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Decentralization and Pollution Spillovers: Evidence from the Re-drawing of County Borders in Brazil*

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Decentralization can improve service delivery, but it can also generate externalities across jurisdictional boundaries. We examine the nature and size of water pollution externalities as rivers flow across jurisdictions. Panel data on water pollution in Brazilian rivers coupled with county splits that change the locations of borders allow us to identify the spatial patterns of pollution as rivers approach and cross borders, controlling for fixed effects and trends specific to each location. The theory of externalities predicts that pollution should increase at an increasing rate as the river approaches the downstream exit border, that there should be a structural break in the slope of the pollution function at the border, and that a larger number of managing jurisdictions should exacerbate pollution externalities. We find support for all four predictions in the data. Satellite data on growth in night-time lights along rivers show that local authorities allow more settlements to develop close to rivers in the downstream portions of counties, which is the likely underlying mechanism. The border effects on pollution are not as pronounced when the cost of inter-jurisdictional coordination is lower.

Key words: Water pollution, inter-jurisdictional externalities, decentralization

JEL Codes: Q56, D62, H23, Q53, O12

1. INTRODUCTION

Many international organizations, national initiatives, and scholars promote decentralization as a means to improve public service delivery (World Bank, 2004). However, actions taken within a jurisdiction often have spillover effects on neighbours, and raise the possibility that decentralized management without inter-jurisdictional coordination leads to inefficiencies (Oates, 1972). The flow of rivers across borders is a case in point. The hundreds of international and intra-national

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conflicts over water use and management[1] have often stemmed from the opening of a diversion gate upstream or the discharge of pollutants into the water as it flows downstream. This article estimates the nature and size of water pollution spillovers as rivers cross county boundaries within the same Brazilian states. The main contribution of the article is to convincingly demonstrate that there are large cross-border negative spillovers under decentralized management, even when the jurisdictions are part of the same governing state or federation.

We compile a rich panel dataset of 5,989 water quality measures collected at quarterly intervals at 372 upstream–downstream pairs of monitoring stations located in all eight major river basins across Brazil. Our empirical strategy overlays these pollution data on a series of Geographic Information System (GIS) maps of county (*municipio*) boundaries which shift and evolve over time due to county splitting. Brazil redraws county borders frequently (the number of counties increased from 3,991 in 1980 to 4,491 in 1990 to 5,507 in 2000), which changes both the number of border crossings between a pair of water quality monitoring stations and the distances of each station to its nearest upstream and downstream borders. This in turn changes the incentive to pollute at a given location, since some downstream constituents become external to the upstream politicians' calculus after the border changes.

The change-in-border based identification strategy we use is critical, because identifying externalities based on cross-sectional comparisons across different rivers would be subject to a number of bias concerns. Geographic and demographic differences between small and large jurisdictions (with more or less frequent border crossings), endogenous placement of monitoring stations, and political differences between counties could all generate omitted variable biases in cross-sectional estimates. Our empirical analysis relies only on inter-temporal *changes* in water quality at a specific location as new borders are drawn closer to the station or as the number of border crossings change between stations, while controlling for location fixed effects.

We model the behaviour of a local policymaker in a decentralized decision-making environment who cares about his own constituency in optimally allocating production (and pollution) along a river that travels through his jurisdiction, but does not account for the external effects on downstream jurisdictions. The theory makes four specific predictions that we test with our data: (1) pollution increases as the river travels towards the downstream border (since there is less harm caused to a politician's own constituents by polluting farther downstream); (2) the pollution increases at an increasing rate as the river travels downstream; (3) there is a structural break in the slope of the pollution function at the border, as the downstream jurisdiction does not allow new emissions at the same high rate at its own most upstream locations, and the pollution traveling into the county attenuates with the flow of water; and (4) pollution along a river increases with a larger number of border crossings.

We estimate the shape of the pollution function implied by this theory, and find support for all four predictions. For every kilometre closer a river is to a downstream border, biochemical oxygen demand (BOD; the pollution measure) increases by 1.5–3%. This increase occurs at a faster rate as the river gets closer to the downstream border, and the pollution function therefore has the steepest positive slope closest to the river's exit point out of the jurisdiction. We also identify a structural break in the slope of the pollution function at the border, which suggests that

1. Recent international disputes over water quality and quantity include conflicts over water rights in the Jordan River (which have aggravated the Israel-Palestine conflict (Mustafa, 1994), disagreements over dams in the Euphrates between Turkey and Syria (Jongerden, 2010), and contention over irrigation canals between Pakistan and India (Wolf, 1998). Intra-national conflicts over use of the Colorado River by Upper- and Lower-basin states have divided the Western U.S. for over 100 years, and have extended to include rural–urban conflicts over water rights, as well as conflict between state and federal governments and Native American populations (Postel, 1999; Hobbs, 2005). Similarly, disputes have arisen between states in India over diversion of water (Richards and Singh, 2002). See Wolf (2002) for a review.

polluting activity is restricted in the upstream areas of counties, but the evidence in favour of this prediction is statistically less strong. Finally, for each additional border crossing induced by a border change, pollution increases by 3%.

While the first three predictions are new, the fourth prediction builds on the results of Sigman (2002, 2005)'s seminal analyses of pollution in international rivers and in rivers in the U.S. Sigman (2002) shows that water pollution increases when a river crosses an international border. However, as that paper notes, proximity to borders may be correlated with unobserved heterogeneity in geography, population density, or economic activities. We document such pollution spillovers within a county using a more stringent design controlling for location fixed effects.

Sigman (2005) shows that decentralization of environmental authority to the state level in the U.S. led to a 4% degradation of water quality downstream of authorized states, with an environmental cost downstream of $17 million annually. This analysis includes monitoring station fixed effects to account for unobserved heterogeneity, but since borders are fixed, it is not possible to study the effects of proximity to upstream and downstream borders in that setup. In contrast, our approach allows for analysis of the pollution function at varying distances from the border, and we estimate the non-linear shape of the pollution function on both sides of the border. This has an important econometric advantage over earlier work, since placement of water quality monitoring stations may not be random. Monitoring stations are often placed by environmental authorities in areas where water pollution is of particular health or legal concern. In our analysis, we identify the pollution impact of changes in distance to the border *controlling for the fixed location* of the monitoring station, using only the variation resulting from the re-drawing of county borders in Brazil.

The central concern with our identification strategy is that a county's decision to split its borders (which generates the required variation in distances to borders) is endogenous. We can address this by directly controlling for the decision to split, and only using the intensive-margin variation in the magnitude of the change in distances to borders (or in numbers of county borders crossed) across only the sub-set of areas that chose to split. Our data are rich enough to directly control for county splits, because some splits lead to a large change in the distance between the pollution monitoring station and the nearest border, while other splits lead to smaller changes. This relative variation in distances *within* the set of split counties allows us to estimate the key parameters of the model, holding constant (the potentially endogenous) decision to split.

Furthermore, the specific non-linear shape of the pollution function we estimate is difficult to reconcile with stories of unobserved confounders driving the results. We control for linear trends specific to each river segment (which should capture effects of gradual changes in population density or economic activity), and rely only on sharply dated county splitting "events" every four years associated with the election cycle for identification. We also model specific forms of endogeneity (where a jurisdictional split occurs in an area with, e.g. high population density), and show that while they can explain one or two of the empirical findings in isolation, it is difficult to rationalize all four pieces of evidence being explained by endogenous variables dependent on border location other than distance from border. Finally, we conduct falsification tests to show that the same pollution patterns do not exist in the years leading up to the split. The pre-trends display no evidence of spurious correlations in favour of our theory.

Brazilian counties' strategic decision to pollute close to a river's downstream point of exit from the county serves as a cautionary tale for decentralization initiatives without adequate inter-jurisdictional coordination. By estimating the magnitude of negative spillovers, we document one aspect of the trade-offs inherent in decentralization.[2] Furthermore, by testing the fourth

2. The merits of decentralized decision-making have been debated in the public finance literature (Oates, 1972; Cumberland, 1981; Oates and Schwab, 1988; Levinson, 1997; Wilson, 1999; Besley and Coate,

prediction (on the number of border crossings) described above, we also estimate the overall effect of decentralization on water quality (i.e. the effect of an additional county managing a river segment).[3]

Many development institutions promote decentralization as a way to improve governance and targeting of services to the poor. This idea featured prominently in the World Bank's flagship publication on public service delivery, which notes that "Decentralizing delivery responsibilities for public services is prominent on the reform agenda in many developing countries. Bolivia, India, Indonesia, Nigeria, Pakistan, and South Africa—to name a few—are all part of a worldwide movement to decentralize." (World Bank, 2004). United Nations Development Programme (UNDP) has also promoted large decentralization programs in Guatemala, the Philippines, Mali, Thailand, and Uganda (Altmann *et al*., 2000). The policy community has noted the need for more empirical evidence on decentralization (World Development Report 2004). We contribute to a growing empirical literature on this topic (List and Mason, 2001; Fisman and Gatti, 2002; Foster and Rosenzweig, 2002; Millimet, 2003; Faguet, 2004; Barankay and Lockwood, 2007), but with a narrower focus on inter-jurisdictional spillovers. This policy issue—that decentralization without coordination can engender inefficient resource use—is relevant to the management of any publicly provided good with spillovers.[4]

Brazil has recognized the problem we document, and now encourages the formation of river basin committees to improve negotiation between upstream and downstream counties and other stakeholders. We collect data on all basin committees in operation, and on the political affiliations of all mayors in power in relevant jurisdictions, to examine whether the deterioration in water quality across borders is mitigated when organizational or political factors lower the cost of negotiation. Indeed, we find larger border effects on pollution in areas where cooperation is more difficult.

Our findings are related to studies of border effects on pollution (Fredriksson and Millimet, 2002; Sigman, 2002, 2005; Helland and Whitford, 2003; Gray and Shadbegian, 2004; Konisky and Woods, 2010; Burgess *et al*., 2011). Also related is a literature on groundwater depletion (Foster and Sekhri, 2008, Sekhri, 2011). More broadly, we contribute to a literature on the determinants of water quality and access to clean water (Choe *et al*., 1996; Chattopadhyay and Duflo, 2004; Galiani *et al*., 2005; Miguel and Gugerty, 2005; Bennear and Olmstead, 2008; Olmstead, 2010; Devoto *et al*., 2011; Kremer *et al*., 2011a, 2011b).

2003; Bardhan and Mookherjee, 2000; List and Mason, 2001; Akai and Sakata, 2002; Foster and Rosenzweig, 2002; Brueckner, 2006; De Janvry *et al*., 2010, forthcoming; Hammond and Tosun, 2011; Hatfield and Kosec, 2011, Hatfield and Padro-I-Miquel, 2012), which contends that decentralization can improve targeting when there is local variation in preferences and fosters efficiency through competition, but that it can also generate externalities across jurisdictional boundaries, a race to the bottom in policy choices, and excessive tax competition. Ogawa and Wildasin (2009) show that in theory, when jurisdictions interact in other spheres relevant to the production of the externality, decentralized decision-making *can* lead to efficient outcomes. Galiani *et al*. (2008) has modeled the tradeoff between service targeting and constituents' voice and finds evidence of positive average effects coupled with adverse distributional consequences.

3. Decentralization can come in many forms (e.g. devolution of financing, or of authority), and it takes a specific form in our context: the geographic splitting of counties leading to a larger number of counties managing the same river segment. This is not the typical decentralization initiative, which often involves devolution of authority to local governments. As described below, each Brazilian county has some authority over decisions that affect water quality. The splitting of counties therefore leads to de facto decentralization in the sense that an increasing number of jurisdictions gain control over water quality of localized river segments.

4. Our focus on water carries particular economic and policy relevance. Over one billion people in the world lack sufficient potable water, and diarrheal diseases kill 1.5 million children every year and account for 17% of under-5 mortality (WHO 2004; UNICEF and WHO 2009). Lack of access to clean water is often related to management challenges: 80% of sewage and 70% of industrial wastes are dumped into surface water untreated (World Water Assessment Program, 2006, 20092009; Wardlaw *et al*., 2010).

Finally, our use of border changes as a source of identification is related to a literature on the economic effects of shifts in borders (Holmes, 1998; Davis and Weinstein, 2002; Chakrabarti and Roy, 2007; Wolf, 2007; Redding and Sturm, 2008).

The rest of the article is organized as follows. Section 2 provides institutional context. Section 3 develops a theory of inter-jurisdictional externalities in river water pollution and develops predictions for the empirical analysis. Section 4 describes our data, and Section 5 presents empirical results. Section 6 offers concluding remarks.

2. CONTEXT

2.1. *Rivers in Brazil*

Brazil is a particularly important country in which to study water pollution spillovers because it controls 15% of the world's total fresh water resources (World Resources Institute, 2003). Lack of sewage treatment is the most important source of water pollution across the densely populated areas of Brazil. Approximately 18% of counties report the presence of open sewers that flow directly into major water systems. Farm runoff is the most important cause of water pollution in rural areas. According to the county environmental census, industrial dumping is also a significant concern in approximately 10% of counties.

2.2. *Can counties affect water quality?*

Although general environmental policy setting and enforcement is determined at the national and state levels, counties in Brazil have important powers over practices affecting the environment within their jurisdiction. Federal law establishes guidelines, norms, and minimum standards of environmental policy, but the importance of county government participation in environmental policymaking has been acknowledged by both state and federal law. The Federal Constitution allows counties to establish local environmental standards that are more strict than the state/federal norms (Engenharia and Projetos, 2006), and to enforce standards within their jurisdiction.

Counties are able to fine and tax their community members for activities that cause pollution. In addition, they can forbid high-pollution practices and use zoning regulations to reduce direct runoff. The use of these enforcement mechanisms may not be evenly distributed within a county; the county administration has an incentive to increase spending on enforcement of pollution restrictions in areas of the county where pollution will be most harmful to its members. Our conversations with water management practitioners in Brazil suggest that the most important way counties affect water quality is through the application of zoning policies. Local policymakers determine whether or not to permit temporary housing with inadequate infrastructural support close to water sources.[5] The National Water Agency (ANA) in Brazil recognizes the associated pollution externality problems, and inter-county cooperation has become a focus of water management policy in Brazil in recent years (Brannstrom, 2004; Formiga-Johnsson and Kemper, 2005).

