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Impact of foot-and-mouth disease status on deforestation in Brazilian Amazon and *cerrado* municipalities between 2000 and 2010 ☆

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ABSTRACT

Deforestation in the Brazilian Amazon released approximately 5.7 billion tons of CO_2 to the atmosphere between 2000 and 2010, and 50–80% of this deforestation was for pasture. Most assume that increasing demand for cattle products produced in Brazil caused this deforestation, but the empirical work to-date on cattle documents only correlations between cattle herd size, pasture expansion, cattle prices, and deforestation. This paper uses panel data on deforestation and foot-and-mouth disease (FMD) status—an exogenous demand shifter—to estimate whether changes in FMD status caused new deforestation in municipalities in the Brazilian Amazon and *cerrado* biomes during the 2000–2010 period. Results suggest that, on average, becoming certified as FMD-free caused a temporary spike in deforestation in the 2 years after a municipality became FMD-free, but caused subsequent deforestation to decline relative to infected municipalities during the 2000–2010 period.

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Introduction

One-third of the world's remaining rainforests are in Brazil, and it is the world's most biodiverse country (Lewinsohn and Prado, 2005). It is also the 3rd largest exporter of global agricultural commodities by value, ranking 1st in sugar and beef exports and 2nd in exports of soybeans (Economic Research Service, 2012). Between 2000 and 2005, Brazil deforested approximately 0.4–0.6% of its Legal Amazon region every year (INPE, 2012)—an area larger than Belize—and 50–80% of these forests were replaced by pasture (Simon and Garagorry, 2005; Morton et al., 2006; Wassenaar et al., 2007; Espindola et al., 2012). Although deforestation rates have slowed since 2005, deforestation in the Brazilian Amazon released approximately 5.7 billion tons of CO_2 to the atmosphere between 2000 and 2010[2] and deforestation and land management in Brazil could contribute significantly to future greenhouse gas (GHG) emissions (Galford et al., 2010). Bustamante et al. (2009) estimate that cattle ranching accounted for more than half of Brazil's total GHG emissions for the 2003-2008 period. Beyond the effects on global climate, the local and regional consequences of deforestation

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[2] Using data from the INPE PRODES database (www.obt.inpe.br/prodes), CO_2 emissions were calculated using a conversion factor of 100 tons C committed to the atmosphere per hectare deforested, which is the (conservative) factor officially used by Brazil's Amazon Fund. The conversion factor from C to CO_2 is 3.66.

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in Brazil include drought, perpetuation of the fire regime, and loss of biodiversity and ecosystem services (Kirby et al., 2006; Nepstad et al., 2008; Nepstad et al., 2009; Martinelli et al., 2010; Stickler et al., 2013).

Policy makers and scientists alike have assumed that cattle ranching causes more than half of new deforestation since more than half of the forest that is cleared is converted to pasture (Comitê Interministerial Sobre Mudança do Clima, 2008; Zaks et al., 2009; Cerri et al., 2010). They cite increasing beef consumption in Brazil (Faminow, 1997; Levy-Costa et al., 2005) and the dramatic increase in exports from roughly 5% to 17% of production between 1990 and 2010 due to increasing global demand for beef (McAlpine et al., 2009; Foreign Agricultural Service, 2015) as the forces driving this expansion. Clearly regional and global demand for beef is one factor driving deforestation for pasture in Brazil, but we know relatively little about the empirical relationship from the existing literature.

There are a number of econometric studies that have looked at the drivers of deforestation and expansion of cattle ranching in Brazil.[3] One category of econometric studies, which makes up much of the economic literature on deforestation in Brazil, combines remotely sensed data on deforestation and land cover or land use change with data collected from federal censuses or surveys conducted by the Instituto Brasileiro de Geografía e Estatística (IBGE). These analyses are usually conducted at the municipality or the census tract level, and are limited by the fact that full censuses have occurred only periodically, every 5 years. IBGE collects other annual data at the municipality level through specific surveys of agriculture or animal production, but these have the disadvantage of not being based on surveys of producers or market data (i.e. they are filled out by a representative at the municipality level that reports total production and/or prices; see IBGE, 2002). Nonetheless, researchers have used these quinquennial data to run separate models for multiple time periods, structuring models such that the dependent variable (or independent variable) is the change between census periods, or pooling data. This body of literature formed the basis for our understanding of the drivers of deforestation in the Brazilian Amazon, including roads, location, and infrastructure; endogenous socioeconomic variables such as GDP, area in pasture or agriculture, and population growth; and climatic and edaphic variables (Reis and Margulis, 1991; Pfaff, 1999; Andersen et al., 2002; Chomitz and Thomas, 2003; Weinhold and Reis, 2008; Pfaff et al., 2007).

Another segment of the econometric literature has used panel data models with different fixed effects specifications to investigate similar research questions. These models have the advantage of controlling for unobserved heterogeneity at the municipality level that does not vary with time, but that may be correlated with other covariates (Wooldridge, 2005). In the case of Brazilian municipalities, such heterogeneity might result from differences in municipality size, soil quality, distance to markets, climate, average levels of infrastructure or governance, or other variables specific to the municipality that impact deforestation rates. Although these fixed effects are controlled for, the corresponding disadvantage of fixed effects models is that the disaggregated impact of each of these variables is not observed when you run a regression—they are lumped together into a fixed effect. Including year fixed effects has a similar result—it allows the researcher to combine and control for factors that vary over time but not at the municipality level, such as changing macroeconomic conditions, agricultural commodity prices or Brazil-wide initiatives.

Ferraz (2001) constructed a state-level panel to look at the determinants of cattle herd density over time, at the state level with state fixed effects. He found that the cattle price was significantly and negatively correlated with herd density, and paved and unpaved road density were positively correlated. Arima et al. (2011) use a panel fixed effects model (with year and municipality fixed effects) to look at the impact of cattle- and soy-related variables on deforestation within a selected area (to get at deforestation at the extensive margin). They conclude from their analysis that a 10% reduction in conversion from pasture to soybeans would have decreased deforestation by as much as 40% in heavily-forested municipalities between 2003 and 2008. Hargrave and Kis-Katos (2013) employ a difference-in-difference spatial panel model (with and without year fixed effects), estimated via generalized method of moments (GMM), to look at the impact of deforestation enforcement on deforestation rates at the municipality level. They find expected signs of coefficients on prices, high rainfall ($-$), and area under protection ($-$) or in smallholder settlement ($+$), and instrument for fining intensity (number or value of fines per area deforested) using state-level IBAMA presence. They find a negative relationship between fining intensity and deforestation.

