technologies such as remote sensing, satellite images, and geo-referenced location, acting throughout the country. After the publication of Decree No. 6.514/08, Annual Management Reports (IBAMA 2008, 2009, 2010) show that the Institute changed its deterrence methodology. Instead of pulverized actions, monitoring operations became larger and focused on "major violators" and critical locations, resulting in fewer inspections, but with higher penalties with the aim of decapitalizing criminals and deterring other potential offenders trough a "pedagogic effect"'.

The agency carries out efforts to investigate actions that might cause pollution or environmental degradation, attacks on fauna and flora, biopiracy and illegal acts in fishing activities. The Institute also performs inspections requested by the Brazilian Public Ministry or through anonymous complaints, with the participation of the civil society.

2.2.3. The law enforcement process

The procedure for investigating infractions and imposing penalties are both defined by IBAMA IN No 10/12. Verified the violation, a notice of infraction is issued and administrative sanctions are applied following the legislation. In this investigation phase, the assessed is given the possibility of defense within 20 days, counted from the date he became aware of the notification. IBAMA has an obligation to inform the Public Ministry if the violator's conduct also configures environmental crime. In that case, alongside the administrative investigation, it will take place the criminal prosecution of the environmental crime, carried out by the Public Ministry. After the defense, IBAMA will proceed with the trial and the offender may appeal within 20 days. Once the notice of infraction is approved, then the enforcement stage begins. At this point, the offender is intimated to pay the fine assigned to him at the time of assessment, the value is increased or reduced by mitigating or aggravating circumstances if any. Recent technological advances are making possible for IBAMA to track all current and past notifications, so the efficiency of the Institute in enforcing the law is increasing, as can be seen by the higher rates of collected fines (IBAMA, 2010). In addition to exercising the power of police and judging authority, IBAMA has an obligation to disseminate environmental legislation and promote educational activities with the aim of reducing violations.

3. Data

All data used in this study came from open sources. Brazilian Access to Information Law guarantees easy access to public interest information produced by government agencies, ensuring mandatory disclosure of data relating to infractions and their penalties imposed by environmental agencies. Data for violations are related to administrative offenses against Flora, between 1998 and 2015. For penalties imposed, we use fine values applied to each infraction[7]. This data is available at IBAMA's website[8].

The database contains violations with fines varying between 50 R$ and 50 million R$, which are the minimum and maximum values as defined by the ECL. To separate the milder cases from those of greater harm to the environment, we classify the offenses into three categories: warnings, infractions, and outliers. The Decree 6.514/08 defines as a warning those administrative infractions that are less harmful to the environment, with a maximum fine not exceeding 1,000R$. We consider as infractions those cases with fines varying between more than 1,000R$ and less than or equal to 2.5 million R$. Outliers are the remaining violations (fines up to 50 million R$)[9]. All this information was grouped at the municipal level for the full set of Brazilian cities[10]. We chose to work only with flora because this category has the largest number of violations in every year of the dataset[11]. Also, there is a clear link between flora infractions and deforestation[12].

Figures 1 to 6 show the distribution of offenses in percentiles for the Brazilian territory (municipalities) and the values of sanction charges for the whole period (aggregated data for 1998 to 2015) separated by violation category (warnings, infractions, and outliers). Figure 7, at the end of this paper, displays violations and individual fine trends for the studied period.

IBAMA records show that the municipalities with the largest number of annual infractions are in the central-west and northern regions of Brazil, mainly in the states that border or are part of the region called Deforestation Arc[13]. Regarding the values of imposed fines, municipalities in the states of Pará (PA), Amazonas (AM), Maranhão (MA) and Mato Grosso (MT) lead the highest positions. It is important to note that there is a significant number of cities, 818 in total, that did not record any assessment or fine from IBAMA over the 18 years studied. In fact, the average number of municipalities per year that registered notifications is 1,658, for a total of 5,482. Therefore, there is a significant number of zeros in the dataset for every year[14]. Another 1,556 cities were assessed only once or twice during the period.

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[7] It's important to stress that fines can be issued with (cumulative penalties) or without other sanctions, therefore being applied to all infractions in every case. The inspection agent, when communicating the infraction, also indicates the appropriate sanctions to the transgressor. The fine gradation must respect the relevant unit of measurement for different types of infractions, maximum and minimum values as defined by the law and decrees for each type of violation, the severity of the offense, potential impacts on the health of neighboring populations, and the identification of the offender's economic capacity and level of education, among other minor factors.

[8] Crude data contains information about the violator (if physical or legal persons, if public or private firms), the year and municipality of the infraction, the magnitude of the applied fine, the status of the payment, and the legal basis of assessment. We are working on separating public and private companies from individual violators, analyzing recidivism, and on categorizing the offenses that also gave rise to criminal proceedings.

[9] We apply these definitions for the entire period. We deflate fine values for the year 2015 and then apply the listed criteria to classify offenses in warnings, infractions, or outliers for each year of the dataset. Warnings represent 27% of the cases, infractions 72,2%, and outliers 0,8%.