Ferraz (2007) documents another way in which counties influence state regulatory agencies. He finds a significant increase in the number of environmental licenses awarded in years of county mayoral elections in the state of Sao Paulo, as local politicians pressure bureaucrats to allow more polluting firms to operate.

5. County governments also play an important role in extending sanitation services in peripheral regions that lack access to the sewer network (Seroa da Motta, 2006).

2.3. *The process of creating new counties*

Our empirical strategy relies on changes in border crossings induced by the creation of new counties, and in this sub-section we describe the conditions under which new counties are created. More details about this process are provided in Supplementary Appendix A. Each county (or *municipio*) is composed of a few districts, and prior to the county mayoral election (which occurs every 4 years beginning in 1988 during our sample period), some districts within a county may choose to split off and create a new county. The process of creating new counties begins with a feasibility study on the projected solvency of the potential county and a referendum on the proposal in both halves of the split county. The referenda are followed by a state law passed by the state legislature and signed by the governor (Tomio, 2002).

Brazilian counties receive fiscal transfers from both the federal and the state governments, which introduce a monetary incentive to create new counties. In addition to a portion of the income and industrial taxes collected in their jurisdiction, counties receive a population-based transfer called the Municipalities' Participation Fund (FPM) which, due to its allocation formula, rewards smaller counties. County splits can also occur due to disagreements over the amount of municipal funds used in the various districts of the original county, differences in economic activity across districts, or the large size of the original county (Bremaeker, 1992). Splits can also occur for purely administrative reasons, or in order to better represent the political affiliation of the district that leaves the original county (Noronha and Cardoso, 1996). To the extent that counties have policymaking authority over any publicly provided good, the creation of new counties is a form of decentralization in the delivery of that public good (e.g. two smaller governments rather than one larger one are supplying the service to the same population).

The process of county splitting is not random (Weese, 2015) and is not necessarily uncorrelated with variables that affect changes in water quality. We examine and address these concerns in great detail in implementing our empirical strategy.

3. A MODEL OF POLLUTION EXTERNALITIES ON A RIVER

We derive theoretical predictions using a highly stylized model that is designed to isolate the water pollution spillover aspect of splitting jurisdictions. The model maps closely to the data and empirical strategy at our disposal.

We model a river on a unit line flowing from left to right, with population distributed along the river according to a probability density function $f(x) > 0$ at all points (see Figure 1). The production and consumption is location-specific: each person at location x consumes q_x at a marginal cost of c, and gains utility $u(q_x)$. There is a one-to-one relationship between their consumption and the pollution this person emits into the river: the consumption of q_x generates q_x units of pollution. This setup most accurately describes municipal pollution from population settlements located close to rivers, which is the most relevant setting for our empirical implementation. County governments have the largest influence on such municipal pollution through their zoning practices and expenditures on sewage treatment, and the pollution measure used in the empirical analysis (biochemical oxygen demand or BOD) reflects emissions from municipal point sources.[6]

Pollution emitted at location x adversely affects people located downstream of x. This pollution exponentially decays as the river flows, and thus the pollution "felt" at downstream point t of

6. In this stylized model, we abstract from the details of micro (firm, human) level reactions to environmental regulation, since we are studying decisions at the level of the jurisdiction using composite data on water pollution. Becker and Henderson (2000) and Greenstone (2002) study firm responses to regulation. In practice the local government can affect household and business locations through zoning laws and the amount of pollution through differential enforcement of environmental regulations.

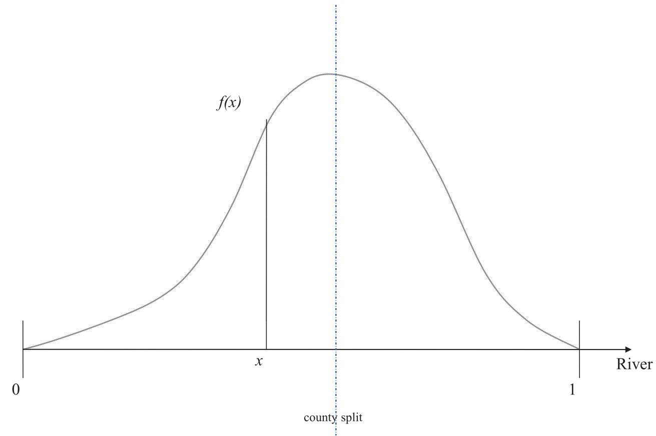

FIGURE 1
Model of river

the emission q_x is $q_x \cdot e^{-(t-x)}$.[7] A regulator decides how much consumption (and pollution) to allow at each location within her jurisdiction by trading off the utility of consumption against the welfare cost of the pollution downstream.

At each point x the regulator chooses q_x to maximize the utility that the mass of individuals at x receive from consuming q_x net of the harm the associated pollution causes downstream, down to point b, where the jurisdictional border lies[8]:

$$\mathrm{W}(x,q_x)=f(x)[u(q_x)-cq_x]-\int_x^b q_x e^{-\alpha[t-x]}f(t)\,dt \tag{1}$$

Total welfare in a jurisdiction integrates the point-wise welfare over the area of the jurisdiction:

$$\mathrm{W}=\int_0^b\left[f(x)[u(q_x)-cq_x]-\int_x^b q_x e^{-\alpha(t-x)}f(t)\,dt\right]dx$$

We take the first-order condition using calculus of variation:

$$\mathrm{W}(\epsilon)=\int_0^b\left[f(x)\left(u'\left(q_x^*\right)-c\right)-\int_x^b e^{-\alpha(t-x)}f(t)\,dt\right]q'(x)\,dx=0$$

7. This is a reasonable decay function for our preferred measure of pollution used in the empirical analysis: BOD. The rate of deoxygenation in rivers is commonly modeled using an exponential decay rate. See, for instance, the Streeter-Phelps model (Tchobanoglous and Schroeder, 1985). This specific functional form for decay also makes the analytical solution for optimal emissions tractable, but is not crucial to predictions that we will take to the data.

8. We assume linear pollution costs to derive analytical predictions. Linear costs are consistent with the way pollution is commonly modeled and measured in the environmental economics literature (Greenstone and Hanna, 2014). For example, Arceo *et al*. (2012) find that health costs are linear in PM-10 levels. Currie and Neidell (2005) and Currie *et al*. (2013) study the effects of water and air pollution (respectively) on fetal and infant health using linear specifications.

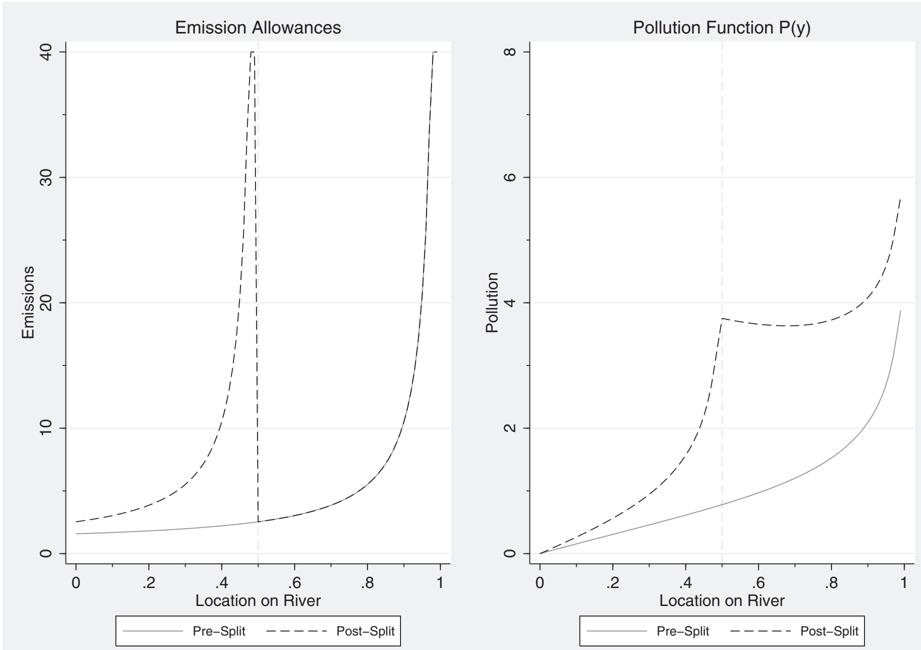

FIGURE 2

Emissions allowance and pollution functions uniform population density

$$\text{Or, } f(x)\left[u'\left(q_x^*\right)-c\right]-\int_x^b e^{-\alpha(t-x)}f(t)\,dt=0,$$

$$\text{which implies}: u'(q_x)-c=\frac{\int_x^b e^{-\alpha(t-x)}f(t)\,dt}{f(x)} \tag{2}$$

We first generate and plot the pollution function for a simple case (uniformly distributed population of mass 1, log utility and $b=1$) in order to build some intuition for the empirically identifiable predictions that we can generate from this model. The solid line in the left panel of Figure 2 plots emissions, and the solid line in the right panel shows the corresponding pollution function that we would observe in the data.[9] Pollution and consumption allowances increase to the right, since the harm caused by upstream emissions is greater than the harm caused by emissions close to the exiting border out of the jurisdiction, and the county optimizes to limit harm to its own constituents.

The empirical analysis will examine changes in pollution once counties split to create additional jurisdictions. We therefore plot in Figures 1 and 2 the optimal emissions and implied pollution if the county splits at location $b=0.5$ on the river (dotted lines). Residents of the upstream half of the county are now allowed to consume and pollute more after the split, because

9. The actual pollution level felt at any point y on the river is the accumulation of all (decayed) pollution allowances to the left of point y: $P(y)=\int_0^y q_x^* e^{-(y-x)}\cdot f(x)\cdot dx$.

the new upstream jurisdiction is only concerned about the harm its consumption decisions cause to its own constituents located in the interval [0,0.5]. Part of the harm is now an externality on the downstream county. The overall pollution level in the river increases due to these negative spillovers brought about by the county split. The right panel shows that the pollution function is no longer monotonically increasing, since there is a sharp discontinuity in the consumption-pollution trade-off calculus for the two regulators making decisions immediately to the left and to the right of the split.

3.1. *Testable predictions*

This numerical exercise, and the implied shape of the pollution function in Figure 2 helps us develop the intuition for four main predictions that we will now prove under general conditions (without the restrictive functional form assumptions), and then take to the data:

Prediction 1: Pollution increases as the river travels towards the downstream border where it will exit the county (the *positive* slope of the pollution function in Figure 2).

Prediction 2: Pollution increases at an increasing rate as river heads closer and closer to the downstream border (the *increasing* slope of the pollution function in Figure 2).

Prediction 3: The discontinuous drop in new emissions at the border creates the *structural break in the slope* of the pollution function there.

Prediction 4: There is a larger increase in pollution between an upstream and a downstream point if the river segment defined by those points crosses more borders. This is the level effect in the right panel of Figure 2 comparing the solid grey and dashed black lines.

3.2. *Proofs of the comparative statics predictions*

The proofs of all four statements associated with predictions 1–4 are in Supplementary Appendix B. We show, by taking derivatives of the first-order condition in (2), that $\frac{\partial q_x^*}{\partial \mathrm{X}} > 0$ (prediction 1), and $\frac{\partial^2 q_x}{\partial x^2} > 0$ (prediction 2). We then show that emissions are lower when approaching the border from the right (entering the downstream county) than from the left (the exit border from the upstream county), or $\lim_{x \uparrow b} \frac{\partial q_x}{\partial \mathrm{X}} > \lim_{x \downarrow b} \frac{\partial q_x}{\partial \mathrm{X}}$, which establishes the discontinuity in the slope of the pollution function in prediction 3. Finally, we use induction to show that when a border is removed, pollution in the bigger territory decreases (prediction 4).

These four predictions jointly determine the shape of the pollution function as the river travels downstream and crosses borders. We use pollution monitoring data to test all four predictions, and in turn estimate the shape of the entire pollution function.

3.3. *Extensions to the model and sensitivity analysis of model predictions*

The model assumes that the population $f(x)$ is distributed exogenously, but in reality, population may be non-uniform around borders due to the endogenous placement of borders. We explore the resulting endogeneity issues in depth (and devise fixes) in the empirical section, and on the theory side, we explore how sensitive the four predictions from the model are to changes in specific assumptions. The results from these sensitivity tests are presented in Supplementary Appendix C.

First, we replace the uniform distribution of population along the river with a triangular population distribution function, so that the county split takes place in the high population density area. Supplementary Appendix C.1 provides the specific functional forms, and Figure C2 graphs the resulting emissions allowance and the pollution function. All four major predictions remain unaltered. The discontinuity in slope at the border is less sharp, because unlike the uniform distribution case, there is a high population density just downstream of the border producing lots of new emissions.

Figure C3 depicts the emissions and pollution functions when the population distribution is assumed to be bi-modal, with the county border drawn in the low density area between the two modes.[10] The key predictions are again un-altered.

Our model assumes a continuum of atomistic (household) polluters, but in reality, there are likely large-scale point-source polluters such as factories, or specific points where (untreated) domestic sewage might be emitted. In Figure C4 we simulate pollution functions resulting from placing 10 non-atomistic factories in each county, and allocating production/pollution permits on the basis of maximizing a welfare function which accounts for the harm to downstream residents from each factory's emission. We randomly place the factories for each simulation, but conduct multiple simulations where the factory locations are a new random draw each time. Figure C4 shows the results of 20 simulations. The pollution functions depicted with dotted lines now have staggered shape (because these are point source polluters with high emissions at specific points), and we also plot solid lines with the best fitting quadratic functions, to match our empirical strategy.

The simulations always indicate that pollution increases as we approach the exit border. In other words, prediction 1 from our basic model remains unchanged. Pollution increases at an increasing rate (the square term in the quadratic is positive) in 12 out of the 20 simulations. Prediction 2 does not hold in the 8 cases where the random draw of factory locations does not place any factories close to the exit border. There is a clear discontinuity in the slope of the pollution function (prediction 3) at the border in 17 out of 20 cases. There is also a positive level effect on pollution from additional border crossings in all cases. We therefore interpret these simulations to imply that predictions 1, 3, and 4 are quite robust to consideration non-atomistic polluters, but prediction 2 may not hold in the data as strongly. Figure C5 plots the "average" best-fit quadratic functions, averaged over the 20 simulations. All four predictions are present in this diagram, but the non-linearity in the pollution function is not as sharp.