Recent work by Assunção et al. (2013a, 2013b) and Assunção and Rocha (2014) uses panel fixed effect models to look at the impact on deforestation of several variables of interest, including whether municipalities were considered “priority municipalities” between 2008 and 2011, intensity of fining, effect of the new DETER monitoring system, and impact of environmental compliance conditions for access to credit. In Assunção et al. (2012), the authors look at the relative impacts of agricultural prices and various conservation policies implemented by the Brazilian government on curbing deforestation. They create exogenous price indices at the municipality level using prices from outside the region and weighting them by the relative contributions of different products in the pre-period to deal with endogeneity in local prices.

[3] For the purposes of this paper, I do not discuss the rich literature on the drivers of household-level decision making about deforestation and cattle ranching in Brazil, which are based on household-level survey data (see, for example: Mattos and Uhl, 1997; Arima and Uhl, 1997; Walker et al., 2000; Perz and Walker, 2002; Walker et al., 2000; Caviglia-Harris, 2004; Caviglia-Harris, 2005; Caviglia-Harris and Sills, 2005; Merry et al., 2008). Many of these studies are cross-sectional, and look at how differences in household and market characteristics at one snapshot in time (e.g. education, location, wealth, income, property rights, household composition, opportunity cost of time) affect decisions about, for example, how much land to clear or how large of a cattle herd to invest in. I also do not discuss in detail a large body of literature that takes a hybrid approach to econometric and geographic modeling (see e.g. Andersen et al., 2002; Mertens et al., 2002; Weinhold and Reis, 2008; Soares-Filho et al., 2010; Mann et al., 2014). Many of these focus on the role of cross sectional variation in soil type, precipitation, slope and other geographic variables in explaining where deforestation occurs at the pixel level, or use a combination of economic and geographic variables (both exogenous and endogenous to the process being modeled) to predict the probability of land being deforested or being in a certain land use in a given period or year. Modeling approaches include Probit or Logit regression, “random reduction” or stepwise regression, as well as non-parametric approaches.

What conclusions can be drawn from empirical work to date about the relationship between cattle and deforestation in Brazil, and—in particular—about how changing demand for Brazilian beef impacts deforestation? First, deforestation is correlated with cattle prices (e.g. Andersen et al., 2002; Weinhold and Reis, 2008; Assunção et al., 2012; Hargrave and Kis-Katos, 2013; Faria and Almeida, 2011). However, because the market price of beef is a function of the many factors that affect supply and demand for beef, demonstrating a correlation between beef prices and deforestation does not show how much of a role changing demand for Brazilian beef (or any other factor affecting supply or demand) plays in causing deforestation. Second, growth in cattle herds or pasture area at the municipality or state levels is correlated with deforestation (e.g. Garcia et al., 2007; Rivero et al., 2009; Barona et al., 2010; Arima et al., 2011). Although the association between cattle herd size or increasing land in pasture and deforestation has been repeatedly documented, scholars of land use change in the Brazilian Amazon—particularly geographers—have suggested there may be reasons in addition to increased demand for beef or even the profitability of raising cattle for beef that forests are cleared for pasture. These include land speculation (Hecht, 1993; Faminow, 1998; Bowman et al., 2012), land rent capture as transportation costs decrease with investments in infrastructure (Walker et al., 2008), or the desire to establish and maintain property rights legally through "productive use" (Faminow, 1998; Margulis, 2004; Arima et al., 2005; Walker et al., 2008). That is, cattle are correlated with the conversion of forest to pasture, but the underlying cause of deforestation is not the profitability of raising cattle. Others suggest that cattle ranching is at least partially a scapegoat for indirect land use change that occurs as other agricultural activities expand in southern and central Brazil and cattle ranching is displaced northward and westward (Walker et al., 2008; Barona et al., 2010; Arima et al., 2011).

In this paper, I employ a unique approach to contribute to the existing literature on cattle, cattle markets, and deforestation in Brazil. I identify a "natural experiment" in beef markets—changes in foot-and-mouth disease (FMD) status in Brazil—and look at the impact of these changes on deforestation rates at the municipality level. To do this, I combine data on deforestation and foot-and-mouth disease status for municipalities in the Brazilian Amazon and *cerrado* biomes, and empirically test whether changes in FMD status—an exogenous shifter of demand for beef—caused new deforestation during the 2000–2010 period. Results from a panel fixed effects model that is robust to spatial autocorrelation and controls for time- and municipality-specific fixed effects suggest that being classified as FMD-free caused annual deforestation at the municipality level to spike initially (41% higher on average in the first year), but to decline after several years to 14–47% lower when compared to municipalities that were never classified as FMD-free during the 2000–2010 period. This result suggests that a shift in demand due to change in FMD status did cause some new deforestation in Brazil between 2000 and 2010, but that the net effect over the long run may be more neutral. While previous work has identified relationships between cattle prices and deforestation and cattle herd size and deforestation, cattle herd sizes are highly endogenous, and beef prices are affected by both supply and demand. This paper is therefore the first attempt to empirically isolate and identify whether an exogenous shift in demand for beef impacted deforestation in Brazil.

The remainder of this paper is structured as follows: in the next section, I discuss the context for the natural experiment. I then summarize the data, follow with my estimation strategy, and present results. The paper closes with a discussion of results, and of potential mechanisms and policy relevance.

Background for the natural experiment: foot-and-mouth disease in Brazil

In Brazil, endemic foot-and-mouth disease historically limited the degree to which Brazilian beef was exported to international markets. Recent progress toward its control is associated with an expansion of beef exports since the late nineties (Walker et al., 2008, Kaimowitz et al., 2004; Cattaneo, 2008; Cederberg et al., 2011). In 1992, the World Organization for Animal Health (OIE) of the United Nations implemented a new protocol whereby *regions* of countries (rather than whole countries) could become certified as FMD-free. By 1993, Brazil had implemented a country-wide, mandatory vaccination policy, and established protocols for vaccination and outbreak procedures (Ministério de Agricultura, do Abastecimento, e da Reforma Agrária, 1993).

Not long after, the Ministry of Agriculture planned how and when to expand the FMD-free area conditional on location. They delineated different "circuits" of the country that would be sequentially certified provided they were outbreak-free for two years prior to submission for approval by the OIE. Mandatory buffer zones were established around FMD-free regions (Ministério de Agricultura e do Abastecimento, 1997; Mayen, 2003; Lima et al., 2005). This certification plan began in the south with the states of Paraná and Santa Catarina in 1997, and moved northward and westward. During the time period of this study (2000-2010), Brazil saw large expansions in the area considered FMD-free, and exports grew from 7% to 17% of production during the same period (Foreign Agricultural Service, 2015). An FMD outbreak also affected central and central western Brazil in 2005 and subsequent years (Fig. 1).