[10] The information provided by IBAMA contained some issues that had to be addressed by the authors, such as duplication of records, fines with lower values than allowed by law, and errors in the description of the municipalities where the violations took place. During the studied period, some municipalities were divided, creating new localities. To avoid potential caveats, we had to adapt the database to only consider the existing municipalities in 1997. Working with Brazilian minimum comparable areas (MCA) is a standard procedure for the spatial econometrics literature. A MCA is a municipality or aggregation of municipalities necessary to enable consistent spatial analyses over time (Da Silva *et al.,* 2016).

[11] There are 190,921 reported cases up to 2012, against 78,432 fauna infractions, the second major category of violations.

[12] The are several published studies on deforestation for Brazil, amongst them: Chomitz and Thomas (2003), Margulis (2003), Oliveira et al (2011), Pfaff (1999), Pfaff et al (2007).

[13] This area is composed of 248 municipalities and extends from Rondônia (RO) to Maranhão (MA).

[14] Because of that we include a quadratic term for fines in the regressions.

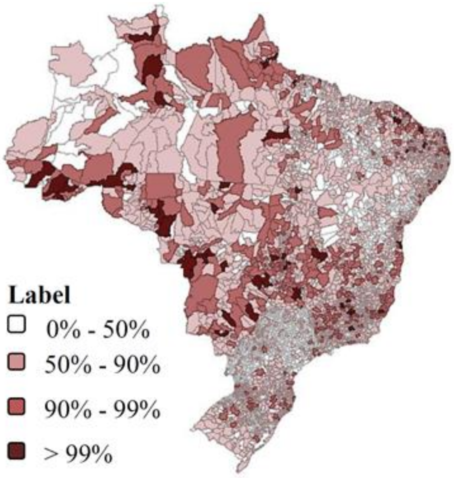

Figure 1 – Percentile map for Warnings

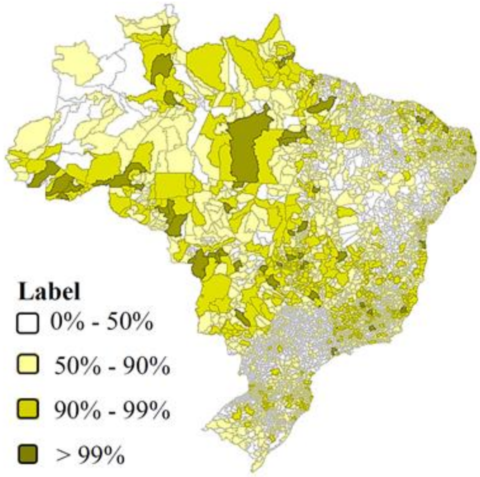

Figure 2 – Percentile map for Values Warn.

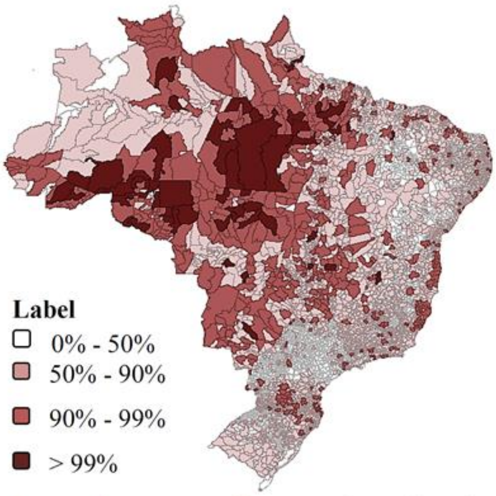

Figure 3 – Percentile map for Infractions

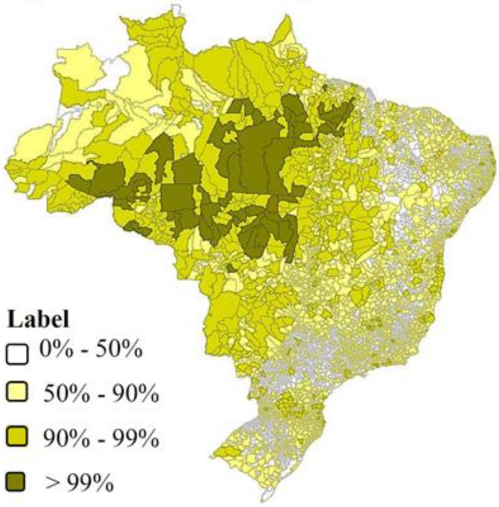

Figure 4 – Percentile map for Values Infr.