Finally, in Figure C6, we relax the assumption that the upstream jurisdiction cares *solely* about the welfare of its own residents, and explore the sensitivity of our predictions to providing partial welfare weights to downstream residents. Predictions 2–4 (non-linearity in the pollution function, the discontinuity at the border and the level effect of additional border crossings) become less sharp as the upstream jurisdiction internalizes more of the external effects on downstream residents. If the upstream county places 50% welfare weight on downstream residents, the non-linearity and the discontinuity are not readily apparent in the pollution functions. We therefore might expect weaker border effects if neighbouring jurisdictions find ways to coordinate.[11]

10. We choose to show the sensitivity tests with the border split at a high density and the opposite case of border split at low density, because these jointly encompass the empirically important cases of where border splits might occur and cause endogeneity concerns. We examine these identification issues more directly in Supplementary Appendix D.

11. Probabilistic voting could yield similar results to a model in which the county puts some welfare weight on downstream counties (see, e.g. Persson and Tabellini, 2002), by relaxing the assumption that groups are homogeneous in the intensity of their preferences across issues. Higher sensitivity among downstream voters or larger voting weights for downstream users would increase the incentive of the regulator to enforce in the downstream area of the county. Further modeling of this will be left to future work.

3.4. *Endogenous county splitting in densely populated areas*

A key concern in the identification of the effect of decentralization on pollution spillovers is the possibility of endogenous splitting of jurisdictions in areas with increasing population density or economic activity (where pollution problems are worsening for an independent reason). We derive the implications of this type of endogeneity on the shape of the pollution function in Supplementary Appendix D. Theory indicates that if county splits occur in high density areas, the pollution function should continue to display a positive slope downstream of the border. A stronger version of the statement in Prediction 3 (that the border causes an inflection point in the pollution function in Figure 2) thus provides an empirical test to distinguish our model from this type of endogeneity. Observing a break in the pollution trend at the border with the slope switching from positive to negative, would be stronger evidence in favour of the strategic spillovers we model, as opposed to endogenous splitting in high (or increasing) density areas.

In Supplementary Appendix D, we further consider the possibility of counties splitting along an area of low density in between two areas of increasing density, using a bi-modal triangular distribution. We show that this form of endogeneity would imply a pollution function with a concave shape (or even a negative slope) just upstream of the border. This implication directly contradicts prediction 2—that pollution should increase at an increasing rate as we approach the downstream exit border—and therefore yields yet another empirical test. In summary, showing the evidence in favour of *all four* key predictions from the model helps to empirically distinguish the model from other plausible stories.

4. DATA AND IDENTIFICATION STRATEGY

4.1. *An example of our identification strategy*

Figure 3 presents a sample map of the evolution of county boundaries from the state of Rio de Janeiro to illustrate our basic identification strategy. Points S1 and S2 mark the locations of two water quality monitoring stations on the river segment flowing from S1 to S2. The theory suggests that the following three variables are important determinants of pollution on this segment: the location of station 1 relative to the nearest downstream border (from S1 to B, which will be termed distance 1D in our empirical analysis, and is defined clearly in Figure 4), the location of station 2 relative to the nearest upstream border (from B to S2, termed U2 in Figure 4), and the number of county boundary crossings (1, at point B).[12]

The theoretical model predicts that the pollution level at station 1 is expected to be higher when 1D is smaller, or in other words, the closer station 1 is to the downstream border (prediction 1). The change in pollution from S1 to S2 should be greater when more county boundaries are crossed (prediction 4). The inflection point in the pollution function at the border (prediction 3) implies that the effect of distance U2 on the pollution level measured at S2 should be smaller than the effect of distance 1D.

It is difficult to empirically identify spillover effects using cross-sectional variation in these variables, because for two different river segments of similar length the number of border crossings and distances of monitoring stations to borders would be correlated with average county size and other county characteristics in those regions. Geographic and hydrologic differences can affect the attenuation rate for pollution (Stream Solute Workshop, 1990), and economic and demographic differences can affect the levels of pollution across different rivers. Our empirical strategy involves

12. In our empirical work, we will also control for the location of station 1 relative to the nearest upstream border (distance U1 defined in Figure 4, which is the segment from X to S1), and the distance of station 2 from the nearest downstream border (distance 2D in Figure 4, which is the segment S2 to Y).

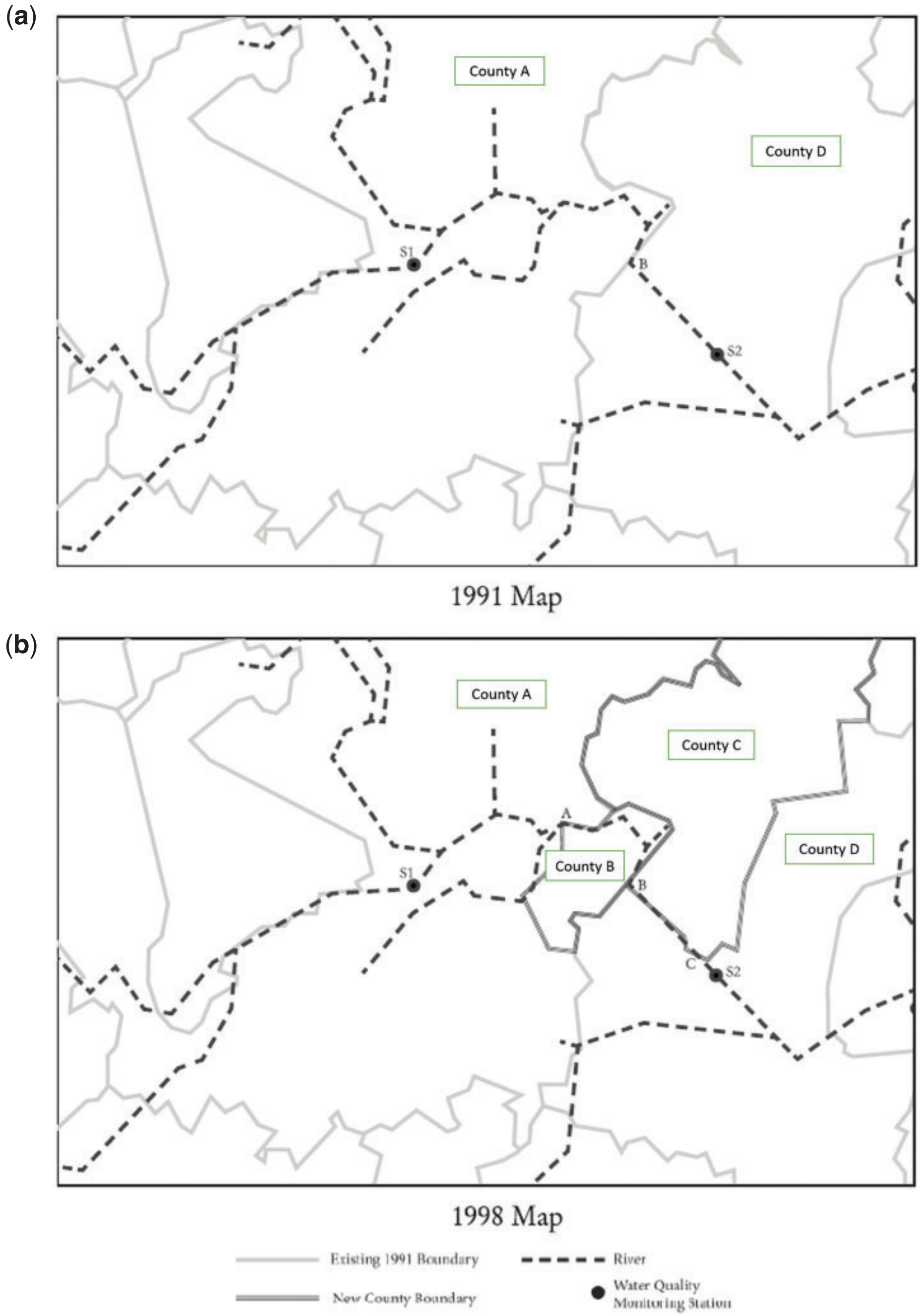

FIGURE 3

Example of the evolution of county boundaries in the state of Rio de Janeiro

Source: Brazilian Institute of Geography and Statistics (IBGE).

adding station-pair (S1,S2) fixed effects, and examining the effects of changes in distances and in border crossing on the inter-temporal changes in water quality at S1 and S2.

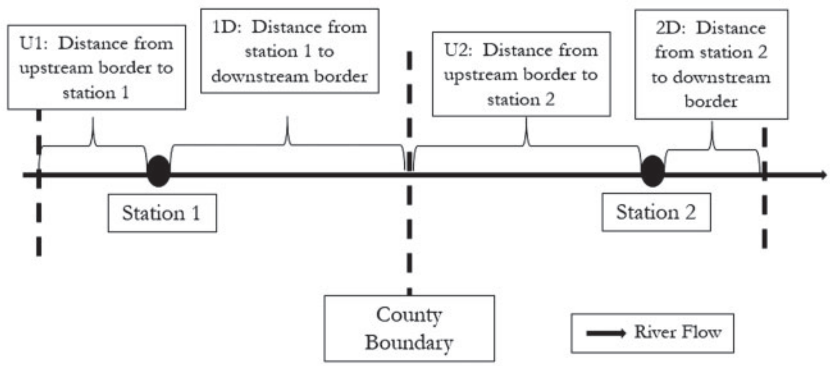

FIGURE 4
Notation on distances

Figures 3 (a) and (b) demonstrate how border crossings and distances to borders vary over time for the same pair of monitoring stations even when the locations of those stations remain fixed. Both County A and adjacent County D experienced splits between 1991 and 2001, which allows us to provide a concise illustration of variables 1D and U2. Counties B and C were recognized as separate counties by state law after the 1998 and 1994 elections respectively. The creation of County B from County A caused distance 1D (from station 1 to the nearest downstream exit border) to decrease from S1-B to S1-A. Prior to 1994 the County A leadership was trading off the benefits of pollution allowance around S1 against the costs of pollution to all downstream constituents located along segment S1-B. After 1994 some of those downstream users were no longer County A voters, and thus the political calculus that determined pollution allowances at S1 changed. Our regressions with the river segment fixed effects identify the inter-temporal *change in* pollution measured at S1 as a result of the *change in* S1's distance to the nearest exit border.

The number of border crossings for the river segment S1–S2 increased from 1 to 3 when County B was created. Prediction 4 implies that since the two new counties now have greater incentives to pollute just upstream of their respective exit borders (i.e. close to points A and B), we should observe that after the split, water quality deteriorates more as the river flows from S1 to S2 (and our results are robust to controlling for the distance the river runs along the county border).

Finally, the creation of the county of County C through the other split reduced distance U2 of station 2 from the nearest entering border (B-S2 to C-S2). This second type of split allows us to identify the effect of U2 (i.e. the slope downstream of the border) while controlling for station-pair fixed effects.

In general, some splits (like the creation of County B) will allow us to identify the effect of 1D, and a different set of splits (like County C) will identify the effect of U2, while both types of splits will identify the effects of the number of border crossings. Furthermore, sometimes there will be splits in counties located *in between* S1 and S2 (but not where either S1 or S2 is located), which will contribute to the identification of border crossings only (but not the effects of 1D or U2). Importantly, only splits that occur *in the counties* where station 1 or station 2 are located contribute to the coefficients on 1D and U2. Figure 3 also points out that sometimes borders are drawn along rivers. We will add controls for borders along rivers in some specifications to address this.

Finally, note that a split can cause either a large change in the distance between a station and the nearest border (e.g. the change from B-S2 to C-S2 through the creation of County C), a small change (e.g. from S1-B to S1-A). This means that in some specifications, we will able

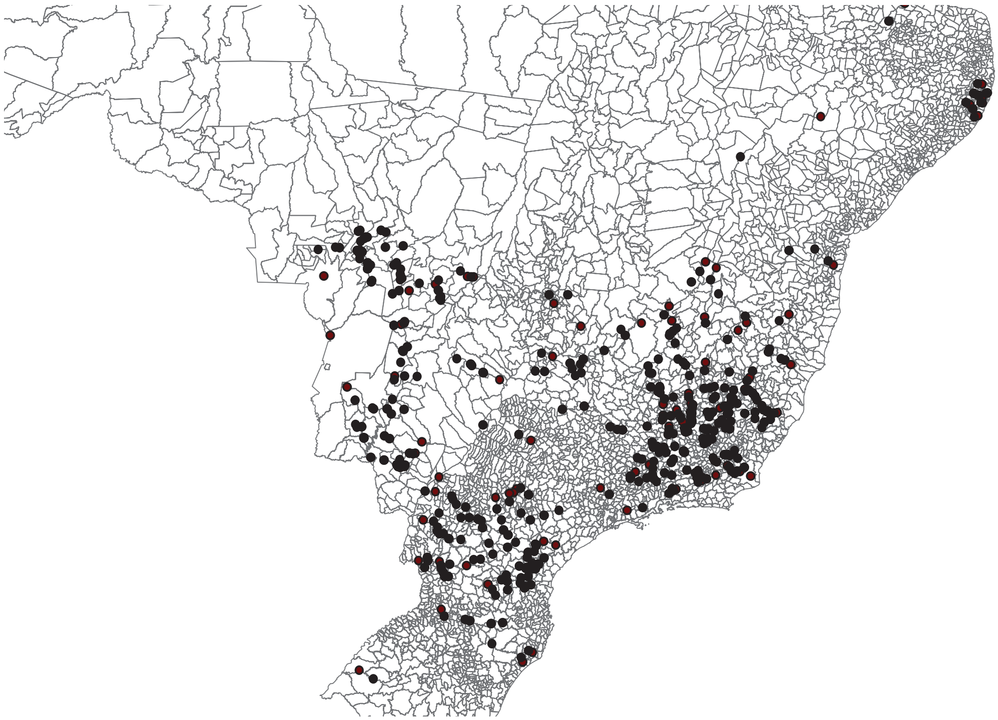

FIGURE 5
Water quality monitoring stations and county boundaries in 1991

to directly control for the decision to split, and identify the effects of the distance variables by exploiting variation in the amount by which the distance to the border shifted due to the split. Restricting attention to areas that split allows us to address concerns about endogeneity in the decision to split: we can investigate the effects of distances to borders on water pollution levels, while holding constant the decision to split.