Empirical strategy and identification

In order to investigate the impact of changes in municipality-year FMD status during the 2000–2010 period, I assume they are exogenous shifters of demand for beef produced in the municipality and test the following hypotheses: 1. being certified as FMD-free caused a significant increase in deforestation at the municipality level when compared to infected

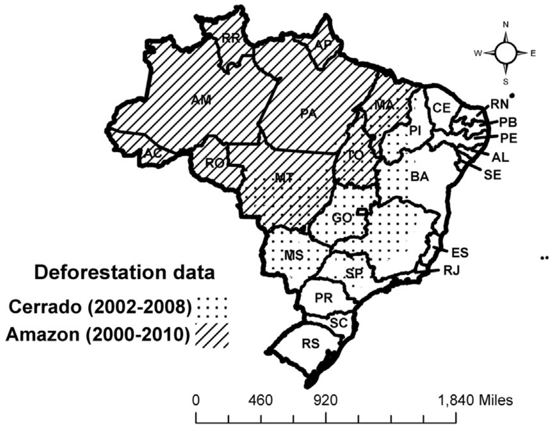

Fig. 1. Coverage of deforestation data for the Brazilian Amazon and *cerrado* biomes, in striped and dotted areas, respectively.

municipalities, and 2. outbreaks of foot-and-mouth disease caused a significant decrease in deforestation at the municipality level when compared to municipalities that are FMD-free. In the first hypothesis, a potential mechanism is that the certified municipality was able to export more beef products to more countries. Because the price of beef for export is higher than the domestic price, average producer prices for beef increased and deforestation increased as a result. Applying the same logic to the second hypothesis, a municipality that experienced an outbreak may have been subject to decreased demand for beef and lower producer prices.

In order to empirically test whether changes in FMD status caused new deforestation during the 2000-2010 period, the following assumptions must hold:

1. The Brazilian Ministry of Agriculture's (MMA) plan for expanding the area free of FMD and, in turn, the "treatment" whereby municipalities are classified as FMD-free is as good as randomly assigned, conditional on municipality location. This assumption is reasonable, as the MMA set out a location-dependent plan for declaring whole circuits of the country successively free of FMD. This plan began with declaring the two southern-most states FMD-free in 1997, and designations of successive areas moved northward and westward with time. According to Mayen (2003):

   "The Ministry of Agriculture divided the country into five circuits, conforming to their geographical positions: Southern Circuit, Eastern Circuit, Centre and Western Circuit, Northeastern Circuit, and Northern Circuit."

   Because this treatment follows a selection on observables design, the inclusion of municipality fixed effects in my empirical specification allows for a causal interpretation of the impact of foot-and-mouth disease status on deforestation if these assumptions hold.

2. The incidence of FMD outbreaks during the period of the study was idiosyncratic, and therefore exogenous to deforestation rates. While not completely analogous, several papers in the literature treat disease events that affect cattle as exogenous shifters of demand for or supply of beef. Jarvis et al. (2005) assume that FMD status of individual countries is an exogenous shifter of demand that is a determinant of the probability of trade between countries. Marsh et al. (2008) and Schlenker and Villas-Boas (2009) also treat incidence of bovine spongiform encephalopathy ("mad cow disease") as an idiosyncratic event that allows them to estimate the impact on cattle prices and consumer and market responses, respectively.

What types of unobserved factors might undermine this first assumption? In particular, municipalities at more advanced stages of development or with better governance capacity may be able to implement vaccination campaigns more effectively (or in some way control endemic foot-and-mouth disease more quickly) during the study period, which in turn might impact how quickly they become FMD-free. For this to be true, these unobserved factors would need to be changing with time, and affecting FMD status. As outlined in Assumption 1 and in the previous section, however, it is not the municipality that makes the determination as to when they are formally considered to be FMD-free. The Ministry of Agriculture laid out the geography and timing of expansion of FMD-free zones prior to the period of study, and several annual reports from the Programa Nacional de Eradicação e Prevenção da Febre Aftosa (National Program for the Eradication and Prevention of Foot-and-Mouth Disease) summarize Brazil's progress toward expansion of the zones (e.g. Ministério da Agricultura, Pecuária e Abastecimento, 2004; Ministério da Agricultura, Pecuária e Abastecimento, 2008). An audit of the program by the Tribunal de Contas da União (Brazilian federal accountability office) suggests that although certain states and regions did not attain FMD-free status as quickly as planned, these determinations to delay status changes were not made by individual municipalities (Zymler, 2005). Unless municipalities were able to lobby to change or affect this federal policy plan, it is unlikely that their actions impacted the timing of their status change. If changes in governance or effectiveness of vaccination campaigns were unobserved factors affecting both changes in FMD status and deforestation, we might expect that they would be negatively correlated with deforestation rates, which would cause an underestimate of the impact of FMD status on deforestation in the first hypothesis, above (or an overestimate, if the estimated effect is negative).[4]

It is also possible that there may be unobserved factors changing over time that are correlated with FMD status where the direction of causality is reversed. In a story where there is increased demand for beef from FMD-free regions and this causes the beef price to increase locally or regionally, we might expect that increased demand (prices) would lead to other local or regional effects in the beef market. In particular, beef companies might choose to invest in infrastructure such as slaughter or processing capacity in these regions, and these investments would have their own impacts on transportation costs and perhaps even on the movement of other inputs (such as fertilizer, veterinary services, or capital) into the region. The impact of these changes and investments, to the extent that they were caused by changes in FMD status, are likely another important mechanism by which increased demand for beef due to changes in FMD status impacts deforestation, and should be considered to be part of the effect sizes estimated in this paper.[5]

While there is no federal database that tracks when and where slaughterhouses opened and closed in Brazil during the study period, the Brazilian Ministry of Agriculture maintains a database of the locations of all federally-inspected slaughterhouses in Brazil[6]. Using this list and a commercial website (https://wooki.com.br/) with information (of unknown quality) on when slaughterhouses opened[7], I cross referenced these two sources to develop a list for a subset of Amazon states (PA, MT, AM, RO, AC) of all *currently inspected slaughterhouses that were opened before 2010*. Of the 80 currently-inspected slaughterhouses in these 6 states, 61% opened between 2000 and 2010. Of this subset that opened during the period of this analysis, 80% opened after the municipality they were located in became certified as FMD-free. This pattern is consistent with increased investment in slaughter infrastructure after regions became FMD-free, and also may suggest that such investment did not precede changes in FMD status (thereby somehow influencing the government to alter their certification planning process outlined in the Background for the natural experiment section).