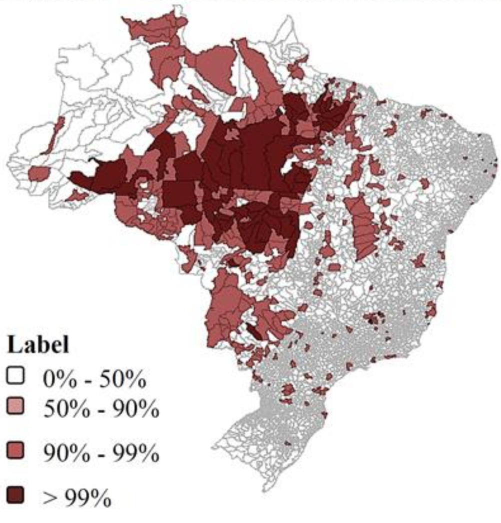

Figure 5 – Percentile map for Outliers

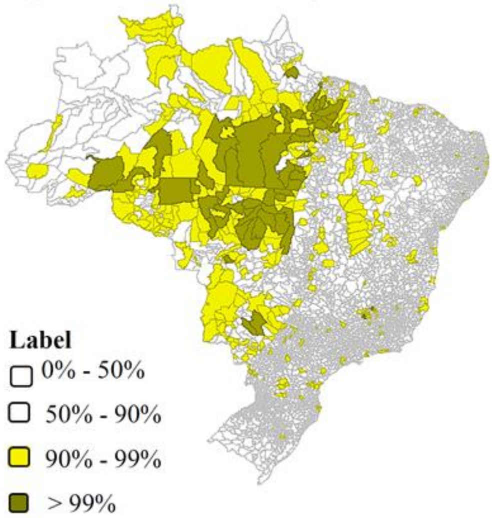

Figure 6 – Percentile map for Values Outl.

The other variables in the dataset are related to municipal agricultural and pastoral production (rice, sugar cane, cattle, coal extraction) available for the entire period, GDP in added value for the agricultural, industrial, and service sectors, available up to 2014, and local population, available for the 1998-2015 period (including projections for the latter years). Data for these socioeconomic variables can be downloaded at the Brazilian Institute of Geography and Statistics (IBGE)[15].

Fine magnitudes are instrumented using variables suggested by the Environmental Crimes Law (Law 9.605/98) as extenuating conditions for the penalty gradation: low income and low levels of education. These variables were obtained at RAIS (Annual Report of Social Information)[16] and refer to the number of workers in the municipality who did not reach the fifth grade of basic education, including illiterates and lower levels of education, and the number of workers in the municipality receiving up to two minimum wages (MW) as monthly income.

Table I presents the variables description and descriptive statistics for the dataset in a panel structure.

Table I - Descriptive Statistics

Variable	Description	mean	sd	max	min
Dependent Variables[a]					
Warnings	Number of assessments with fine values ≤ R$ 1,000	0.288	2.449	252	0
Infractions	Number of assessments with R$1,000 <fine values ≤ R$ 2,5mi	1.813	9.892	763	0
Outliers	Number of assessments with R$ 2,5mi<fine values ≤ R$ 50 mi	0.025	0.402	38	0
Total offenses	Total number of assessments	2.127	11.107	945	0
Sanction Charges[a] (R$)					
Value Warn.	Imposed fines for warnings	162.99	1,267	147,696	0
Value Infrac.	Imposed fines for infractions	151,234	1,6mi	125m	0
Value Outl.	Imposed fines for outliers	237,855	5,2mi	560mi	0
Value Total	Total value of imposed fines	389,251	6,0mi	567mi	0
Controls					
Population	Resident population	33,732	200,164	12mi	724
Rice	Ha. of rice production	554.20	2,885	91,229	0
Sugar Cane	Ha. of sugar cane production	1,336	4,965	114,000	0
Cattle	Cattle livestock	35,996	83,119	2,3mi	0
Coal Extract.	Coal extraction in metric tons.	312.13	3,924	506,888	0
Agro. GDP[ab]	Gross value added of agriculture	24,787	47,492	1,7mi	0
Ind. GDP[ab]	Gross value added of industry	120,99	1,0mi	67mi	-2,9mi
Serv. GDP[ab]	Gross value added of services	268,29	3,8mi	411mi	1,194
Instruments (rates per 100,000 workers)					
Low Income	Workers earning up to 2 MW	69,854	17,975	100,000	0
Low Education	Workers with 4th grade or lower	21,834	15,351	100,000	0

Notes: [a]calculated using 2015 prices/deflated to 2015, [b] Values per 1,000R$. Statistics calculated at the municipal level in panel structure.

4. Method

The standard dynamic spatial panel methodology does not cope with spatial dependence. However, models can be extended to incorporate these effects. One advantage of

[15] <http://seriesestatisticas.ibge.gov.br/>
[16] <http://www.rais.gov.br/sitio/shows.index.jsf>

the panel approach is that it deals with many aspects of spatial heterogeneity as well (Anselin et al., 2008). Our empirical strategy is to use a "time-space dynamic model", as called by Anselin (2001), or more generally, a Spatial Dynamic Panel Data (SDPD) model (Lee and Yu, 2010a) including both spatial, dynamic, and spatial-time effects to investigate the patterns of dependence on environmental violations at municipal level. We want to capture the direct and indirect effects to access IBAMA's claim that there is pedagogic deterrent effect in monitoring and enforcement actions affecting actual and potential offenders.