4.2. *Data*

The empirical analysis uses water quality measures taken at 372 station pairs across Brazil (see Figures 5) sampled at quarterly intervals between 1990 and 2007, which results in an unbalanced panel of 8,878 individual BOD observations, or 5,989 unique observations for "station pairs" when stations are matched to the neighbouring station along the river. We convert our data to the station-pair format for some of the analysis, since a pair of adjacent stations defines a river segment over which both number of border crossings and pollution changes can be measured.

The preferred pollution variable (BOD) is a measure of the milligrams of oxygen used over a five day period in oxidizing the organic matter contained in one litre of river water (Tchobanoglous and Schroeder, 1985). Higher BOD is associated with increased bacterial count and organisms in the water, which accumulate wherever there is a high level of pollution from organic matter. It is commonly used to measure pollution from industrial, sewage, and runoff sources, and indicates the general level of health of the river. BOD is the preferred measure used in the prior literature (e.g. Sigman, 2002) because it is relatively easy to measure

TABLE 1
Summary statistics

	Obs.	Mean	Std. Dev.
Border variables			
Number of border crossings	5,989	8.422	11.218
Distance of station 1 from its nearest upstream border	5,989	4.741	8.303
Distance from station 1 to its downstream border	5,989	5.844	7.885
Distance of station 2 from its nearest upstream border	5,989	9.683	13.848
Distance from station 2 to its downstream border	5,989	12.344	18.726
County characteristics			
GDP in Downstream County in 100,000 Reais	5,989	4.388	17.343
Population in Downstream County in 100,000 people	5,989	0.648	2.023
Area in Downstream County in 100,000 square kilometres	5,989	0.025	0.040
GDP in upstream county in 100,000 Reis	5,989	3.897	16.629
Population in Upstream County in 100,000 people	5,989	0.559	1.721
Area in Upstream county in 100,000 square kilometres	5,989	0.020	0.022
Water quality			
BOD at upstream station	5,989	3.529	12.529
BOD at downstream station	5,989	3.382	15.247

by standard procedures, helping to ensure data quality and consistency. BOD tends to be measurable farther downstream than some other pollutants, which makes it appropriate for a study on inter-jurisdictional spillovers. More details about the properties of BOD are in Supplementary Appendix E.

Table 1 shows that BOD concentrations in Brazilian rivers are relatively high on average, but with large variation. Unpolluted water typically has BOD with levels of 2 or less, while moderately polluted water has BOD levels of between 4 and 8. Treated sewage has BOD levels of 20, while raw sewage has BOD levels of 300 or more (Tebbutt, 1992). Water in our sample has a median (mean) concentration of approximately 2 (3.5). Water quality is worse on average and has higher variance near county boundaries: average BOD levels at stations within 3 km of a county border are nearly one milligram per litre higher than at stations more than 3 km away from any border. This provides some descriptive indication of the basic premise of the theory of cross-border externalities.

Using GIS modelling, we combine water quality monitoring station data with maps of rivers to measure changes in BOD as the river flows from an upstream station (S1) to a downstream station (S2). We use elevation maps to identify the direction of water flow. We overlay maps of counties (or *municipios*) and catalogue the number of jurisdictional boundaries the river crosses (see Figure 5), distances traversed in each jurisdiction, and distances of monitoring stations to nearest upstream and downstream borders in that year.[13]

Brazil re-drew its county boundaries four times between 1990 and 2007, which implies that each water quality observation for a station falls into one of five different county boundary regimes. The number of counties in Brazil increased from 4,492 in 1991 to 5,807 in 2005. Of the 372 station pairs in the sample 191 experienced at least one border change during the sample period. 3,252 of the 5,989 water quality observations (i.e. 55%) are for those 191 station pairs. Each river segment between a pair of stations traverses through four counties and crosses eight

13. The county boundaries, and therefore the distances to borders, change over time. These distance calculations are subject to some measurement error, since GIS maps of county boundaries exhibit small variations from year to year. This measurement error likely leads to some attenuation bias.

borders on average. Monitoring stations in our sample are on average 6.7 km downstream from the last county border, and 9 km from the river's exit point out of the county.

Beyond analysis of water quality, we also attempt to uncover the underlying mechanisms by which a county is able to spatially target the pollution towards its downstream areas. This requires within-county, finely, spatially disaggregated data on the exact location of pollution and/or enforcement activities. Unfortunately, the county is usually the most disaggregated spatial unit in Brazilian data, and more specific information on location is difficult to find. We therefore compile satellite-based data on night-time lights for the years 1992–2012, and overlay them on maps of county boundaries and rivers, to create measures of light intensity in a buffer surrounding each river, at varying distances to county borders.[14] These data allow us to analyse the spatial distribution of the growth in population and economic activities along the river *within* counties. Satellite-based data is especially useful for this purpose, because a leading hypothesis to explain the pollution effects we document is that counties allow more favelas and informal settlements without adequate sanitation coverage in its downstream regions. Growth in informal activity is better captured through satellite-based measures than through traditional surveys (Henderson *et al*., 2012).

5. ESTIMATION STRATEGY AND RESULTS

We present the empirical results in five steps. We first set up the data such that each observation is a water pollution measure at a specific monitoring station in a specific month. The resulting station-level regression specification is the simplest way to test the first three theoretical predictions, because distance coefficients are easiest to interpret in this format. To test the fourth prediction (on the effects of additional border crossings between a pair on monitoring stations), we next set up the data in a station-pair format where each observation is the change in water quality from an upstream to the adjacent downstream station during a specific month.

After presenting the main tests of the theory in the first two steps, we discuss additional results in Section 6 that address identification concerns relating to the endogeneity of county splitting. In Section 7 we use satellite data on light intensity that proxies for growth *within* upstream and downstream areas of counties, and data on different types of pollutants, to shed light on the underlying mechanisms by which the water pollution changes occur after decentralization. The fifth step compiles data on the electoral make-up across adjacent counties, and on the locations of "water basin management committees"—an emerging organizational form in Brazil designed to manage water, to examine whether Coasian negotiations and political economy mechanisms can mitigate the cross-border pollution spillovers that we document with our water quality data.

5.1. *Station-level regressions*

The estimating equation at the station level is:

$$\begin{aligned}\ln(BOD_{i,t}) = {} & \alpha_i + \sum \delta_{\text{basin-month}} + \sum \gamma_{\text{basin-year}} + \eta_1 \cdot \text{Dist\_Upstr\_Border\_to\_Station } (\mathbf{U1})_{i,t} \\ & + \eta_2 \cdot \mathbf{U1}^2_{i.t} + \eta_3 \cdot \text{Dist\_Station\_to\_Downstr\_Border } (\mathbf{1D})_{i,t} \\ & + \eta_4 \cdot \mathbf{1D}^2_{i.t} + \sum_k \lambda_k \cdot X^k_{i,t} + \alpha_i \cdot \theta_t + \varepsilon_{i,t} \qquad (4)\end{aligned}$$

14. The light intensity data are from the Defense Meteorological Satellite Program-Operation Line Scan (DMSP-OLS) night-time light rasters. We provide details on data and variable construction in Supplementary Appendix F.

Please refer to Figure 4 for our notation on distances U1 and 1D. This equation examines the determinants of variation in BOD over time, controlling for a station fixed effect, seasonal and annual variations in pollution, and time-varying distances to the nearest upstream (U1) and downstream (1D) borders. We have about 16 water pollution observations for each station on average. We control for station fixed effects (α_i) so that the coefficients on the distance variables of interest (η_1,η_2,η_3,η_4) are only identified from changes in border locations over time. Another advantage of the location fixed effects estimates is that natural geographic variation in pollutants and the pollution attenuation rate across different rivers would make cross-sectional estimates less precise. To account for the natural seasonal variation in water quality both within and across years and any secular trends in water quality and decentralization, we include year dummies interacted with indicator variables for each of the eight river basins (γ), and also month dummies specific to each river basin δ (since seasonal effects may vary across the river basins).[15] X is a vector of time-varying controls for key factors which might affect both water quality and county splits, including GDP, population and area of the county where the monitoring station is located. $\alpha_i \cdot \theta_t$ are trends specific to each station that account for gradual changes in unmeasured components of geography, economic activity or demographics, ensuring that the identification of the distance variables of interest is based only on the sharply dated county mayoral elections and associated county splits. Standard errors are clustered by station.

There are two distance variables of interest: (1) Distance from the upstream border to the pollution monitoring station (U1 in Figure 4), and (2) Distance from the station to the border further downstream which is the river's exit point out of the county (1D).[16] Prediction 1 from the theory states that pollution should increase when 1D decreases. Prediction 2 states that the rate of increase in pollution should be faster as 1D gets smaller. To test this prediction we include a non-linear (squared) term for 1D in the specification. Prediction 3 states that the coefficients on 1D and U1 should be different from each other, because this corresponds to a change in slope from upstream to downstream of the border.[17]

5.2. *Results with station-level regressions*

Table 2 shows the results of estimating equation (4) above. In model (1), the coefficient on the variable 1D (distance from station to downstream border) shows evidence consistent with prediction 1 from the theory. For every kilometre closer that a river gets to its exit point out of the county, pollution increases by 2.1%. Furthermore, the statistically significant coefficient on $1D^2$ (distance squared) shows evidence consistent with prediction 2: the increase in pollution as the river approaches the border occurs at a faster rate the closer we get to the border. Ten kilometres from the border, pollution increases at a rate of 1.4% per kilometre, whereas 1 kilometre from the border it increases at a rate of 2.0%. We conduct the non-linearity test with a quadratic specification here, and later will present more flexible tests with splines at varying distances from the border.[18]

15. Some specifications in the regression table will add fixed effects for every month of every year, or fixed effects for every month of every year specific to each river basin and demonstrate that the results are robust to these alternative ways of controlling for seasonality and trends.

16. Using GIS we measure distance along the river, and in most cases this is longer than straight-line crow-fly distance.

17. Note that we measure pollution at monitoring stations, not at borders, and therefore this test compares the slopes of the pollution function upstream of a monitoring station (which is downstream of a border) and downstream from that monitoring station (which is upstream of the next border).

18. If areas far from newly drawn borders are different from areas near borders, then the non-linear term can pick up this heterogeneity. This is why it is important to test for the endogeneity of the location of county splits.

TABLE 2

Station-level regression: determinants of changes in pollution at a station

Dependent variable: 100*LogBOD measured at the station							
Distance from station to downstream border (1D)	−2.097***	−2.108***	−1.773**	−1.961**	−2.080***	−3.118**	−3.355**
	(0.742)	(0.770)	(0.703)	(0.827)	(0.777)	(1.267)	(1.299)
Squared distance from station to downstream border ($1D^2$)	0.034***	0.034***	0.031***	0.033***	0.034***	0.038*	0.040**
	(0.011)	(0.011)	(0.009)	(0.011)	(0.011)	(0.020)	(0.020)
Distance from upstream border to station (U1)	−0.226	−3.295	−3.602	−3.017	−3.393	1.019	−5.027
	(0.934)	(3.171)	(2.788)	(3.241)	(3.173)	(1.954)	(5.252)
Squared distance from upstream border to station ($U1^2$)		0.187	0.182	0.142	0.190		0.411
		(0.192)	(0.181)	(0.223)	(0.191)		(0.376)
Distance follows border downstream of station					−0.107		
					(0.267)		
Distance follows border upstream of station					−0.109		
					(0.531)		
GDP of the county in which the station is located in 100,000 Reis	0.357	0.344	0.253	0.230	0.344	0.004	−0.002
	(0.345)	(0.347)	(0.344)	(0.348)	(0.347)	(0.668)	(0.660)
Population of the county, in 100,000	2.173	1.589	0.971	2.885	1.573	4.914	3.146
	(1.992)	(2.091)	(2.216)	(2.391)	(2.093)	(6.493)	(6.754)
Area of the county, in 100,000 square kilometres	−326.120***	−278.313**	−239.443**	−276.697**	−281.818**	−326.684***	−270.532**
	(125.340)	(114.756)	(113.752)	(120.435)	(117.186)	(94.501)	(119.139)
Basin*year fixed effects	Y	Y	N	N	Y	Y	Y
Basin*month fixed effects	Y	Y	N	N	Y	Y	Y
Month* year fixed effects	N	N	Y	N	N	N	N
Basin*year*month fixed effects	N	N	N	Y	N	N	N
Station trends	N	N	N	N	N	Y	Y
Observations	5,989	5,989	5,989	5,989	5,989	5,989	5,989
R-squared	0.065	0.065	0.060	0.098	0.065	0.134	0.135
Number of station fixed effects	370	370	370	370	370	370	370
F-stat for slope of pollution function upstream = slope downstream (evaluated at 1km from border)	3.157	2.590	3.455	2.130	2.597	0.80	2.223
Prob >*F*	0.0764	0.108	0.0374	0.145	0.108	0.370	0.137
F-stat for slope of pollution function upstream = slope downstream (evaluated at 3km from border)	2.911	2.904	4.363	2.656	2.893	0.711	2.360
Prob >*F*	0.0888	0.0892	0.0638	0.104	0.0898	0.400	0.125
F-stat for slope of pollution function upstream = slope downstream (evaluated at 5km from border)	2.660	3.233	6.177	3.257	3.192	0.620	2.220
Prob >*F*	0.1037	0.0730	0.0134	0.0719	0.0748	0.432	0.137

Notes: Robust standard errors in parentheses.
*** $p<0.01$, ** $p<0.05$, * $p<0.1$.
The dependent variable is 100*the log level BOD at the upstream station. All regressions include station fixed effects. Standard errors are clustered by the station. All regressions include an indicator variable for stations which are not separated by a border, and the distance 1D and U2 (the distance from station 1 to the nearest downstream border and the distance from the nearest upstream border to station 2 are set equal to 0). An indicator variable is also included for cases in which there were no intermediate counties for GDP variables (cases of 0 or 1 crossings).