One final note: in this paper I assume that changes in FMD status shift only demand but not supply. While this assumption likely holds true for expansions in the FMD-free zone over time, it may be less true in the case of outbreaks, where culling of animals is standard outbreak response protocol. In response to the FMD outbreak in 2005, Brazil slaughtered or destroyed 84,676 animals, more than half of which were in the state of Mato Grosso do Sul (World Organization for Animal Health, 2007). These concurrent inward shifts in supply and demand would have an uncertain impact on prices (if beef production were significant enough to impact prices). It is not totally clear how this affects estimates of the impact of an inward shift in demand for beef on deforestation at the municipality, and depends upon the true sign of the relationship between changes in FMD status and deforestation. For simplicity, if we follow the assumption laid out in the second hypothesis in the Empirical strategy and identification section—that an outbreak leads to a decrease in deforestation—this inward shift in supply would introduce a bias toward zero on the magnitude of the coefficient of the impact of decreased demand on deforestation, and produce an underestimate of the impact of an FMD outbreak on deforestation.

Methods and estimation

I combined data on deforestation, foot-and-mouth disease status, and other variables to create an unbalanced panel dataset of 1356 municipalities in the Amazon and *cerrado* biomes of Brazil that exhibited any new deforestation between 2000 and 2010. Deforestation and land cover data come from the PRODES dataset at the Instituto Nacional de Pesquisas Espaciais (Instituto Nacional de Pesquisas Espaciais, 2012) for the Amazon (667 municipalities; 2000-2010), and from the Laboratório de Processamento de Imagens e Geoprocessamento (LAPIG) at the Universidade Federal de Goiás (Laboratório de Processamento de Imagens e Geoprocessamento, Universidade Federal de Goiás, 2012) for the *cerrado* biome (689 municipalities; 2002–2008). The extent of and overlap between these two datasets is depicted in Fig. 1.[8] Data on foot-and-

[4] Conversely, we might also be concerned that municipalities become FMD-free at a stage of development that correlates with a period of deforestation (i.e. that being at the deforestation frontier corresponds in both space and time with becoming FMD-free). If this were true, it would result in an overestimate of the impact of FMD status on deforestation in the first hypothesis (or an underestimate, if the estimated effect is negative).

[5] Because increased investment in infrastructure or technology, reduced transportation costs, and other factors impact input prices and the fixed and marginal costs of beef production, these types of changes could impact production decisions at both the intensive and the extensive margins (i.e. they could make it either more or less appealing to deforest land for cattle production vs. intensify production on an existing land base, depending upon relative input and output prices).

[6] I began by developing a complete list of all federally registered slaughterhouses, here: http://sigsif.agricultura.gov.br/sigsif_cons/!ap_estabelec_nacional_rep . I then proceeded to retrieve additional information on individual slaughterhouses, here: http://sigsif.agricultura.gov.br/sigsif_cons/!ap_estabelec_nacional_cons .

[7] It is entirely possible that this website may list a date of opening for a slaughterhouse if the slaughterhouse was bought by another company and re-opened under a different name. Thus, these calculations should in no way be cited as a credible or verified source. Also note that ABIEC, the Brazilian Beef Exporters Association, lists only 48 slaughterhouses in these same 6 states as current members, which could reflect error in the federal database (i.e. slaughterhouses still listed as active that have closed but were not removed), or merely reflect that there is a large number of inspected slaughterhouses in operation that do not export, or do not belong to ABIEC (http://www.abiec.com.br/mapadasplantas.asp).

[8] Because the area where the dotted and striped areas overlap is within the Amazon, I use deforestation estimates from the PRODES dataset for these municipalities to avoid double counting, and because the LAPIG dataset covers fewer years.

mouth disease status at the municipality level were compiled using legislation (including Portarias, Instruções de Servício, and Instruções Nomativas) relevant to the prevention and control of foot-and-mouth disease in Brazil from 1995 to present (Table 1, Fig. 2) using the Sistema de Legislação Agrícola Federal (SISLEGIS) of the Ministério da Agricultura, Pecuária e Abastecimento (Ministerio da Agricultura do Brasil, 2011), and were entered by hand in ArcMap into a georeferenced map of

Table 1
List of federal declarations and laws relevant to foot-and-mouth disease status of Brazilian municipalities.

Date	Legislation	Action
August 28, 1997	Portaria Nº 91	Established procedures for the entry of potentially infected animals and their products and derivatives into the states of Rio Grande do Sul and Santa Catarina.
December 28, 1999	Portaria Nº 618	Created a buffer zone that separates the area considered FMD-free with vaccination from infected areas in the listed municipalities in the states of Paraná, São Paulo, Minas Gerais, Goiás and Mato Grosso.
April 27, 2000	Portaria Nº 153	Declared the states of Rio Grande do Sul and Santa Catarina as an FMD-free zone, without vaccination.
August 25, 2000	Instrução de Serviço Nº 8	Limited the transportation of animals and products of animal origin due to an outbreak of FMD in Rio Grande do Sul.
December 28, 2000	Portaria Nº 582	Created a buffer zone that separates the area considered FMD-free with vaccination from infected areas in the listed municipalities in the states of Tocantins and Bahia.
December 10, 2002	Instrução de Serviço Nº 29	Clarifies the location of the internationally-recognized FMD-free zone, and defines the procedure for the entry and passage through the state of Santa Catarina of animals that are susceptible to FMD and their products and derivatives.
June 11, 2003	Instrução Normativa Nº 7	Added the state of Rondônia to the FMD-free zone constituted by the states of Bahia, Espírito Santo, Goiás, Mato Grosso, Mato Grosso do Sul, Minas Gerais, Paraná, Rio de Janeiro, Rio Grande do Sul, Santa Catarina, São Paulo, Sergipe, Tocantins and the Distrito Federal.
July 6, 2005	Instrução Normativa Nº 14	Included the state of Acre and the municípios of Boca do Acre and Guajará in the state of Amazonas in the FMD-free zone constituted by the states of Bahia, Espírito Santo, Goiás, Mato Grosso, Mato Grosso do Sul, Minas Gerais, Paraná, Rio de Janeiro, Rio Grande do Sul, Rondônia, Santa Catarina, São Paulo, Sergipe, Tocantins and the Distrito Federal.
November 24, 2005	Instrução Normativa Nº 36	Reduced the area subject to restrictions due to sanitary risked posed by the outbreak earlier in the year for specified regions.
February 10, 2006	Portaria Nº 43	Declared the municipalities of the center-south region of the state of Pará as FMD-free with vaccination.
June 28, 2007	Instrução Normativa Nº 25	Included the municipalities of the center-south region of the state of Pará as part of the internationally-recognized FMD-free zone.
November 23, 2007	Instrução Normativa Nº 53	Recognized and consolidated the situation with respect to FMD in the 27 Brazilian states