4.1. The Spatial Limited Information Maximum Likelihood (LIML) Estimator[17]:

Consider the model

$$y_{nt} = \rho W_n y_{nt} + \tau y_{nt-1} + \eta W_n y_{nt-1} + Y_{1nt}\gamma + X_{2nt}\beta + \epsilon_{nt} \tag{1}$$

with

$$Y_{1nt} = X_{1nt}\Pi_1 + \Pi_2 y_{nt-1} + \Pi_3 W_n y_{nt-1} + X_{2nt}\Pi_4 + U_{nt} \tag{2}$$

Consider that Y_{1nt} is potentially correlated with ϵ_{nt}. X_{1nt} is a set of instrumental variables that directly affect Y_{1nt} and X_{2nt} is a set of regressors that impact the endogenous variables y_{nt} and Y_{1nt}. It is assumed that the errors U_{nt} are independent and identically distributed (iid) so that $E(U_{nt}) = 0$ and $E(U_{nt}'U_{nt}) = \Sigma_u$. The correlation between Y_{1nt} and ϵ_{nt} is captured by $E(U_{nt}'\epsilon_{nt}) = \sigma_{u\epsilon}$.

Let's define $S(\rho) = I_{nt} - \rho W_{nt}$, $Y_{nt}(\rho) = [S(\rho)y_{nt},\ Y_{1nt}]$ and $\Gamma = \begin{bmatrix} 1 & 0 \\ -\gamma & I_g \end{bmatrix}$. So, the model can be written in its short form as $Y_{nt}(\rho)\Gamma = Z_{nt}B + V_{nt}$, where $Z_{nt} = [X_{1nt}, y_{nt-1}, Wy_{nt-1}, X_{2nt}]$, $B = \begin{bmatrix} 0 & \Pi_1 \\ \tau & \Pi_2 \\ \eta & \Pi_3 \\ \beta & \Pi_4 \end{bmatrix}$ and $V_{nt} = [\epsilon_{nt}, U_{nt}]$.

Assuming that the joint distribution of errors is normal, then the density of $V_{nt,i}$ is given by $(2\pi)^{-(g+1)/2}|\Sigma|^{-1/2}\exp(-\frac{1}{2}V_{nt,i}\Sigma^{-1}V_{nt,i})$, where $\Sigma = \begin{bmatrix} \sigma_\epsilon^2 & * \\ \sigma_{u\epsilon} & \Sigma_u \end{bmatrix}$. The Jacobian of the transformation of V_{nt} into $[y_{nt},\ Y_{1nt}]$ is $\begin{vmatrix} S_{nt}'(\rho) & \gamma'\otimes I_{nt} \\ 0_{ntg\times nt} & I_{ntg} \end{vmatrix} = |S_{nt}(\rho)|$.

Therefore, the log likelihood function of this model is given by

$$\begin{aligned} \mathcal{L}(\theta, \Pi, \Sigma) = &-\frac{n(g+1)}{2}\ln(2\pi) + \ln|S_{nt}(\rho)| - \frac{n}{2}\ln|\Sigma| \\ &-\frac{1}{2}\sum_i \left[Y_{nt,i}\Gamma - Z_{nt,i}B\right]\Sigma^{-1}\left[Y_{nt,i}\Gamma - Z_{nt,i}B\right]' \end{aligned} \tag{3}$$

where $\theta = [\rho,\ \tau, \eta, \beta]$.

It is convenient to concentrate the log-likelihood function with respect to Σ^{-1}, as suggested by Davidson and MacKinnon (1993). As $\frac{\partial\mathcal{L}}{\partial\Sigma^{-1}} = \frac{n}{2}\sigma - \frac{1}{2}[Y_{nt}\Gamma - \mathrm{Z_{nt}}B]'[Y_{nt}\Gamma - \mathrm{Z_{nt}}B]$, then we have that $\Sigma = \frac{1}{n}[Y_{nt}\Gamma - \mathrm{Z_{nt}}B]'[Y_{nt}\Gamma - \mathrm{Z_{nt}}B]'$. The concentrate log-likelihood function become

$$\begin{aligned} \mathcal{L}(\theta, \Pi) &= c + \ln|S_{nt}(\rho)| - \frac{n}{2}\ln\left|\frac{1}{n}[Y_{nt}\Gamma - \mathrm{Z_{nt}}B]'[Y_{nt}\Gamma - \mathrm{Z_{nt}}B]\right| \\ &= c + \ln|S_{nt}(\rho)| - \frac{n}{2}\ln|V_{nt}'V_{nt}| \end{aligned} \tag{4}$$

where c is a constant.

Consider now the following representation of equation (1)

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[17] Liu (2012) derives the LIML estimator for a spatial autoregressive model with endogenous regressors. We extend that to the panel case.

$$y_{nt} - \rho W_n y_{nt} = \tau y_{nt-1} + \eta W_n y_{nt-1} + Y_{1nt}\gamma + X_{2nt}\beta + \epsilon_{nt}$$
$$= z_{nt} b' + \epsilon_{nt}$$
where $z_{nt} = [y_{nt-1}, W y_{nt-1}, X_{2nt}, Y_{1nt}]$ and $b = [\tau, \eta, \beta, \gamma]'$. Applying a Cochrane-Orcut transformation to this equation we obtain
$$y_{nt} - \rho W_n y_{nt} = z_{nt}(z'_{nt} z_{nt})^{-1} z'_{nt}(y_{nt} - \rho W_n y_{nt}) + \epsilon_{nt}$$
and then, we can express ϵ_{nt} as the sum of the two terms,
$$\epsilon_{nt} = \epsilon_{nt}^{0} - \rho \epsilon_{nt}^{L} \tag{5}$$
where $\epsilon_{nt}^{0} = y_{nt} - z_{nt}(z'_{nt} z_{nt})^{-1} z'_{nt} y_{nt}$ and $\epsilon_{nt}^{L} = W y_{nt} - z_{nt}(z'_{nt} z_{nt})^{-1} z'_{nt} W y_{nt}$.