Next we examine prediction 3—that there should be a break in the slope of the pollution function at the border (or at least an inflection)—by statistically comparing the coefficients on U1 and 1D.[19] Our data do not provide pollution measures *at the border*, so we cannot conduct the usual regression discontinuity test, but the coefficients on 1D and U1 tell us, respectively, the slopes of the pollution function to the left (i.e. upstream) of the border and to the right. As predicted by theory, we find that the slope downstream from a border is more negative than the slope upstream of that border, suggesting a slowing of emissions as the river enters a new county. The coefficient on U1 has the correct sign and implies that the pollution function is negatively sloped to the right of the border. Importantly, the slopes implied by coefficients on 1D and U1 ($+2.097$ and -0.226) are statistically different from each other (p-value for F-test $= 0.076$), which is consistent with prediction 3. Model (2) adds a quadratic term for U1, and the statistical evidence in favour of the break in trend remains strong. The coefficients in model (2) imply that the slope of the pollution function changes from $+2.1$ to -3.3 as we cross the border (p-value of the difference ranges from 0.07 to 0.10 depending on the distance from the border at which the F-statistic is evaluated).

The next three specifications show that the evidence in favour of predictions 1, 2 and 3 from the theory are robust to alternative ways of controlling for seasonality and trends and to adding other controls.[20] These results imply that the pollution function we estimate is very similar in shape to the pollution function implied by the simple theory of externalities (Figure 2). Pollution increases at an increasing rate as the river approaches the downstream (exit) border, but the next county does not allow as much new emissions at its own most upstream locations. Furthermore, the pollution function actually has a negative slope just downstream of the border. This last result is doubly useful, because Supplementary Appendix D shows that this negative slope would be very difficult to reconcile with the possibility that the spillover effects we document are spuriously generated by new borders being drawn in areas with high (or increasing) density.

The last two regressions add a linear trend specific to each station to control for gradual changes in economic activity, geography or population density that may be correlated with county splits. The trends absorb some of the variation in the data, and the standard errors on our coefficients of interest increase. We still find a statistically significant (and slightly larger) effect consistent with Prediction 1: we observe a 3.1–3.4% increase in pollution for every kilometre closer the river gets to the downstream (exit) border. The squared term for distance 1D remains equally large, at 0.38–0.40, and significant. The slope of the pollution function on either side of the border (implied by coefficients on 1D and U1) are different from each other with a p-value of 0.12 to 0.14.

5.3. *Station-pair regressions*

The simple station-level set up does not allow us to test prediction 4 from the theory, since number of border crossings is not defined for a single station. We now set up our data such that a pair of water pollution observations taken in the same quarter from adjacent water quality monitoring stations on the same river forms our unit of observation. We examine the determinants of increases in water pollution from an upstream point (station 1 in Figure 4) to a downstream point (station 2) as a function of county borders crossed in between, and distances of each station to the nearest

19. The appropriate statistical test is coefficient on U1 = - coefficient on 1D, since the coefficient on 1D gives us an indication of the *negative* of the slope of the pollution function.

20. Model 3 introduces fixed effects for every month of every year, and model 4 is more stringent with those fixed effects specific to each river basin. Rivers sometimes form borders and we control for that directly in model 5. Interestingly those (small and statistically insignificant) coefficients imply that when two counties share the river as their border, there is not as much pollution allowed.

upstream and downstream borders:[21]

$$\ln(BOD^2_{i,t})-\ln(BOD^1_{i,t})=\alpha_i+\alpha_i\cdot\theta_t+\sum\delta_{\text{basin-month}}+\sum\gamma_{\text{basin-year}}+\beta_1\cdot\ \text{Border\_Crossings}$$
$$+\beta_2\cdot\ \text{Dist\_Station1\_to\_Downstr\_Border}\ (\mathbf{1D})_{i,t}+\beta_3\cdot\text{Dist\_Upstr\_Border\_to\_Station2}\ (\mathbf{U2})_{i,t}$$
$$+\beta_4\cdot\mathbf{U1}_{i,t}+\beta_5\cdot\mathbf{2D}_{i.t}+\sum_k\lambda_k\cdot X^k_{i,t}+\varepsilon_{i,t} \tag{5}$$

The three coefficients of interest in this regression corresponding to the theoretical predictions are β_1, β_2, and β_3. Prediction 4 states that we should expect β_1 to be positive: pollution increases along a river as a larger number of county borders are crossed. Prediction 1 implies that β_2 is *positive*: as station 1's distance to the exit point out of the county (1D) decreases, pollution measured at station 1 [ln(BOD^1)] should increase, which in turn makes the dependent variable ΔBOD=[ln(BOD^2) −ln(BOD^1)] smaller.[22] Prediction 3 implies that the β_2 and β_3 coefficients should not be equal, and in particular, a negative β_3 would indicate that the pollution function actually changes slope from positive to negative across the border.

In the station-pair setup, we have a larger set of control variables (in the vector X), since each time-varying control—GDP, population, and area—is now measured separately for the county where the upstream monitoring station (1) is located, the county where the downstream station (2) is located, and the distance-weighted average for the "intermediate" counties that the river segment flows through while traveling from station 1 to station 2. Furthermore, in this specification and in all subsequent specifications we control for linear trends specific to each station pair (denoted $\alpha_i\cdot\theta_t$ in the estimating equation). Additionally, we control for the distances of each station to the nearest borders that lie outside of the river segment (U1 and 2D in Figure 4) because our theory suggests that those variables may affect pollution measured at either station 1 or 2. Other fixed effects are the same as in the station-level analysis, and we cluster standard errors by the downstream station in the pair in all specifications.

5.4. *Results in station-pair framework*

The first specification in Table 3 examines the effects of county border crossings on pollution in the river. For each additional border crossed, pollution increases by 3.2%. The next three specifications show that this finding is robust to including a variety of distance controls, including controls for the river forming the county border at various locations. We find robust evidence in favour of prediction 4 in the model: that pollution increases as more borders are crossed. By including a station-pair fixed effect, we derive this evidence on the basis of additional borders crossed by the same river segment in later years due to county splitting. We directly control for time-varying GDP and population in all counties,[23] and add linear trends specific to each river segment, to account for unobserved components of population density and economic activity which may be growing gradually over time and which may be correlated with county splitting.

Re-examining the effects of distances to borders in the station-pair setup, we again find strong evidence in favour of the model's Prediction 1: as the river approaches the downstream exit border

21. Station pairs not separated by a county border are categorized as having zero distances to the borders that don't exist, and we include indicator variables for these cases in all regressions.

22. Note that this is opposite to the expected sign on variable 1D in Table 1, because now pollution measured at station 1 [ln(BOD^1)] appears on the left-hand side of the equation with a *negative* sign.

23. GDP and population affect pollution in the expected direction: population in the county where station 2 is located increases the dependent variable [ln(BOD^2)−ln(BOD^1)], and GDP in the county where station 1 is located decreases the dependent variable [ln(BOD^2)−ln(BOD^1)].

TABLE 3

Station-pair regressions: change in pollution from upstream to downstream station over time

Dependent Variable: Log Difference in BOD (downstream minus upstream)*100				
Number of borders crossed between station 1 and station 2	3.200*	3.595**	3.418**	3.886**
	(1.647)	(1.536)	(1.494)	(1.550)
Distance from station 1 to downstream border (1D)		1.526*	1.771*	1.740*
		(0.885)	(1.029)	(1.028)
Distance from upstream border to station 2 (U2)		−3.101	−3.347	−3.442
		(1.965)	(2.108)	(2.097)
Outside station-pair control variable: distance from upstream border to station 1 (U1)		−1.676	−1.597	−2.179
		(2.244)	(2.244)	(2.257)
Outside station-pair control variable: distance from station 2 to its downstream border (2D)		−0.115	0.119	0.076
		(0.522)	(0.606)	(0.609)
Distance river follows the border to upstream station			0.401	0.590*
			(0.331)	(0.344)
Distance river follows the border to downstream station			1.472	1.302
			(2.274)	(2.273)
Distance river follows the border between stations			0.403	0.320
			(0.640)	(0.624)
Distance river follows the border downstream of downstream station				−0.000
				(0.001)
Distance river follows the border upstream of upstream station				−0.001
				(0.001)
GDP of the county in which the upstream station is located in 100,000 Reis	0.027	−0.233	−0.224	−0.252
	(0.693)	(0.650)	(0.674)	(0.678)
GDP of the county in which the downstream station is located in 100,000 Reis	−0.048	0.009	0.001	0.006
	(0.195)	(0.206)	(0.205)	(0.209)
Population of the upstream county, in 100,000	−6.456	−4.722	−4.024	−3.973
	(7.469)	(7.162)	(7.492)	(7.509)
Population of the downstream county, in 100,000	19.427***	24.111**	20.912**	21.507**
	(5.399)	(9.619)	(9.979)	(10.276)
Area of the upstream county, in 100,000 square kilometres	136.379	234.667	−8.623	7.237
	(210.705)	(204.781)	(438.153)	(430.683)
Area of the downstream county, in 100,000 square kilometres	−144.256**	82.426	114.246	145.269
	(68.011)	(195.500)	(227.955)	(230.920)
Average GDP in intermediate counties in 100,000 R$ in constant 2,000 R$	0.001	0.001	0.001	0.001
	(0.001)	(0.001)	(0.001)	(0.001)
Average Population in intermediate Counties in 100,000 people	−0.000	−0.009	−0.011	−0.012
	(0.009)	(0.014)	(0.014)	(0.014)
Average area in 100,000 square kilometres	−0.230***	−0.190***	−0.207***	−0.180**
	(0.049)	(0.047)	(0.067)	(0.077)
River basin*year FE	Y	Y	Y	Y
River basin*month FE	Y	Y	Y	Y
Station-pair trends	Y	Y	Y	Y
Observations	5,989	5,989	5,989	5,989
R-squared	0.120	0.122	0.122	0.122
Number of pair	372	372	372	372
F-test for slope of pollution function upstream of border = slope downstream of border		5.90	5.72	5.94
Prob >*F*		0.015	0.017	0.0153

Notes: Robust standard errors in parentheses.
*** p<0.01, ** p<0.05, * p<0.1.
The dependent variable is 100*the log difference in BOD between the downstream station and the upstream station. All regressions include station-pair fixed effects, station-pair trends, river basin-year, and river basin month dummies. All regressions also include controls for GDP, population, and area in the upstream county, the downstream county, and the average in the intermediate counties. Standard errors are clustered by the downstream station. All regressions include an indicator variable for stations which are not separated by a border, and the distance 1D and U2 (the distance from station 1 to the nearest downstream border and the distance from the nearest upstream border to station 2 are set equal to 0. An indicator variable is also included for cases in which there were no intermediate counties for GDP variables (cases of 0 or 1 crossings).

out of the county (distance 1D), pollution increases by 1.5–1.7% per kilometre. The coefficient on U2 shows that as the river crosses over to the other side of the border, the slope of the pollution function reverses from $+1.5\%$ to -3.1% per kilometre. The structural break in slope is statistically significant: the *p*-value of the difference in 1D and U2 coefficients is 0.077. The distance results are therefore consistent with both predictions 1 and 3 from the model: pollution increases as the river approaches the downstream (exit) border, but there is a structural break in the slope of the pollution function at the border, and the second (downstream) county appears to not allow new emissions at the same rate in its most upstream region.

Table 3 indicates that the evidence in favour of predictions 1, 3, and 4 is quite robust to alternate specifications and controls. We control for additional distance variables for each station to their nearest borders outside of the river segment (U1 and 2D in Figure 4), and time-varying GDP, population, and area of all counties in between the pair of stations. Some specifications add controls for distances that the river forms a border in different parts of the river segment.[24] Supplementary Appendix G shows that all main results are robust to exclusion of 1, 3 or 5% of outliers in the pollution data.

5.5. *Flexible non-linearity tests of predictions 2 and 3*

In Table 4, we examine (1) the non-linearity in the pollution function at varying distances from the downstream exit border (prediction 2), without imposing a quadratic parametric restriction on the shape of the function like we did in Table 2; and (2) the structural break in the slope of the pollution function at the border, evaluated with data from monitoring stations at varying distances from the border. We conduct these tests with a limited number of splines because we do not have enough data (after controlling for fixed effects and relying on county splits) to present fully non-parametric flexible tests.

For prediction 2, we study the effects of variable 1D (distance of station 1 to nearest downstream border) for stations located close to the border (i.e. within 1, 3, 5, or 15 km from the border in the different specifications) separately from stations located farther from the border. The theoretical expectation is that the effect of 1D measured close to the border should be larger than the effect measured farther away from the border. The point estimates on coefficients imply a pattern consistent with prediction 2: that increases in pollution per kilometre are the largest very, very close to the border. However, estimated standard errors are large, and we cannot precisely identify differences in slope at these varying distance bins, and cannot reject linearity.

For prediction 3 (inflection or break in slope at the border) we test whether the coefficients on 1D and U2 are different from each other, when they are evaluated within 1km of the border (and then 3, 5 and 15km in turn). The coefficients are all consistent with the theoretical prediction, but they are often imprecise. Evaluated within 1km of the border, the slope changes from $+9.4\%$ to -9.5% across the border, but both estimates are imprecise. Evaluated within 3km of the border, the slope changes from $+7.8\%$ to -13%, and these coefficients are significantly different from each other. Further away from the border, the estimates are smaller and statistically insignificant, which is consistent with the theory.

In summary, the coefficient estimates for the flexible non-linearity tests are all generally consistent with the model, but they provide only suggestive evidence. The large standard errors make it clear that the variation in the data is not rich enough to support the border changes-based identification of pollution effects when the data are parsed into small bins.

24. We added these controls in both Table 2 and Table 3 noting (from Figure 3) that the border is sometimes drawn along rivers. Many borders along rivers is already controlled for through the station pair fixed effect, and the variation that remains is the change in the distance the river flows along borders after counties get split.