All documents downloaded from: Ministerio da Agricultura do Brasil. Sistema de Consulta à Legislação (*SISLEGIS*). Available at: http://www.agricultura.gov.br/legislacao/sislegis. Accessed November 1, 2011

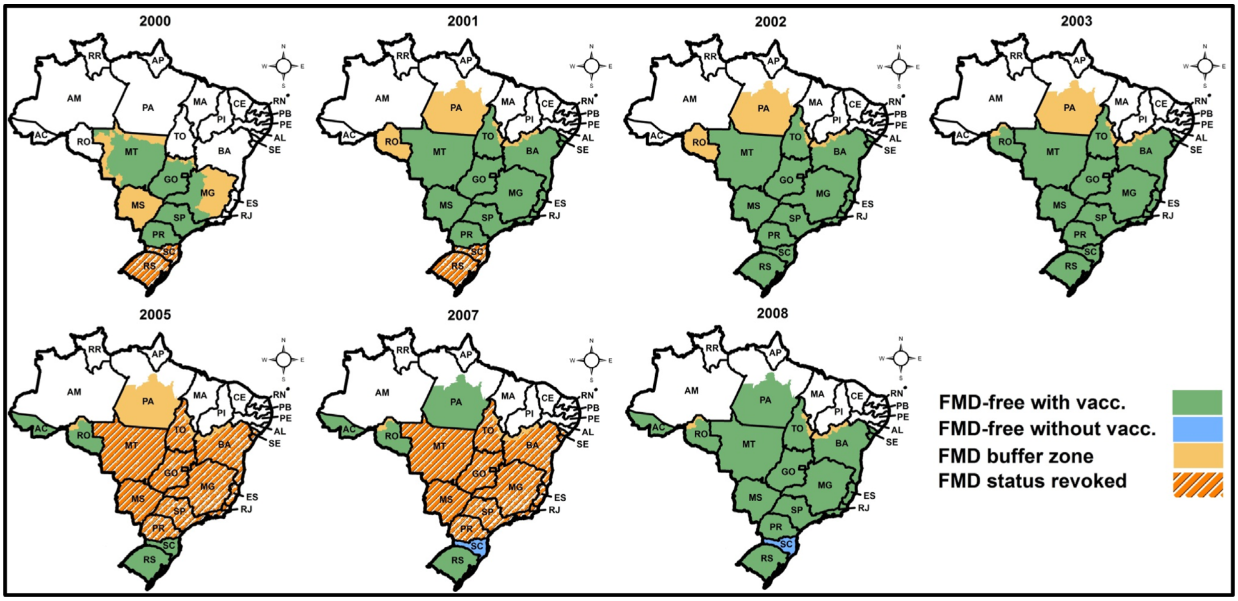

Fig. 2. Changes in foot-and-mouth disease status in Brazil between 2000 and 2010. Data for omitted maps (2004, 2006, 2009, and 2010) are identical to the previous year. Source data were compiled using the SISLEGIS system of the Brazilian Ministry of Agriculture (http://www.agricultura.gov.br/legislacao/sislegis) and digitized and geo-referenced by the author.

Brazilian municipalities obtained from the Instituto Brasileiro de Geografia e Estatística (IBGE) (Instituto Brasileiro de Geografia e Estatística, 2007). Finally, data on soy prices were obtained from IBGE's Produção Agrícola Municipal (PAM) survey[9]; data on precipitation were obtained from NASA's Tropical Rainfall Measuring Mission (TRMM) and kindly provided by Eugenio Arima at the University of Texas at Austin; and a list of “priority municipalities” that were targeted for deforestation enforcement between 2008 and 2010 was obtained from the Brazilian Ministry of the Environment (Ministério do Meio Ambiente do Brasil, 2014).

My panel fixed effects regression equation directly relates annual deforestation in municipality i in year t to FMD status at the municipality level.

$$\begin{aligned}\text{Log Deforestation}_{it} = {} & \alpha_i + \gamma_t + \beta_1 \text{FMD-free}_{it} + \beta_2 \text{log years FMD-free}_{it} + \beta_3 \text{affected by FMD outbreak}_{it} \\ & + \beta_4 \text{FMD buffer zone}_{it} + \beta_5 \text{log years in buffer zone}_{it} + \beta_6 \text{state soy price}_{it} \\ & + \beta_7 \text{log precipitation}_{it} + \beta_8 \text{priority municipality}_{it} + \epsilon_{it}\end{aligned}$$

Variables of interest include whether the municipality was FMD-free in a given year, was previously FMD-free but saw a drop in exports as a result of an FMD outbreak, or is in an FMD buffer zone, as well as variables representing the length of time since the municipality was first declared FMD-free, and the number of years the municipality has been in a buffer zone.[10] Year fixed effects (γ_t) are included to control for factors common across municipalities that vary with time, such as annual commodity prices, rate of inflation, and overall trends in political, macroeconomic, or socioeconomic variables affecting deforestation. Municipality-level fixed effects (α_i) control for time-invariant characteristics (or average levels of variables during the period of study) unique to the municipality such as location, size, average land quality, climate, local institutions, distance to market, and average differences in deforestation enforcement or transportation infrastructure at the municipality level, and other characteristics. Using a fixed effect framework in this context means that, instead of exploiting variation *between* different municipalities to look at how their deforestation rates differ, I am in essence looking at the impact of the variables of interest on the deforestation pattern *within* an individual municipality over time, and estimating the average effect of those variables in my sample. I also include three additional control variables: the state average soy price, total annual municipality precipitation (natural logged), and whether the municipality was included on Brazil's Ministry of the Environment list of “priority municipalities”. The first two of these variables are largely exogenous to municipality-level deforestation in a given year, though the municipality-level soy prices collected by IBGE are arguably endogenous and highly subject to measurement error[11]. The third, whether a municipality was a “priority municipality”, is somewhat endogenous as it was determined by a combination of factors, including whether the municipality was among the top deforesting municipalities, the total amount deforested during the previous 3 years, and whether the municipality had an increasing deforestation rate during at least 2 of the 3 previous years. Nonetheless, being added to the list implied a significant shift in attitude of the federal government toward both enforcement of deforestation law and provision of resources to listed municipalities to work toward curbing deforestation (Ministério do Meio Ambiente do Brasil, 2014). Recent empirical results suggest that the impact of being listed on deforestation at the municipality level is negative and significant (Assuncão and Rocha, 2014).

Finally, in order to correct for spatial and serial correlation, I use the standard error correction method employed by Hsiang (2010) that combines GMM methods to correct for spatial autocorrelation with a non-parametric correction for serial correlation.