Substituting (5) and V_{nt} we have
$$V_{nt} = [\epsilon_{nt}^{0} \;\; \epsilon_{nt}^{L}, U_{nt} \;\; 0_{nt}][1 \;\; -\rho]'$$
Consequently, we can write
$$|V'_{nt} V_{nt}| = \begin{vmatrix} \epsilon_{nt}^{0\prime} \epsilon_{nt}^{0} - \rho \epsilon_{nt}^{0\prime} \epsilon_{nt}^{L} - \rho \epsilon_{nt}^{0} \epsilon_{nt}^{L\prime} + \rho^2 \epsilon_{nt}^{L\prime} \epsilon_{nt}^{L} & (\epsilon_{nt}^{0} - \rho \epsilon_{nt}^{0})' U_{nt} \\ U'_{nt}(\epsilon_{nt}^{0} - \rho \epsilon_{nt}^{0}) & U'_{nt} U_{nt} \end{vmatrix}$$
Finally, we can rewrite the log-likelihood (4) as
$$\mathcal{L}(\rho) = c + \ln|S_{nt}(\rho)| - \frac{n}{2} \ln s(\rho, b) \tag{6}$$
where $s(\rho, b) = (\epsilon_{nt}^{0\prime} \epsilon_{nt}^{0} - \rho \epsilon_{nt}^{0\prime} \epsilon_{nt}^{L} - \rho \epsilon_{nt}^{0} \epsilon_{nt}^{L\prime} + \rho^2 \epsilon_{nt}^{L\prime} \epsilon_{nt}^{L}) U'_{nt} U_{nt} - 2 \times U'_{nt}(\epsilon_{nt}^{0} - \rho \epsilon_{nt}^{0})$.

This function can be maximized as a usual spatial model, employing the 2SLS as start point to calculate ϵ_{nt}^{0} and ϵ_{nt}^{L}. To avoid efficiency questions, sensitive in LIML context, we employed the bias correction suggested by Yu et al. (2012).

4.2. Regression Equation

We estimate the following regression for each category of offenses:
$$y_{nt} = \alpha + \rho W_n y_{nt} + \tau y_{nt-1} + \eta W_n y_{nt-1} + \gamma_1 F_{nt} + \gamma_2 W_n F_{nt} + \gamma_3 F_{nt}^2 + \gamma_4 W_n F_{nt}^2 + X_{2nt}\beta_1 + W_n X_{2nt}\beta_2 + \varepsilon_{nt} \tag{7}$$
for $n = 5{,}482$ (Brazilian municipalities); $t = 1998, \dots, 2015$ (years); y_{nt} is the logarithm of the offense rate per 100 thousand inhabitants for a given location and year; F_{nt} is the natural logarithm of total value of imposed fines for a given location; X_{2nt} represents control variables (all in natural logarithm); W_n is the spatial weights matrix[18], α is the constant, and ε_{nt} is the error term. The set of parameters to be estimated is given by $(\alpha, \rho, \tau, \eta, \gamma_1, \gamma_2, \gamma_3, \gamma_4, \beta_1, \beta_2)$. Fines are instrumented using the Low-income and Low education variables (and their spatial lags) discussed earlier. We included quadratic terms for fines due to the expressive number of municipalities without registered violations in each period.

In equation (7) the value of the dependent variable (violations) for one location is jointly determined with that of the neighboring municipalities. Therefore, $W_n y_{nt}$ is the weighted average of the neighboring observations, with weights defined by W_n; $W_n y_{nt-1}$ is the weighted average of the neighboring observations one year prior; and y_{nt-1} is the number of violations in the same location is the previous year. The coefficients ρ, τ, η, represent the pure spatial effect, the spatial-time effect, and the pure dynamic effect, respectively.

5. Results and Discussion

Results for the spatial dynamic model, not considering the endogeneity of fines, are shown in Table II and are separated by violation category (warnings, infractions, and all offenses). The coefficients in Table II are estimated using dynamic spatial panel techniques, controlling for spatial and time-specific effects (Yu et al.,2008; Yu et al., 2012; Lee and Yu,

[18] The size of the spatial weights matrix was chosen using the Akaike criterion for data adjustment (Stakhovych and Bijmolt, 2009). The best fit was obtained with a matrix q = 5 nearest neighbors. Anyway, we tested changing the matrix to q= 15, 20 and 25 and the estimated coefficients did not alter significantly.