TABLE 4
Non-linearity in the pollution function, at varying distances from borders

	Split at $x=1$	Split at $x=3$	Split at $x=5$	Split at $x=15$
U2—far from border (distance from upstream border to station 2 * beyond x km of station)	−2.523	−3.129	−2.624	−1.290
	(1.990)	(1.957)	(1.987)	(1.460)
U2—close to border (distance from upstream border to station 2 * within x km of station)	−9.510	−12.887***	−4.347	−4.040
	(18.927)	(4.621)	(4.262)	(3.509)
1D—close to border (distance from station 1 to downstream border within x km of station)	9.372	7.765	0.446	−0.734
	(15.566)	(4.722)	(2.235)	(2.118)
1D—far from border (distance from station 1 to downstream border * beyond x km from station)	1.941*	2.125**	1.794*	1.609*
	(1.066)	(1.000)	(1.075)	(0.956)
2D Distance from station 2 to downstream border	−0.025	0.124	−0.009	−0.916
	(0.485)	(0.501)	(0.494)	(0.799)
U1 Distance from upstream border to station 1	−2.452	−2.369	−2.453	−2.158
	(2.278)	(2.197)	(2.310)	(2.275)
Observations	5,989	5,989	5,989	5,989
R-squared	0.120	0.121	0.120	0.120
Number of pair	372	372	372	372
F-stat for slope upstream of border = slope downstream of border (U2 close = ID close)	0.628	8.418	0.808	0.558
Prob >F	0.429	0.00410	0.370	0.456
F-stat for test of non-linearity in slope (1D close = 1D far)	0.230	1.442	0.565	1.865
Prob >F	0.632	0.231	0.453	0.173

Notes: Robust standard errors in parentheses.
*** p<0.01, ** p<0.05, * p<0.1.
The dependent variable is 100*the log difference in BOD between the downstream station and the upstream station. All regressions include station-pair fixed effects, station-pair trends, river basin-year, and river basin month dummies. GDP, population, area controlled in all specifications but not shown. Standard errors are clustered by the downstream station. All regressions include an indicator variable for stations which are not separated by a border, and the distance 1D and U2 (the distance from station 1 to the nearest downstream border and the distance from the nearest upstream border to station 2 are set equal to 0). An indicator variable is also included for cases in which there were no intermediate counties for GDP variables (cases of 0 or 1 crossings).

6. ENDOGENEITY OF COUNTY SPLITS

A key concern for our estimation strategy based on county border changes is whether the non-random choice of locations where new borders are drawn can explain the patterns in the data we report. The most straightforward example is that if districts with increases in population density or economic activity are more likely to separate from the county, then water quality may deteriorate around new borders anyway. We will address these concerns in three ways in addition to the controls for time-varying population density and local GDP, and the location-specific trends to account for gradual changes in other unmeasured attributes that we have already added.

First, theoretical exercises in Supplementary Appendix D show that alternative mechanisms would not easily generate the four results associated with predictions 1–4 that we document in the data. Supplementary Appendix D first considers the specific case of new borders drawn in high density areas and shows that the result associated with prediction 3 (the structural break in slope at the border) is not replicated in that model. Another potential theory—that new borders are drawn in outlying low density areas of counties in between two areas of increasing density which split to form their own jurisdictions—is not easy to reconcile with the empirical results we obtain for prediction 2 (that pollution increases at an increasing rate as we approach borders). Such splits could lead to a negative slope for the pollution function as we approach the downstream border, in contrast to what we actually find.

Second, we conduct pre-trend analysis of our main specifications by setting up a falsification test where we assume that the county splits (and associated distance and border crossing changes) occur in the years *before* they actually occurred, to explore whether the same pollution effects can be uncovered in those "placebo" years. Table 5 reports the results of both station-level (replicating specifications found in Table 2) and station-pair (replicating Table 3) regressions that use only the sub-sample of "pre-trend data" (before splits actually occur). To set up these placebo tests, we incorrectly code county splits to have already occurred during the pre-trend years and exclude the data for years following the true split. This is the most direct way to test whether the pre-existing water pollution patterns around county borders that get split are such that we would see spurious evidence in favour of the theoretical predictions.

The first three columns of Table 5 display no evidence in favour of predictions 1, 2, or 3 in the placebo setup, compared to the evidence presented in Table 2. There is no statistically significant increase in pollution as the river approaches the exit border, no evidence of non-linearity in the pollution function, and there is no discontinuity in the pollution function at the border. The clearest piece of evidence that there is no effect in the placebo test is in column 2, where the slopes of the pollution function to the left and to the right of the border are almost identical to each other.

The last two columns show that there is also no evidence in favour of prediction 4 during the placebo period. Additional (fake) border crossings at the locations where borders *will be drawn* do not lead to any statistically significant increase in pollution. The coefficient sign on border crossings is in the same direction as the actual effect documented in Table 3, but it is only about half as large. The coefficient on distance to the (fake) border is in the opposite direction to what is predicted by theory (and documented in Table 3): the pollution function slopes downward as the river approaches the location where the exit border *will be drawn*. In summary, the pre-trends in the data do not mirror the pollution patterns consistent with the theory that we document *after* the county split actually occurs and new borders are drawn. This makes it unlikely that the effects reported in this article are spuriously driven by the pre-existing pollution characteristics around locations where counties are split.

We introduce a third method to address concerns about endogenous splitting which takes advantage of the fact that there is sufficient variation in the data such that we can directly control for county splitting—and therefore all other factors associated with the decision to split—while also estimating the pollution effects of distance to borders. This is because different county splits in the data change monitoring stations' distances to the nearest border (1D) to different extents—sometimes leading to a large decrease in the number of kilometres, and other times a small decrease. The splits also cause variation in the number of border crossings between two monitoring stations (e.g. from 1 to 2, or sometimes from 4 to 6). In Table 6, we re-estimate (4) (and reconstruct Table 3, the station-pair regressions), except that we directly control for a set of indicators for whether the county split occurred in each period at the upstream and at the downstream monitoring station. In principle, these indicators should account for all political, demographic and economic factors associated with the decision to split.

The county split indicators soak up much of the variation in the data that is useful for identifying our coefficients of interest, and some of the standard errors increase accordingly. However, the main results we report in the article remain quantitatively and qualitatively similar. Each additional border crossing is associated with a 4.8–5.5% increase in pollution (prediction 4), and this effect remains highly statistically significant. The coefficient on 1D remains positive (prediction 1), but now loses statistical significance. The coefficient on U2 (slope of the pollution function downstream of the border) is negative and significant, and importantly, the coefficients on 1D and U2 are still different from each other (p-value of 0.062–0.078), which implies that there is a structural break in the slope of the pollution function at the border (prediction 3), as predicted by the theory.

TABLE 5
Falsification tests: using pre-split periods as a placebo check

	(1)	(2)	(3)	(4)	(5)
Dependent variable:		100*LogBOD measured at the station		Log difference in BOD (downstream minus upstream)*100	
Number of borders crossed between station 1 and station 2				2.069	2.257
				(2.390)	(2.136)
Distance from station to downstream border (1D)	−0.316	−1.217	−1.341		−5.153
	(1.298)	(2.251)	(2.439)		(3.674)
Squared distance from station to downstream border ($1D^2$)	0.014	0.016	0.018		
	(0.016)	(0.029)	(0.032)		
Distance from upstream border to station (U1)	−2.991	1.231	−1.798		−1.142
	(3.358)	(3.007)	(6.698)		(6.124)
Squared distance from upstream border to station ($U1^2$)	0.202		0.211		
	(0.269)		(0.604)		
Distance from upstream border to station 2 (U2)					−0.565
					(1.474)
Outside station-pair control variable: distance from upstream border to station 1 (U1)					0.373
					(2.601)
GDP of the county in which the upstream station is located in 100,000 Reis	0.339	−0.013	−0.012	0.951	0.936
	(0.367)	(0.693)	(0.687)	(0.827)	(0.821)
GDP of the county in which the downstream station is located in 100,000 Reis				−0.081	−0.037
				(0.250)	(0.248)
Population of the upstream county, in 100,000	−0.806	5.420	4.432	−13.690	−7.430
	(1.648)	(8.271)	(8.190)	(8.849)	(11.447)
Population of the downstream county, in 100,000				13.454	20.707
				(50.385)	(53.399)
Area of the upstream county, in 100,000 square kilometres	−376.438***	−309.724***	−282.247**	529.153	506.645
	(130.168)	(118.678)	(110.504)	(438.771)	(441.325)
Area of the downstream county, in 100,000 square kilometres				224.024	269.203
				(411.403)	(414.911)
Average GDP in intermediate counties in 100,000 R$ in constant 2,000 R$				0.001	0.001
				(0.001)	(0.001)
Average population in intermediate Counties in 100,000 people				0.009	0.008
				(0.009)	(0.009)
Average area in 100,000 square kilometres				−0.113	−0.130
				(0.172)	(0.175)
River basin*year FE	Y	Y	Y	Y	Y
River basin*month FE	Y	Y	Y	Y	Y
Station-pair trends	N	Y	Y	Y	Y
Observations	5,139	5,139	5,139	4,239	4,239
R-squared	0.068	0.141	0.141	0.148	0.149
Number of station FE	344	344	344	327	327
F-test for slope of pollution function upstream of border = slope downstream of border					1.180
Prob >*F*					0.279
F-stat for equality of dist coefficients	0.740	0.000	0.156		
Prob >*F*	0.390	0.986	0.694		
F-stat for equality of dist coefficients	0.755	0.002	0.154		
Prob >*F*	0.385	0.966	0.695		
F-stat for equality of dist coefficients	0.659	0.005	0.110		
Prob >*F*	0.417	0.945	0.742		

Robust standard errors in parentheses. Sample includes observations for years prior to and during a county split, and observations for counties with no splits. Sample size differs between the station and station-pair specifications because of differences in timing of splits between upstream and downstream stations. *** $p<0.01$, ** $p<0.05$, * $p<0.1$.

TABLE 6
Station-pair regressions directly controlling for county splits

Dependent variable: Log difference in BOD (downstream minus upstream)*100				
Number of borders crossed between station 1 and station 2	4.785**	5.258***	4.966***	5.494***
	(1.994)	(1.576)	(1.507)	(1.519)
Distance from station 1 to downstream border (1D)		1.022	1.386	1.368
		(0.927)	(1.103)	(1.096)
Distance from upstream border to station 2 (U2)		−4.630*	−4.769*	−4.847**
		(2.527)	(2.467)	(2.447)
Outside station-pair control variable: distance from upstream border to station 1 (U1)		−1.899	−1.791	−2.536
		(3.367)	(3.347)	(3.201)
Outside station-pair control variable: distance from station 2 to its downstream border (2D)		−0.083	0.209	0.160
		(0.500)	(0.597)	(0.589)
Distance river follows the border to upstream station			−0.055	0.286
			(0.471)	(0.539)
Distance river follows the border to downstream station			2.332	2.104
			(2.180)	(2.195)
Distance river follows the border between stations			0.490	0.473
			(0.688)	(0.683)
Distance river follows the border downstream of downstream station				0.000
				(0.001)
Distance river follows the border upstream of upstream station				−0.002
				(0.001)
New county post-split, downstream	−6.120	−31.682*	−27.819*	−26.062*
	(14.428)	(16.645)	(14.235)	(14.425)
Old county post-split downstream	9.614	2.385	0.115	1.620
	(16.903)	(18.613)	(19.316)	(19.684)
New county post-split upstream	10.324	12.414	9.835	9.765
	(19.023)	(22.660)	(21.250)	(21.770)
Old county post-split upstream	24.975*	22.617	22.450	22.552
	(15.013)	(16.106)	(16.934)	(17.080)
GDP of the county in which the upstream station is located in 100,000 Reis	0.381	0.313	0.339	0.322
	(0.750)	(0.805)	(0.825)	(0.835)
GDP of the county in which the downstream station is located in 100,000 Reis	−0.086	−0.093	−0.104	−0.104
	(0.182)	(0.176)	(0.176)	(0.181)
Population of the upstream county, in 100,000	−5.028	−7.791	−6.358	−5.609
	(8.072)	(9.177)	(9.524)	(9.631)
Population of the downstream county, in 100,000	17.566*	10.954	8.212	8.813
	(9.244)	(10.734)	(11.525)	(11.562)
Area of the upstream county, in 100,000 square kilometres	−96.025	−41.334	−487.624	−547.910
	(195.025)	(176.710)	(489.395)	(493.358)
Area of the downstream county, in 100,000 square kilometres	−253.363*	130.387	177.779	222.210
	(144.184)	(270.482)	(291.354)	(300.591)
Average GDP in intermediate counties in 100,000 R$ in constant 2,000 R$	−0.000	−0.000	−0.000	−0.000
	(0.001)	(0.001)	(0.001)	(0.001)
Average population in intermediate counties in 100,000 people	0.007	−0.002	−0.003	−0.005
	(0.011)	(0.015)	(0.016)	(0.015)
Average area in 100,000 square kilometres	−0.323***	−0.241	−0.215	−0.111
	(0.124)	(0.162)	(0.188)	(0.210)
River basin*year FE	Y	Y	Y	Y
River basin*month FE	Y	Y	Y	Y
Station-pair trends	Y	Y	Y	Y
Observations	5,540	5,540	5,540	5,540
R-squared	0.121	0.125	0.125	0.126
Number of pair	366	366	366	366
F-test for slope of pollution function upstream of border = slope downstream of border		3.134	3.400	3.523
Prob >*F*		0.078	0.066	0.062

Notes: Robust standard errors in parentheses.
*** p<0.01, ** p<0.05, * p<0.1.
The dependent variable is 100*the log difference in BOD between the downstream station and the upstream station. All regressions include station-pair fixed effects, station-pair trends, river basin-year, and river basin month dummies. All regressions also include controls for GDP, population, and area in the upstream county, the downstream county, and the average in the intermediate counties. Standard errors are clustered by the downstream station. All regressions include an indicator variable for stations which are not separated by a border, and the distance 1D and U2 (the distance from station 1 to the nearest downstream border and the distance from the nearest upstream border to station 2 are set equal to 0. An indicator variable is also included for cases in which there were no intermediate counties for GDP variables (cases of 0 or 1 crossings).

6.1. *Characteristics of counties that split*

We find strong, robust evidence that additional border crossings are associated with increased pollution, which suggests that the overall effect on water quality of the decentralization embodied in county splitting is negative. In this sub-section, we use additional public finance and census data to shed light on the various socio-economic and budgetary changes that occur when counties split, so that we gain a more comprehensive understanding of how counties change following a split. We also investigate the characteristics of split areas before splits occur, because our empirical strategy identifies pollution effects specifically from such areas. Identifying these characteristics helps us understand the types of locations that our estimated local average treatment effect represents.