Results

Regression results suggest that, on average, being classified as foot-and-mouth disease free caused municipality-level deforestation to increase in the first two years but decrease thereafter relative to municipalities not yet classified as FMD-free when controlling for time- and municipality-specific trends (Table 2, Col. III). This total effect is a combination of the positive coefficient on “Municipality is FMD-free” and the negative coefficient on “Log number of years since municipality was first declared FMD-free”, which are jointly significant.[12] Drawing on predicted values of deforestation presented in Table 3, results suggest that being FMD-free caused annual deforestation at the municipality level to be 41% higher in the first year, roughly equal by the third year, and 47% lower after 11 years, on average, during the 2000–2010 period (comparing column I with columns IV–VII). In addition, although the results for municipalities in FMD buffer zones or experiencing FMD outbreaks were not robust to correction for spatial correlation, they suggest that being in an FMD buffer zone may cause a

[9] Statewide averages were used for this analysis except for the states of Acre, Roraima, and Amapá, for which there was not sufficient reporting of prices in all periods, and Brazil-wide averages were used. Reported prices were adjusted using the World Bank GDP deflator (2000 as the base year).

[10] For both of the time variables, as well as precipitation and the dependent variable, I add one before transforming.

[11] IBGE's methodology for collecting municipality-level annual data on soy production and prices involves a county-level representative filling out a questionnaire. Thus, the prices reported may or may not be actual average market prices of soybeans within the municipality during the year (Instituto Brasileiro de Geografia e Estatística, 2002).

[12] A hypothesis test as to whether the additive effect of the coefficients is significantly different from zero reveals that $F(2, 9215) = 10.41$, or that they are jointly significantly different from zero at the < 0.01 level.

Table 2
Regression of log hectares deforested/year on foot-and-mouth disease export status at the municipality level: 2000–2010

	I. Pooled OLS	II. Fixed Effects	III. Fixed Effects with Conley's SEs
Municipality is FMD-free	2.89*** (0.21)	0.75*** (0.14)	0.75*** (0.27)
Log number of years since municipality was first declared FMD-free	−1.69*** (0.10)	−0.54*** (0.09)	−0.54*** (0.16)
Exports affected by FMD outbreak in 2006/2007	0.04 (0.18)	−0.25** (0.12)	−0.25 (0.20)
Municipality lies in an FMD buffer zone	4.05*** (0.41)	0.15 (0.21)	0.15 (0.38)
Log number of years municipality has been in an FMD buffer zone	−0.82* (0.50)	0.25 (0.17)	0.25 (0.26)
Log average state soy price	−1.13*** (0.14)	0.35*** (0.07)	0.35*** (0.12)
Log annual municipality precipitation	2.54*** (0.24)	1.14*** (0.17)	1.14*** (0.34)
Municipality was designated as a "priority municipality"	3.47*** (0.17)	−0.32** (0.13)	−0.32*** (0.12)
Year fixed effects	Y	Y	Y
Municipality fixed effects	N	Y	Y
SEs corrected for spatial correlation[a]	N	N	Y
SEs corrected for autocorrelation[b]	N	N	Y

1355 municipalities, unbalanced panel.
Column I: Dependent variable mean: 4.81 ǀ R^2=0.17 ǀ F=114.24***
Columns II and III: Dependent variable mean: 4.81 ǀ Within R^2=0.12 ǀ F=69.64***
* <0.10.
** <0.05.
*** <0.01.
[a] Kernel of 180 km.
[b] Lag=2.

significant increase in deforestation (see also Table 3, Column III), and that FMD outbreaks may cause deforestation rates to decline.

We also see that municipality-level variation in total precipitation (natural log) had an impact on deforestation rates, and not in the direction that is usually expected (Chomitz and Thomas, 2003; Andersen et al., 2002; Arima et al., 2011; Hargrave and Kis-Katos, 2013). However, many previous studies look specifically at the relationship between extreme precipitation and deforestation in cross section, and this result is fundamentally different; it is picking up the impact of deviations from average municipality precipitation. This estimated effect is worthy of further research. As expected, the state level soy price has an expected positive and significant sign. Finally, these results support previous research that suggests that the establishment of "priority municipalities" by the MMA (and associated efforts) was positively and significantly correlated with reducing deforestation in those municipalities that were targeted (Assunção and Rocha, 2014).

Robustness checks

Sample selection

The full sample for which I was able to obtain panel data on deforestation was a sample of 1798 municipalities. Of these, 442 municipalities registered no variation in the dependent variable, i.e. had zero deforestation in every period. Thus, the final regression results presented in Table 2 are based on the sample of 1355 municipalities that had positive deforestation in at least 1 year. Comparing results from the full-sample regression (Table 4) to the preferred specification in Table 2, the sign of the coefficients of interest is robust to this sample selection, though the magnitude of the coefficients in the full-sample regression is smaller, as would be expected for a regression in a panel sample with such a large proportion of zeroes in the dependent variable. Finally, when the sample is limited to only the municipalities within the Legal Amazon region, the sign and significance of the results of interest are robust within the Amazon region (Table 5).

Accounting for spatial autocorrelation

Based upon the existing literature on deforestation in the Brazilian Amazon, the data are likely to exhibit spatial autocorrelation (see Ferraz, 2001 and Hargrave and Kis-Katos, 2013 for discussions of the need to employ spatial panel models to model deforestation in the Brazilian Amazon). I use the standard error correction employed by Hsiang (2010) that combines GMM methods to correct for spatial autocorrelation with a non-parametric correction for serial correlation. These methods follow from Conley (1999, 2008). In order to choose a bandwidth appropriate to my data, I graphed the standard errors from my main coefficient of interest at bandwidths from 20–200 km (with a Bartlett kernel, as the degree of correlation with respect to deforestation processes should be expected to decay with distance). Because municipalities vary in size and more rural municipalities are often larger, a large bandwidth is necessary to capture the degree of spatial correlation between such large units; the standard errors on the FMD-free estimate stabilized at around 140–160 km, and I used a bandwidth of 180 km to be conservative.