2010b[19]). Results for the Spatial LIML Estimator are presented in Table III also separated by violation category (warnings, infractions, and all offenses). The classic LM tests and the robust LM tests for choosing between lagged or error specifications in all estimations in Tables II and III point that the hypotheses of no spatially lagged dependent variable and no spatially autocorrelated error term are both rejected. However, the Robust LM tests indicate for all estimations in Tables II and III that the spatial lag specification is preferred to the spatial error model, since the calculated values are slightly smaller for the no spatial lag hypothesis. Ignoring spatial dependence in the disturbances might lead to a loss of efficiency, but the cost of ignoring spatial dependence in the dependent variable is high since the estimator of the coefficients for the remaining variables will be biased and inconsistent (LeSage and Pace, 2009; Greene, 2005).

Table II – Results for the Spatial Dynamic Model

	Warnings	Infractions	All Violations
Time lag (y_{nt-1})	0.029243***	0.034970***	0.042539***
Spatial time lag ($W_n y_{nt-1}$)	0.005912**	0.018367***	0.005921**
Fines (F_{nt})	0.771677***	0.450404***	0.524978***
Square fines (F_{nt}^2)	-0.060910***	-0.018553***	-0.024494***
Neighbors' fines ($W_n F_{nt}$)	-0.096080***	-0.088208***	-0.10057 ***
Neighbors' square fines ($W_n F_{nt}^2$)	0.002365	0.003921***	0.003600***
Spatial lag ($W_n y_{nt}$)	0.357835***	0.299750***	0.363772***
R^2 (overall)	0.7392	0.7998	0.7800
Log Likelihood	-291794.43	-229706.81	-369746
Akaike	100.9233	80.0351	128.2811
LM test no spatial lag	274.12***	24993.14***	45270.94***
Robust LM no spatial lag	2743474.5***	2285565.71***	5309068.54***
LM test no spatial error	107053.87***	89479.93***	140433.47***
Robust LM no spatial error	2850254.3***	2350052.50***	5404231.07***
Observations	87.712	87.712	87.712

Notes: Control variables are Population, Rice, Sugar Cane, Cattle, Coal Extraction, Agro. GDP, Ind. GDP, Serv. GDP, and their spatial lags. Regressions include a constant, time fixed effects, and space fixed effect. Levels of significance: ***1%, **5%, *10%.

The estimated coefficients for the pure spatial effect ($W_n y_{nt}$), the spatial-time effect ($W_n y_{nt-1}$), and the pure dynamic effect (y_{nt-1}) in Tables II and III are all positive and significant across specifications, with combined values less than one (not explosive). They indicate the existence of time and space dependence for violations in all categories. Municipalities with more offenses in the past or that are surrounded by other municipalities with a high number of violations tend to present a higher number of assessments. That might indicate that some regions are more propitious for environmental offenses than others and that, because of it, IBAMA focuses continuously on the same locations in a process called *Regulator Targeting.* As

[19] Lee and Yu (2010b) develop a bias-corrected maximum likelihood estimator for the dynamic spatial panel specification with time-period fixed effects.

pointed by Alm and Shimshack (2014), *Regulator Targeting* might build in a potentially misleading positive correlation between environmental violations and IBAMA actions, suggesting that assessments might be less effective than they really are. That is possibly why we observe positive signs instead of negative signs for these variables.

The coefficient for Fines (F_{nt}) is also positive and significant for all models in both estimation procedures, but the quadratic term (F_{nt}^2) is negative indicating the existence of an inflection point. As pointed before, we included a quadratic term due to the expressive number of municipalities without registered violations in each period. In a linear regression, this large number of zeros can pull the regression line down towards it, mixing up the interpretation about the effectiveness of sanction charges. With the quadratic term, we still consider those cases with zero offenses, but we can capture fine impacts more clearly. On the other way, fines applied in neighboring municipalities (W_nF_{nt}) have a negative signal, with a positive quadratic effect ($W_nF_{nt}^2$). However, these coefficients cannot be interpreted directly, because they do not represent the partial derivatives (LeSage and Pace, 2009). To do that we must calculate the direct (own-economy) and indirect effects (spillovers) as suggested by LeSage and Pace (2009). Direct, indirect, and total effects are presented in Table IV for the short-run and long-run (Elhorst, 2012) and were calculated for the Spatial Dynamic Model with endogeneity only.

Table III – Results for the Spatial Dynamic Model with Endogeneity (SLIML Estimator)

	Warnings	Infractions	All Violations
Time lag (y_{nt-1})	0.027987***	0.034461***	0.041713***
Spatial time lag (W_ny_{nt-1})	0.004653*	0.016672***	0.004643*
Fines (F_{nt})	0.795785***	0.464668***	0.548639***
Square fines (F_{nt}^2)	-0.062872***	-0.019403***	-0.026240***
Neighbors' fines (W_nF_{nt})	-0.103943***	-0.092236***	-0.105661***
Neighbors' square fines ($W_nF_{nt}^2$)	0.003220*	0.004229***	0.004149***
Spatial lag (W_ny_{nt})	0.349831***	0.294758 ***	0.353774***
R^2 (overall)	0.7371	0.8002	0.7808
Log Likelihood	2083745.8	1695662.9	1595747.3
Akaike	-759.2350	-617.6506	-581.1983
LM test no spatial lag	109.3325***	20897.43***	40666.20***
Robust LM no spatial lag	2618040.5***	2147774.83***	4910717.01***
LM test no spatial error	103430.38***	85855.17***	134076.47***
Robust LM no spatial error	2721361.5***	2212732.58***	5004127.28***
Observations	87.712	87.712	87.712