Table 7 shows that prior to a split per capita public expenditures look very similar between municipalities which split and those which remain intact. The total budget allocated to the local governments increases when counties split, because the combined replacement budget of the two new counties typically exceeds the budget of the original county. Areas that are split are generally more developed—less rural, more electrified, and have 5 percentage points more networked water connections. Development and budgetary allocations may have opposing effects on water quality but they generally would not explain the spatial pollution shifting towards borders.

The lower panel of Table 7 shows some of the effects of increased municipal budgets after the split—increases in municipal capital expenditures and regional development expenditures per capita. The deteriorating water quality we observe in our data occurs in spite of the increase in local spending that is likely to have a cleansing effect on the water.

7. UNDERSTANDING MECHANISMS USING SATELLITE DATA AND SPECIFIC POLLUTANT DATA

Our interpretation of the specific spatial patterns of pollution within counties that we document requires that politicians have access to policy levers that allow them to spatially target emissions into rivers. Our conversations with water management practitioners in Brazil indicate that there are two primary ways that this could happen: (1) informal zoning decisions and permissions that determine how close to water bodies slums or *favellas* with inadequate water and sanitation support are allowed to locate, and (2) differential enforcement of pollution permit regulations for firms and settlements in downstream locations relative to portions of the county further upstream. This sub-section uses additional data sources to examine these mechanisms.

Directly testing these mechanisms would require data on the location of favellas or the locations of polluting firms *within* counties. Unfortunately, the exact placement of pollution emissions within a county in Brazil cannot be directly identified.[25] The most disaggregated spatial indicator for any useful census data (e.g. on households with or without sewage connections) is the county. To get around the data vacuum, we compile satellite-based data on light intensity along rivers from 1992 to 2012. The data sources and compilation process are described in Supplementary Appendix F. Overlaying maps of the evolving county boundaries on annual maps of night-time lights and rivers data allow us to construct measures of the spatial patterns of growth along rivers *within* counties. To explore the mechanisms that practitioners have cited, we examine whether there is greater growth (of both formal and informal settlements) in downstream portions of counties after counties split.

25. To our knowledge the best available evidence on direct emissions in Brazil is Ferraz (2007) work on firms' environmental licenses, but that work also does not have within-county spatial information. Some other research using province-level analysis in China (analogous to Brazilian states, which is a higher level of jurisdictional aggregation) shows that polluting firms are more likely to be located in downstream counties within provinces.

TABLE 7
Summary statistics for counties involved in splits

	Obs.	Mean	Std. Dev.	Obs.	Mean	Std. Dev.	Diff. p-value
	Not split in 1994			Split in 1994			
Municipal capital expenditures (1,993 R$ per capita)	3,915	2.206	3.334	278	2.371	2.547	0.420
Municipal operating expenditures (1,993 R$ per capita)	3,928	1.065	3.275	278	1.258	0.882	0.328
Regional development expenditures (1,993 R$ per capita)	3,928	0.008	0.087	278	0.004	0.024	0.460
Habitat and urban development Expenditures (1,993 R$ per capita)	3,928	0.626	1.511	278	0.571	0.534	0.544
Health and sanitation expenditures (1,993 R$ per capita)	3,928	0.709	1.795	278	0.643	0.871	0.543
Capital investments (1,993 R$ per capita)	3,915	2.018	3.249	278	2.080	2.510	0.756
Capital transfers from others (1,993 R$ per capita)	3,915	0.480	0.990	278	0.654	1.980	0.010
Percent rural (1991)	3,928	0.459	0.230	278	0.407	0.227	0.000
Percent employed (1991)	3,928	0.381	0.101	278	0.560	0.163	0.000
Percent connected to networked water (1991)	3,928	0.390	0.242	278	0.439	0.234	0.001
Percent electrified (1991)	3,928	0.712	0.229	278	0.792	0.204	0.000
Percent with installed bathrooms (1991)	3,928	0.148	0.249	278	0.126	0.233	0.152
Population (as of 1991)	3,928	31,388	197,061	278	36,932	68,122	0.640
	Obs.	Mean	Std. Dev.	Obs.	Mean	Std. Dev.	Diff. p-value
	Not new as of 1997			New as of 1997			
Municipal capital expenditures (2,000 R$ per capita)	4,746	73.363	133.270	548	91.492	77.467	0.002
Municipal operating expenditures (2,000 R$ per capita)	4,746	101.660	415.311	548	99.833	80.489	0.918
Regional development expenditures (2,000 R$ per capita)	4,746	0.343	2.501	548	0.604	4.420	0.036
Habitat and urban development Expenditures (2,000 R$ per capita)	4,746	48.693	150.748	548	40.609	46.232	0.212
Health and sanitation expenditures (2,000 R$ per capita)	4,746	89.467	127.990	548	88.331	61.896	0.838
Capital investments (2,000 R$ per capita)	4,746	62.341	130.269	548	86.421	75.158	0.000
Capital transfers from others (2,000 R$ per capita)	4,746	4.804	32.348	548	3.977	16.127	0.555
Capital transfers from the state (2,000 R$ per capita)	4,746	5.369	41.276	548	5.062	17.593	0.863
Percent rural (2000)	4,746	0.390	0.226	548	0.577	0.235	0.000
Percent employed (2000)	4,746	0.392	0.082	548	0.386	0.101	0.137
Percent connected to networked water (2000)	4,746	0.597	0.223	548	0.396	0.254	0.000
Percent electrified (2000)	4,746	0.871	0.150	548	0.762	0.212	0.000
Percent with installed bathrooms (2000)	4,746	0.249	0.294	548	0.075	0.169	0.000

TABLE 8
Effects of borders on the intensity of lights along rivers

	(1)	(2)	(3)	(4)	(5)	(6)
	Full sample	Points that ever became "downstream" in only counties that experienced a split			Excludes "city centres"	
Downstream area indicator [0,0.1]	0.082***	−0.109		0.126*	0.135***	0.078***
	(0.031)	(0.104)		(0.068)	(0.039)	(0.027)
Normalized distance upstream from border	0.325***	−1.171***	−0.362**		0.588***	
	(0.079)	(0.299)	(0.179)		(0.096)	
(Distance upstream)^2	−0.312***	1.037***	0.348*		−0.638***	
	(0.069)	(0.271)	(0.207)		(0.078)	
Downstream × distance upstream	−3.707***	−3.070		−4.090*	−7.742***	−7.816***
	(1.002)	(2.323)		(2.266)	(1.245)	(1.248)
Downstream × distance upstream^2	32.694***	30.022		29.568	60.608***	64.726***
	(9.437)	(19.556)		(19.186)	(13.811)	(13.803)
Constant	1.360***	0.789***	0.591***	0.543***	0.816***	0.889***
	(0.021)	(0.075)	(0.027)	(0.032)	(0.029)	(0.005)
Observations	7,300,531	108,288	108,288	108,288	3,672,371	3,672,371
R-squared	0.030	0.022	0.022	0.022	0.025	0.025
Number of 1km rasters (where brightness measurements are taken)	456,374	6,768	6,768	6,768	246,152	246,152

Notes: Robust standard errors in parentheses.
*** p<0.01, ** p<0.05, * p<0.1.
Columns 3–5, the downstream only sample includes only areas with stations which are downstream of another station at some point in the data. The no city centre sample excludes areas with high relative population density. The dependent variable is the brightness of lights at night in each 1km gridded raster near rivers in Brazil.
20% of river distance around the brightest point.

Table 8 shows the effects of distance to the downstream exit border on light intensity in a buffer along the river, controlling for fixed effects for each of the 456,374 points where the light measures are taken. The coefficients are therefore identified on the basis of time-variation in distances, as borders change due to county splits. We measure proximity to the exit border as a fraction of total distance that the river traverses through that county. The first variable used for analysis is an indicator for the downstream portion of the county, defined as distance values ∈[0,0.1]—or the portion of the county which is within 10% of the exit border. This allows us to study whether more settlements are permitted in the areas that become the most downstream portion of the county once another district splits off. We also control for distance and distance-squared, and the interaction between the downstream area indicator and these distances, to examine how the light density changes within downstream areas as we approach the exit border.

The first coefficient in Table 8 shows that there is an extra growth in lights in areas that become the downstream portion of the county after a split occurs, relative to other river-bank areas further upstream. This indicates that counties are more likely to allow formal and informal settlements to grow close to the river in its most downstream locations. To be clear, the magnitude of the effect is small, although it is statistically significant: this represents an extra 0.04% growth in lights in downstream areas, relative to the mean value of the index of brightness.

We also study the precise spatial pattern of light growth in downstream areas using the variable "distance from the exit border" (its square term, and the interactions with the downstream indicator). The coefficients are reported in column 1, and the resulting estimated values of light intensity at varying distances to the border are plotted in Figure 6. There is clear evidence of a non-linear increase in light brightness as the river heads towards the exit point out of the county.

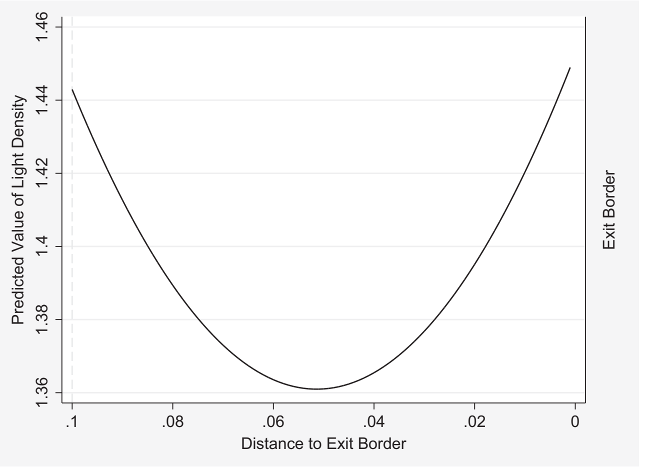

FIGURE 6

Predicted value of lights in downstream area full sample

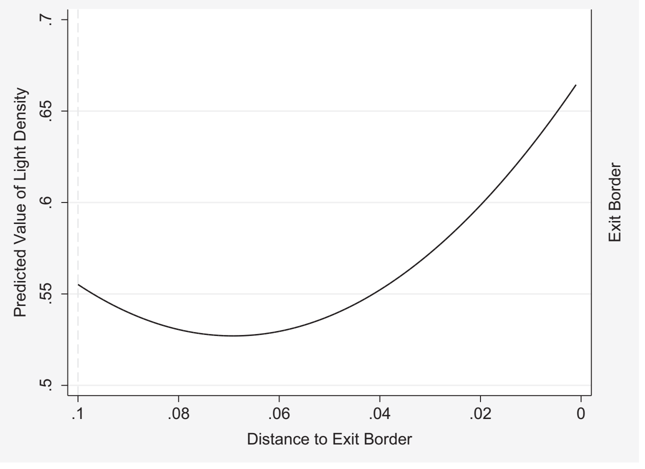

FIGURE 7

Predicted value of lights in downstream area downstream stations only

Notes: Fitted values based on regression results found in Column 4 of Table 8.

In the next three columns (and associated Figure 7), we estimate these relationships focusing only on counties that experienced a split, and the points that became downstream due to the split. We focus on this sub-sample so that identification is only based on points that are affected by county splits and border changes. Figure 7 shows clear evidence of increasing night-time light intensity as the river heads towards the downstream exit point out of the county. The effects remain statistically significant in this sub-sample, and the magnitudes remain modest—the index of brightness increases by 0.02% of mean value for every percentage point increase in proximity for the river to the exit border. The last two columns of Table 8 show that these results are robust to excluding city centres, where more of the growth is likely to be "formal" with proper sewage connections. In this sub-sample, brightness increases by 0.03% for each percentage point increase

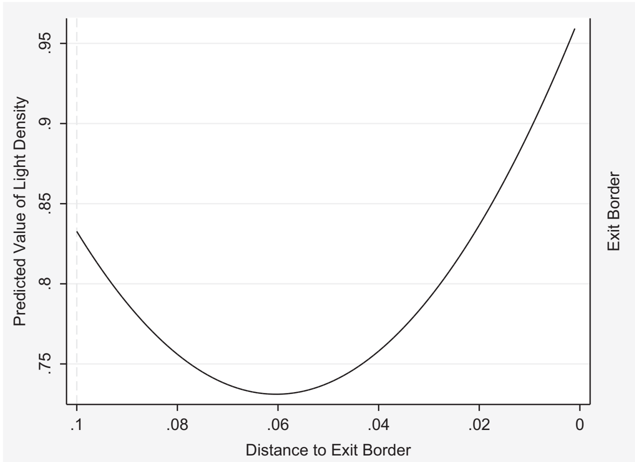

FIGURE 8

Predicted value of lights in downstream area excluding city centres

Notes: Fitted values based on regression results found in Column 6 of Table 8.

in proximity of the river to the exit border. The non-linear pattern as the river approaches the exit border is shown in Figure 8.

While the effect sizes are modest, these results are consistent with local water experts' hypothesis that some of the border pollution effects are derived from informal settlement construction without proper sewage treatment closer to water bodies. These results provide some systematic support to anecdotes such as "vast amounts of raw sewage leak into the waters, with less than 40% currently treated" in the bay downstream of Rio de Janeiro city, and The Rio State Environmental Institute's estimates that "more than 10% of the trash [in Rio] is not collected … and flows through canals and degraded rivers" (New York Times, 2014).

Descriptive surveys also support this story. Table 9 uses the 2002 Environmental Census conducted by the Brazilian National Statistical Agency to describe the major sources of water pollution. The single most common source of pollution reported by counties is domestic sewage which is managed at the county level. To be sure, the data show that counties can affect water quality through other policy choices as well: 12% of all counties (and 35% of those with water pollution problems) cite poor enforcement of pollution regulations as a source of pollution problems. Panel B in Table 9 shows that counties engage in a wide range of activities to address the problem, including monitoring and fining polluters. Feler and Henderson (2011) report many instances of systematic under-provision of public water and sanitation services in slums across Brazil, strong prevalence of informal housing, and they document strategic under-provision of public services by counties.