Table 3
Deforestation estimates using predictions from specification in Table 2, Column III

	Regression coefficients from Table 2	Predictions: not FMD-free			Predictions: FMD-free				
		I	II	III	IV	V	VI	VII	VIII
Number of years since municipality first became FMD-free (for reference only)					1	2	3	4	11
Municipality is FMD-free	0.75*** (0.27)	0	0	0	1	1	1	1	1
Log number of years since municipality first became FMD-free[a]	−0.54*** (0.16)	0	0	0	ln(2)	ln(3)	ln(4)	ln(5)	ln(12)
Exports affected by FMD outbreak in 2006/2007	−0.25 (0.20)	0	0	0	Mean	Mean	Mean	Mean	Mean
Municipality lies in an FMD buffer zone	0.15 (0.38)	Mean	0	1	0	0	0	0	0
Log number of years municipality has been in an FMD buffer zone[a]	0.25 (0.26)	Mean	0	Mean	0	0	0	0	0
Predicted value of dependent variable (Delta method SE)		4.93 (0.20)	4.91 (0.21)	5.07 (0.34)	5.27 (0.13)	5.05 (0.13)	4.89 (0.15)	4.77 (0.17)	4.29 (0.28)
Predicted hectares deforested/year [95% CI]		137.85 [93.39 203.48]	135.06 [89.43 203.99]	158.61 [82.63 305.04]	194.37 [150.76 250.59]	156.04 [120.97 201.28]	133.52 [99.98 178.32]	118.32 [85.04 164.61]	73.63 [42.63 127.18]

Linear predictions and corresponding delta-method standard errors were obtained using Stata's “margins” command at the values of the independent variables specified in Columns I–VIII (and at the mean of all other variables).
*** < 0.01.
[a] Variable is transformed after first adding one. Thus, the value of the variable when the municipality is not FMD-free is ln(1), and in the first year it is ln(2) etc. as noted in columns IV–VII.

Table 4
Regression of log hectares deforested/year on foot-and-mouth disease export status at the municipality level: 2000–2010 (Municipalities with no deforestation during the sample period *included*).

	I. Pooled OLS	II. Fixed effects	III. Fixed effects with Conley's SEs
Municipality is FMD-free	3.03*** (0.23)	0.56*** (0.13)	0.56** (0.27)
Log number of years since municipality was first declared FMD-free	−1.96*** (0.10)	-0.30*** (0.07)	−0.30** (0.13)
Exports affected by FMD outbreak in 2006/2007	0.19 (0.17)	-0.20** (0.09)	−0.20 (0.15)
Municipality lies in an FMD buffer zone	5.96*** (0.35)	0.42** (0.19)	0.42 (0.36)
Log number of years municipality has been in an FMD buffer zone	−2.08*** (0.43)	0.18 (0.14)	0.18 (0.22)
Log average state soy price	−1.75*** (0.17)	0.28*** (0.06)	0.28** (0.11)
Log annual municipality precipitation	3.63*** (0.22)	0.77*** (0.13)	0.77*** (0.26)
Municipality was designated as a "priority municipality"	4.21*** (0.17)	-0.58*** (0.13)	−0.58*** (0.12)
Year fixed effects	Y	Y	Y
Municipality fixed effects	N	Y	Y
SEs corrected for spatial correlation[a]	N	N	Y
SEs corrected for autocorrelation[b]	N	N	Y

1797 municipalities, unbalanced panel, municipalities with zero hectares deforested in all periods INCLUDED
Column I: Dependent variable mean: 3.58 | R^2=0.22 | F=202.73***
Columns II &III: Dependent variable mean: 3.58 | Within R^2=0.09 | F=52.59***
[a] Kernel of 180 km.
[b] Lag=2.
** < 0.05.
*** < 0.01.

Table 5
Regression of log hectares deforested/year on foot-and-mouth disease export status at the municipality level: 2000-2010. (Comparison of full sample with Amazon-only sample).

	I. FE with Conley's SE (Full sample: Amazon + *cerrado*)	II. FE with Conley's SE (Amazon only)
Municipality is FMD-free	0.75*** (0.27)	1.06*** (0.25)
Log number of years since municipality was first declared FMD-free	−0.54*** (0.16)	−0.74*** (0.15)
Exports affected by FMD outbreak in 2006/2007	-0.25 (0.20)	0.04 (0.18)
Municipality lies in an FMD buffer zone	0.15 (0.38)	0.09 (0.37)
Log number of years municipality has been in an FMD buffer zone	0.25 (0.26)	0.30 (0.25)
Log average state soy price	0.35*** (0.12)	0.31*** (0.12)
Log annual municipality precipitation	1.14*** (0.34)	1.26** (0.49)
Municipality was designated as a "priority municipality"	−0.32*** (0.12)	−0.26** (0.12)

All model specifications have year fixed effects and municipality fixed effects, and the SEs are corrected for autocorrelation (Lag=2) and spatial correlation (Kernel of 180 km)
Column I: 1355 municipalities, unbalanced panel
Dependent variable mean: 4.81 | Within R^2=0.12 | F=69.64***
Column II: 666 municipalities, unbalanced panel
Dependent variable mean: 5.52 | Within R^2=0.20 | F=85.85***
** < 0.05.
*** < 0.01.

Fixed effects

In order to identify the causal effect of changes in FMD status on deforestation, I used a fixed effects model to account for time-invariant characteristics unique to the municipality such as location, local institutions, differences in deforestation enforcement at the municipality level, etc. I also included year fixed effects to control for factors common across municipalities that vary with time, such as average commodity prices, and overall trends in political, macroeconomic, or socio-economic variables affecting deforestation. This approach is equivalent to individually including these variables at the country-year level. Looking at the year fixed effects from the model (Fig. 3) gives us an idea of overall deforestation trends during the period of interest. As expected, these exhibit a general downward trend that reflects falling deforestation rates due to a combination of factors during the period of study.

Additional covariates

To test the robustness of my model specification, I gathered information on several additional covariates that change during my period of study (Col. III–V, Table 6). In an attempt to get at changes in the road network over time, I used two imperfect measures of road network extent: kilometers of paved roads at the state level (as used in Ferraz, 2001; from statistical yearbooks of the Departamento Nacional de Infraestrutura de Transportes (DNIT) and the Agência Nacional de Transportes Terrestres (ANTT)), and annual municipality expenditures on transportation from IBGE. Including the first of these, kilometers of paved roads at the state level, requires dropping two years of data—and probably does not add any useful variation, since this analysis is at the municipality level and it is the proximity to roads that affects deforestation processes (Col. III, Table 6). Because Brazil implemented a vast network of protected areas during the period of study and protected areas have been shown to deter deforestation (Mertens et al., 2002; Soares-Filho et al., 2010; Hargrave and Kis-Katos, 2013), I included information at the municipality level on area in protected areas, indigenous territories, and sustainable use together with expenditures on transportation (from IBGE) in Col. IV of Table 6. Finally, though highly endogenous, I include municipality herd size from IBGE's Produção da Pecuária Municipal (PPM) survey in Col. V of Table 6.