Notes: Control variables are Population, Rice, Sugar Cane, Cattle, Coal Extraction, Agro. GDP, Ind. GDP, Serv. GDP, and their spatial lags. Regressions include a constant, time fixed effects, and space fixed effect. Instrument variables are Low Income, Low Education, and their spatial lags. Levels of significance: ***1%, **5%, *10%.

The calculated direct, indirect, and total effects have different magnitudes depending on the category of offense. For Fines, all three effects are positive and significative for all categories of violation in the short and long-run. For the quadratic term, all three effects are negative and significative. So, specific deterrence (direct effect), spillovers (indirect effect), and general deterrence (total effect) all obey an inverted U pattern, indicating the existence of an inflection point after which increases in sanction charges have a negative impact on violations at the same municipality and on neighboring locations. In Table V we present the maximum values for fines, also calculated for the Spatial Dynamic Model with endogeneity for the short and long-run.

For warnings, amounts totaling more than 540 Reais are sufficient to discourage new violations in the same municipality where the fines were imposed (direct effect). Regarding neighbors (indirect effect), even fines totaling low values (around 110 Reais) are enough to discourage further offenses. Perhaps because these are less harmful violations with lower financial returns, only the observation that IBAMA is monitoring offenders (even with low penalties) is enough to deter potential offenders. Considering both effects, inflection values calculated for specific deterrence are overestimated for the short and long terms in comparison to general deterrence values. When we consider spillover effects, the necessary value in applied fines to restrain warnings at the municipal level is reduced by 39%, to 330 Reais (total effect).

For infractions, inflection values suggest that offenders observe (or consider) only high magnitudes of sanctions charges being applied in neighboring municipalities. For the short-run, IBAMA must apply fines totaling more than 3,2 million in neighboring localities to discourage new infractions. Considering the long-run, when the environmental authority's reputation in applying big fines is considered, the inflection value is reduced to around 1,4 million in fines. If sanction charges are too small, they are either not observed (IBAMA's actions aren't known) or aren't big enough to discourage offenders (they are known, but not intense enough). If we only consider specific deterrence, inflection values for infractions are underestimated. The necessary value in applied fines to restrain infractions at the municipal level is around 213 thousand, 33% higher than the calculated value for the direct effect.

Table IV – Short-term and Long-term Direct and Indirect Effects

	Short-term Effects			Long-term Effects		
Warnings	*Direct*	*Indirect*	*Total*	*Direct*	*Indirect*	*Total*
Fines	0.807837	0.25626	1.0641	0.83266	0.28768	1.12034
Square Fines	-0.06417	-0.0276	-0.0918	-0.06616	-0.03044	-0.0965
Infractions	*Direct*	*Indirect*	*Total*	*Direct*	*Indirect*	*Total*
Fines	0.46716	0.06092	0.52809	0.48498	0.08439	0.56937
Square Fines	-0.01949	-0.0020	-0.0215	-0.02023	-0.00297	-0.02311
All Violations	*Direct*	*Indirect*	*Total*	*Direct*	*Indirect*	*Total*
Fines	0.55483	0.13065	0.68549	0.580341	0.15812	0.73846
Square Fines	-0.02660	-0.0076	-0.0342	-0.02783	-0.0081	-0.03683

Notes: all significant at 1% level. The presented effects are the respective elasticities for the Spatial Dynamic Model with Endogeneity.

We have found evidence that there is a *pedagogic deterrent effect* associated with fine values. Sanction charges imposed in the municipality of the infraction and in the neighborhood, are important to discourage new offenses. Low fine values encourage further violations, but the quadratic effect of sanction charges shows that after certain values, offenses fall. However, IBAMA's reputation for imposing heavy fines on neighboring municipalities appears to be important only in the case of infractions. In the case of Warnings, even low values applied in neighboring municipalities are sufficient to discourage further violations, suggesting that, for this category of offense, monitoring may be more important than the imposed penalty. Considering all violations, for the long run, fines above 33.7 thousand applied in one municipality are already sufficient to deter offenses in the same municipality. Considering the indirect effects (spillovers), the necessary fine values applied in the municipality and in the neighboring localities is of 22.6 thousand (general deterrence).