Yet another form of evidence about the underlying mechanisms comes from examination of specific pollutants. It is easier for policymakers to spatially target emissions for point-source pollutants than for diffuse sources such as run-off from farms. If the political economy mechanism that our model highlights is correct, then we should not observe the same spatial patterns of pollution when we examine pollution created by diffuse sources of emissions. The preferred water pollution measure we use (BOD) is most closely associated with municipal sewage, although it may also indicate chemical pollution from firms or farms. In Table 10, we examine the effects of distance to borders on three pollution measures associated with soil erosion: suspended solids, turbidity, and electrical conductivity of the water. Erosion tends to be heavily influenced by

TABLE 9
Causes of and responses to water pollution

Panel A. County-reported causes of water pollution	Count*
Mining	235
Oil and gas from boats	81
Animal Waste	832
Materials from the processing of sugar	160
Industrial dumping	521
Domestic sewage	1,595
Poor solid waste management	821
Poor enforcement of river pollution regulations	648
Poor enforcement of underground water rights licensing	228
Use of pesticides and fertilizers	901
Others	160
Total counties reporting water pollution	2,121
Panel B. County actions to reduce pollution	
Fining Households with inadequate sewer systems	2,462
Fining Companies with inadequate industrial waste management systems	1,007
Monitoring of potentially polluting industrial activities	596
Taxing mining industries	1,027
Taxing automobiles	104
Management of toxic waste	483
Trash collection program	1,654
Recycling program	1,082
Creation of sewers	1,949
Other	564

Notes: *Counts are as of 2002. There were 5,560 counties in Brazil in 2002. *Source:* IBGE Environmental Census.

non-point source (agricultural) pollution. In these placebo tests, we do not find any strong evidence of strategic pollution shifting around borders. In other words, for emissions sources that are not easy for county policymakers to manipulate, there are no systematic effects of county borders.

8. NEGOTIATED SOLUTIONS: EVIDENCE FROM WATER BASIN COMMITTEES AND POLITICAL AFFILIATION

The border effects on pollution that we observe in our data suggest that inter-jurisdictional cooperation is essential for protecting water quality and health. Brazil has now recognized this problem, and has initiated a policy shift toward integrated river basin management (Porto and Kelman, 2005). River basins are the natural geographic units which encompass the interests of all potential users and many water sector experts promote management at this level (Abu-Zeid and Biswas, 1996; Saleth, 2002; Mody, 2004). Basin committees in Brazil encourage participation by all actors with a vested interest: federal, state and county government representatives, user groups, and members of civil society. Committee discussions are meant to increase the flow of information and spur bargaining over water quality and quantity between upstream and downstream counties. In line with Ostrom (1990, **?**), we interpret these committees to be institutions that mitigate a tragedy of the commons problem. We describe a history of these committees in Brazil, and further details on their mandate and structure in Supplementary Appendix H. We have collected data on the 153 basin committees operating in Brazil, and the years that they have been active. We use these data to investigate whether the presence of basin committee-based negotiations between upstream and downstream jurisdictions helps to mitigate the sharper increases in water pollution at borders that we have documented.

In the first two columns of Table 11, we re-estimate our main station-level specification (from Table 2) separately for station-years in which a water basin committee was operating and

TABLE 10
Non-point source pollution measures (placebo check)

	Log total dissolved solids Top 1% dropped		Log turbidity Top 1% dropped		Log conductivity Top 1% dropped	
Distance from station 1 to Downstream border (1D)	−0.880	0.142	−0.690	−0.172	−0.604	−0.358
	(1.758)	(1.803)	(1.427)	(1.769)	(0.928)	(1.509)
Squared distance from station 1 to downstream border ($1D^2$)	−0.027	−0.018	0.064**	0.055**	−0.019	−0.031
	(0.025)	(0.024)	(0.027)	(0.027)	(0.016)	(0.026)
Distance from upstream border to station 1 (U1)	−2.492	−1.860	0.337	−4.169	2.468	2.849
	(3.434)	(3.611)	(5.138)	(6.522)	(2.696)	(3.265)
Squared distance from upstream border to station 1 ($U1^2$)	0.394*	0.286	0.038	0.129	−0.326*	−0.164
	(0.235)	(0.237)	(0.289)	(0.364)	(0.192)	(0.179)
GDP of the county in which the upstream station is located in 100,000 Reis	0.153	0.112	0.534	1.058***	0.262	−0.041
	(0.185)	(0.214)	(0.683)	(0.249)	(0.300)	(0.201)
Population of the upstream county, in 100,000	1.784	0.050	−4.429	−15.395***	−1.452	−4.173
	(2.741)	(3.745)	(7.553)	(5.859)	(4.053)	(6.149)
Area of the upstream county, in 100,000 square kilometres	46.575	−146.387	649.018	866.618**	−262.508	−118.067
	(195.073)	(387.602)	(423.448)	(342.418)	(293.611)	(372.832)
Includes station-pair trends	N	Y	N	Y	N	Y
Observations	4,883	4,883	5,454	5,454	5,651	5,651
R-squared	0.213	0.276	0.374	0.428	0.133	0.228
Number of station FE	300	300	357	357	363	363

Notes: Robust standard errors in parentheses.
*** p<0.01, ** p<0.05, * p<0.1.
All regressions include station-pair fixed effects. Standard errors are clustered by the station. All regressions include an indicator variable for stations which are not separated by a border, and the distance 1D and U2 (the distance from station 1 to the nearest downstream border and the distance from the nearest upstream border to station 2 are set equal to 0). An indicator variable is also included for cases in which there were no intermediate counties for GDP variables (cases of 0 or 1 crossings).

station-years in which there was no basin committee. Column 1 shows that our main results replicate almost exactly in the sub-sample with no basin committee presence: Water pollution increases closer to the downstream exit point out of the county (prediction 1) at an increasing rate (prediction 2), and there is a statistically significant change in the slope of the pollution function at the border (prediction 3). These predictions do not hold in the sub-sample where basin committees operate: none of these coefficients are significant in the second column. The third column runs this test using the full sample and interaction terms. The coefficient on the basin committee term suggests that pollution levels are generally lower when basin committees are in operation, but this effect is not statistically significant.[26] The distance interaction terms show that (1) without basin committees, pollution increases by 2.1% every kilometre closer the river is to the downstream exit border, but in areas with basin committees, the effect is 0.3% (−2.1+1.8), and not distinguishable from zero; (2) pollution increases at an increasing rate as we approach the border in areas without basin committees, but there is no such non-linearity (the coefficient on the square term is of the opposite sign) in committee areas. In summary, the data suggests that basin committees enhance neighbouring jurisdictions' ability to cooperate or negotiate, and the spatial patterns of pollution consistent with a model of inter-jurisdictional externalities are no longer present when committees operate.[27]

26. Basin committees were still a novel concept during the period of our data, and our data coverage for committees is therefore sparse. These results are only suggestive, and this is a fruitful area for further research.

27. These results are merely suggestive, because basin committee formation may be endogenous to other characteristics of the jurisdiction that are correlated with pollution patterns. However, the qualitative literature on basin

TABLE 11

Station-level regressions: are border effects on pollution mitigated when basin committees are formed, or party affiliations of mayors in neighbouring counties match?

Dependent variable: 100*LogBOD measured at the station	No basin committee	Water basin committee in operation	Full sample	Full sample (1996 onwards)	Full sample (1996 onwards)
Distance from station 1 to downstream border (1D)	−2.181***	2.603	−2.154***	−3.009**	−2.823**
	(0.779)	(4.857)	(0.778)	(1.383)	(1.406)
Squared Distance from station 1 to downstream border ($1D^2$)	0.033***	0.414	0.034***	0.044*	0.038*
	(0.011)	(0.465)	(0.011)	(0.023)	(0.023)
Distance from upstream border to station 1 (U1)	0.178	0.822	0.187	0.267	0.244
	(0.194)	(0.600)	(0.192)	(0.326)	(0.329)
Squared Distance from upstream border to station 1 ($U1^2$)	−3.224	−16.662	−3.294	−4.555	−4.160
	(3.201)	(12.294)	(3.177)	(3.969)	(3.993)
Basin committee in operation (1=Yes)			−10.757		
			(9.271)		
Basin committee * distance from station 1 to downstream border (1D)			1.840		
			(2.216)		
Basin Committee * squared distance from station 1 to downstream border (1D)			−0.096		
			(0.100)		
Downstream party match (1=Yes)				3.234	
				(4.501)	
Downstream party match * Distance from station 1 to downstream border (1D)				0.109	
				(0.462)	
Downstream party match * squared distance from station 1 to downstream border (1D)				0.002	
				(0.005)	
Upstream party match (1=Yes)					5.661
					(6.581)
Upstream party match * Distance from station 1 to downstream border (1D)					0.010
					(0.019)
Upstream Party Match * squared distance from station 1 to downstream border (1D)					−0.441
					(0.786)
GDP of the county in which the station is located in 100,000 Reis	0.364	−1.496	0.355	0.078	0.129
	(0.343)	(1.530)	(0.348)	(0.375)	(0.383)
Population of the county, in 100,000	1.336	22.296	1.425	0.523	1.081
	(2.119)	(51.330)	(2.084)	(4.037)	(4.328)
Area of the county, in 100,000 square kilometres	−280.355**	−4,600.778	−278.219**	−147.393	−229.993**
	(114.043)	(5,687.165)	(114.526)	(123.928)	(115.816)
Observations	5,650	339	5,989	4,716	4,716
R-squared	0.068	0.209	0.066	0.038	0.037
Number of stations	366	23	370	307	307
F-stat for slope of pollution function upstream = slope downstream (evaluated at 1km from border)	2.560	1.88	2.616	3.248	2.783
Prob >*F*	0.110	0.185	0.107	0.0725	0.0963
F-stat for slope of pollution function upstream = slope downstream (evaluated at 3km from border)	2.940	0.790	2.939	3.937	3.416
Prob >*F*	0.0872	0.383	0.0873	0.0481	0.0655
F-stat for slope of pollution function upstream = slope downstream	3.401	0.0454	3.281	3.871	3.393
(evaluated at 5km from border) Prob >*F*	0.0660	0.833	0.0709	0.0500	0.0664

Notes: Robust standard errors in parentheses.
*** $p<0.01$, ** $p<0.05$, * $p<0.1$.

More generally, political factors may also play a role in either facilitating or hindering negotiation. A qualitative literature has noted the difficulty of getting leaders from different counties with different political affiliations to cooperate on water management decisions (Formiga-Johnsson and Kemper, 2005). Cooperation can become difficult if political partisanship obstructs leaders' ability to negotiate with neighbouring counties, or commit to long term cross-border projects. We therefore also use data from the Brazilian Election Commission to investigate whether a match in party affiliation between the mayors in neighbouring upstream–downstream jurisdictions mitigate the border effects on water pollution.

Column 4 displays the heterogeneity in border pollution effects across areas where the county mayor's party affiliation does (or does not) match with the party in power immediately downstream. We designate the political affiliation of the county mayor as reported to the Brazilian election commission (TSE) as the party in power. We use the party affiliation data from 1996 onwards.[28] When the county where water pollution is measured is governed by a mayor whose party affiliation *does not* match the party in power immediately downstream, the main results from Table 2 are replicated: pollution increases by 3% for every kilometre increase in the river's proximity to the downstream exit border, and this increase occurs at an increase rate. When the party affiliations of the upstream and downstream mayors match, then these effects disappear: the pollution function essentially has a zero slope (statistically insignificant −0.2% per kilometre) as the river approaches the border. The last column repeats the same analysis, but investigates the effect of a party affiliation match with the mayor that is immediately *upstream* of the county where the pollution measure is taken. We see very similar patterns.

Evidently both political and organizational factors play a role in mitigating cross-border pollution externalities. There are smaller deteriorations in water quality around county borders when inter-jurisdictional negotiation costs are lower, either due to the presence of committees or if the jurisdictions share the same political leanings.

9. CONCLUSION

The evidence indicates that counties behave strategically in deciding where and how much to pollute, consistent with a simple theory of externalities. In this section, we consider implications of these results for policy.

Are the magnitude of spillovers and the excess pollution induced by strategic behaviour large enough to warrant policy intervention? To shed light on this, we compute the predicted change in BOD associated with a new county border drawn close to a representative monitoring station in our sample, and then interpret the magnitude of that change in BOD in terms of U.S. Environmental Protection Agency (EPA) water quality standards. County splitting introduces one new border between the modal monitoring station in the sample and its downstream neighbour, and the new border reduces that station's distance to the nearest downstream exit point out of the county from 6 km to 3 km. Our regression estimates imply that these two changes jointly increase the BOD measured at this station by about 9%.[29] At the sample average station, this translates into an

committees (see Supplementary Appendix H) suggest that the impetus for forming committees is largest where pollution problems are more acute, and endogenous committee formation is therefore likely to take these results in the opposite direction to what we report. In other words, we observe committees mitigating pollution spillovers *in spite of* this endogeneity.

28. Brazil returned to democratic rule with a regular schedule of election only from 1988 onwards, and party affiliations and coalitions were quite fluid prior to 1996.

29. In Table 3, the coefficients on "number of borders crossed" suggests a 3.5-3.9% pollution effect from one extra border crossed, and the coefficient on 1D implies a 4.5-5.4% pollution increase from a 3 km decrease.

increase in BOD from 3.5 to 3.9 mg/L. While this is an environmentally significant change, in that water with BOD exceeding 4 mg/L is not considered acceptable for recreational use (Sigman, 2002), the effect may not be highly visible to a casual observer or voter in the average county.

Brazil *has* shifted toward integrated river basin management in recent years in response to deteriorating water quality and increased conflicts over water use (Porto and Kelman, 2005), and our analysis indicates that such efforts have been successful in mitigating the pollution spikes around county borders. These committees are being introduced slowly across Brazil, and the earliest innovations started occurring towards the end of our sample period. A case study-based descriptive literature reports that river-basin management has met with mixed success around the globe, but quantitative or empirical evaluations of such initiatives is lacking (Biswas and Tortajada, 2001; Kemper *et al*., 2007). Given this article's findings, this would be a natural topic on which to conduct more rigorous and extensive follow-up research.

This article presents convincing evidence of strategic location of polluting activities near borders. Solutions to water conflicts across borders may require active regulatory involvement by upper-level bodies, or the creation of a forum for negotiation and cooperation, especially if compensation in the form of direct inter-jurisdiction financial transfers is practically and politically feasible to implement. Institutions promoting decentralization ought to be vigilant in assessing externality costs and evaluating them against other potential benefits of the policy.

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Supplementary Data

Supplementary data are available at *Review of Economic Studies* online.

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