Table V – Short-term and Long-term Inflection Values for Fines (R$)

	Short-term			Long-term		
	Direct	*Indirect*	*Total*	*Direct*	*Indirect*	*Total*
Warnings	542	104	330	540	113	330
Infractions	160.638	3.276.057	213.510	160.875	1.465.662	213.510
All Violations	33.835	5.500	22.610	33.774	6.536	22.610

Notes: Maximum values calculated for the Spatial Dynamic Model with Endogeneity

6. Conclusions

We found evidence for the existence of time and space dependence for environmental violations in all categories studied. Municipalities with more offenses in the past or that are surrounded by other municipalities with a high number of violations tend to present a higher number of assessments. Regulator Targeting is the possible explanation for that result. We also found evidence that there is a *pedagogic deterrent effect* associated with fine values. Sanction charges imposed in the municipality and in the neighborhood are important to discourage new offenses. Low fine values encourage further violations, but the quadratic effect of sanction charges shows that after certain values, offenses fall. This result can open the discussion and base future public policies about changes in the minimum values of fines.

On the other way, increased sanction charges won't be effective if fines aren't collected at all. As pointed by Da Silva and Bernard (2016), only a small number of fines are paid. For future research, we are working on separating assessments by payment status to consider prescriptions, cancellations and other issues associated with non-payment. In Brazil, as for other countries, administrative penalties such as sanction charges are far more common than civil or criminal prosecutions. However, for future research, we are also working on separating the administrative offenses that are also prosecuted as environmental crimes to see the impact of the possibility of incarceration and other heavier penalties on violations. The evaluation of municipal characteristics (that disappear under the panel structure) and recidivism are also to be considered.

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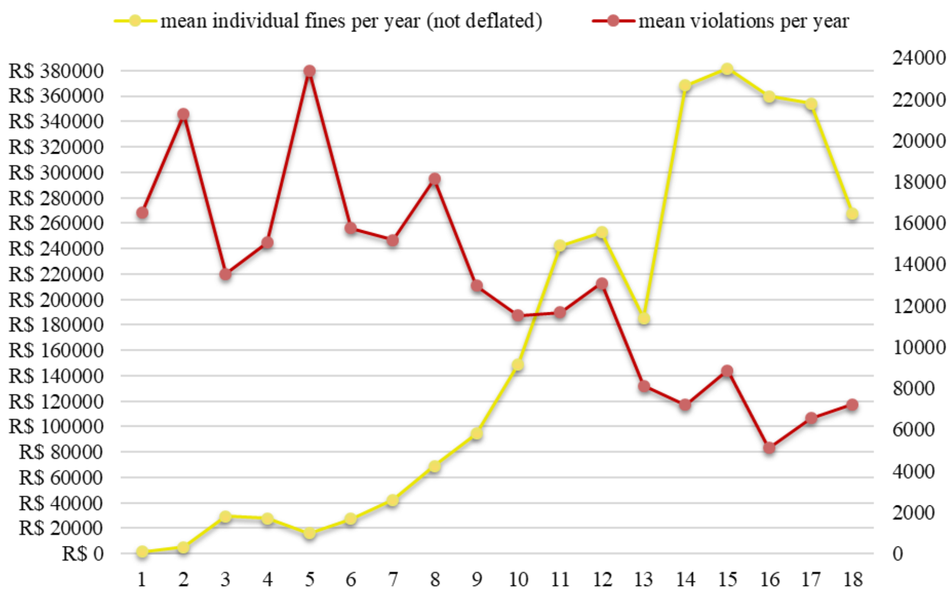

Figure 7 - Violations and Fine Trends

Table VI - List of relevant Federal Laws, Decrees, and IBAMA Norms

Name	Summary	Current legislation
Law No. 4.771/65	Establishes the Forestry Code	Revoked by Law No. 12.651/12
Law No. 6.938/81	Discusses the National Environmental Policy	Yes
Fed. Constitution/88	Brazilian Federal Constitution	Yes
Law No. 7.735/89	Creates IBAMA	Yes
Law No. 9.433/97	Establishes the National Water Resources Policy	Yes
Law No. 9.605/98	Discusses the criminal and administrative sanctions derived from conducts and activities that are harmful to the natural environment.	Yes
Decree No. 3.179/99	Discusses the specification of penalties applicable to conducts and activities that are detrimental to the natural environment.	Revoked by Decree No. 6.514/08
IBAMA No. 08/03	Discusses the process of assessment and debt recovery procedures.	Revoked by IBAMA No.14/09
Law No. 11.516/07	Discusses the creation of the Chico Mendes Institute	Yes
Decree No. 6.514/08	Addresses administrative offenses related to the environment and the applicable penalties, establishes the federal regulatory process for investigating such crimes.	Yes
Decree No. 6.686/08	Modifies Decree No. 6.514/2008.	Yes
IBAMA No. 14/09	Discusses the procedures for verification of administrative violations, the imposition of sanctions, the defense, the appeal system and the collection of fines, among other duties.	Revoked by IBAMA No. 10/12
IBAMA No. 10/12	Regulates the procedures for verification of administrative violations, the imposition of sanctions, the defense, the appeal system and the collection of fines under IBAMA.	Yes
Law No. 12.651/12	Establishes the New Forestry Code	Yes

Notes: Federal Laws and Decrees can be accessed at http://www.planalto.gov.br/ccivil_03/ and IBAMA normative instructions are available at http://www.IBAMA.gov.br/legislacao-IBAMA