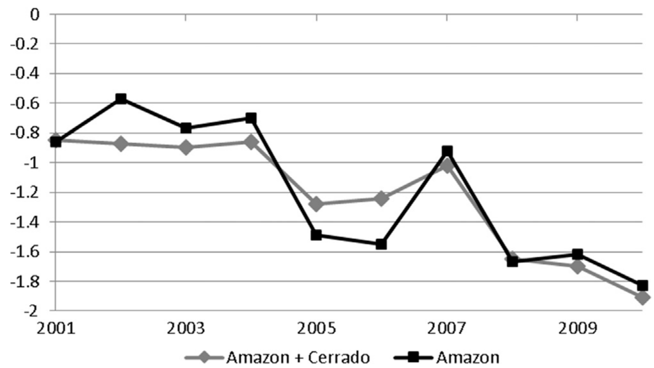

Fig. 3. Coefficients on year fixed effects from Full-sample (Table 2, 3rd Col. and Table 4, 1st Col.) and Amazon-only (Table 4, 2nd Col.) regressions. Fixed effects are relative to the year 2000.

Table 6
Fixed effects regressions with additional controls (dependent variable = log hectares deforested)

	I (2000–2010)	II (2000–2010)	III (2000–2008)	IV (2000–2010)	V (2000–2010)
Municipality is FMD-free	0.77*** (0.27)	0.75*** (0.27)	0.48* (0.26)	0.68*** (0.24)	0.63*** (0.24)
Log number of years since municipality was first declared FMD-free	−0.54*** (0.15)	−0.54*** (0.16)	−0.34 (0.22)	−0.56*** (0.15)	−0.55*** (0.15)
Exports affected by FMD outbreak in 2006/2007	−0.23 (0.20)	−0.25 (0.20)	−0.31 (0.21)	−0.20 (0.19)	−0.19 (0.19)
Municipality lies in an FMD buffer zone	0.35 (0.40)	0.15 (0.38)	−0.06 (0.37)	0.12 (0.37)	0.13 (0.38)
Log number of years municipality has been in an FMD buffer zone	0.14 (0.26)	0.25 (0.26)	0.36 (0.26)	0.20 (0.26)	0.16 (0.26)
Log average state soy price		0.35*** (0.12)	0.16 (0.13)	0.31** (0.12)	0.32*** (0.12)
Log annual municipality precipitation		1.14*** (0.34)	1.25*** (0.19)	1.07*** (0.31)	1.06*** (0.31)
Municipality was designated as a “priority municipality”		−0.32*** (0.12)	−0.64*** (0.19)	−0.41*** (0.11)	−0.45*** (0.12)
Log km paved road in state (for years 2000-2008)			−0.04 (0.28)		
Log municipality expenditures on transportation				−0.002 (0.005)	−0.002 (0.005)
Log area in protected areas				0.02 (0.01)	0.02 (0.01)
Log area in indigenous territories				0.000 (0.008)	0.000 (0.008)
Log area in “sustainable use”				0.01 (0.01)	0.01 (0.01)
Log municipality herd size					0.15** (0.07)
Year and municipality fixed effects	Y	Y	Y	Y	Y
SEs corrected for spatial correlation[a] and autocorrelation[b]	Y	Y	Y	Y	Y

I: 1356 municipalities, unbalanced panel | Dep Var mean = 4.81 | Within R^2 = 0.10 | F = 75.49***
II: 1355 municipalities, unbalanced panel | Dep Var mean = 4.81 | Within R^2 = 0.12 | F = 69.64***
III: 1355 municipalities, unbalanced panel | Dep Var mean = 4.83 |Within R^2 = 0.08 | F = 45.64***
IV: 1351 municipalities, unbalanced panel | Dep Var mean = 4.79 | Within R^2 = 0.12 | F = 59.68***
V: 1351 municipalities, unbalanced panel | Dep Var mean = 4.79 | Within R^2 = 0.12 | F = 57.07***

* < 0.10.
** < 0.05.
*** 0.01.
[a] Kernel of 180 km.
[b] Lag = 2.

Coefficients on the variables related to foot-and-mouth disease status are mostly robust to these additions, with the exception of the specification where two years of data were dropped. Including herd size in specification V gives us the anticipated result: a positive and significant correlation with municipality-level deforestation, and a slightly lower coefficient on the Municipality is FMD-free variable relative to the preferred specification (Col. II).

Discussion

As discussed in the introduction to this paper, researchers from multiple disciplines have suggested that deforestation for pasture in the Amazon and increasing cattle herd sizes are the result of some combination of increased demand for beef and cattle products both within Brazil and globally, as well as a result of complex interactions of other factors such as land speculation, claiming property rights through productive use, and indirect land use change due to the expansion of soybean production. This paper is the first to isolate and empirically identify whether an exogenous shift in demand for beef—changes in foot-and-mouth disease status—impacted deforestation in Brazil. It builds on the existing literature on the relationship between cattle production, clearing of forest for pasture, and deforestation in Brazil both by investigating a single phenomenon that impacted beef markets, and by using panel data methods that control for spatial autocorrelation in the deforestation process.

My results suggest that when a municipality became foot-and-mouth disease free during the 2000–2010 period, it caused in a short-term spike in deforestation followed by a longer-term decline in deforestation relative to other municipalities that had never been FMD-free. This short term spike would be consistent with a story where becoming FMD-free and obtaining greater access to beef export markets raised the average producer price, which in turn drove expansion of beef production at the extensive margin. Several studies and reports within Brazil add credence to this explanation; Carvalho et al. (2009) show that the wedge between producer beef prices in the state of Rondônia when compared to São Paulo was significantly larger prior to the state being certified as FMD-free, and Teixeira et al. (2008) and Costa et al. (2011) document depressed producer prices due to the 2005 FMD outbreak. As mentioned in the Results, including municipality herd size, which is endogenous to deforestation (Table 6, specification V) suggests that at least one potential mechanism by which changes in FMD status impact deforestation in these initial years is through increasing the size of the cattle herd (and, plausibly, the land area in pasture) immediately after becoming FMD-free.[13]

Decreased deforestation after the third year of being FMD-free could be due to a number of factors, including decreased demand for land if FMD-free status was accompanied by changes in technology and pasture productivity (expansion of production at the intensive margin). Many researchers have emphasized that the cattle sector is, on average, using land more intensively in Brazil and adopting more productive management techniques, which may reduce the demand for land for pasture (Polaquini et al., 2006; Steiger, 2006; Cattaneo, 2008; Euclides et al., 2010; Millen et al., 2011; Martha et al., 2012; Pacheco and Poccard-Chapuis, 2012). Changes in FMD status might accelerate such processes. It is also possible that, as multinational corporations invested in processing infrastructure in newly FMD-free regions, they came under increased pressure to source from deforestation-free supply chains, and put pressure on producers not to deforest (see Greenpeace International, 2009; Nepstad et al., 2014; Gibbs et al., 2015).

This work also suggests that FMD outbreaks may have caused a drop in deforestation during the same period, though this result is not robust when I correct for spatially correlated errors. As mentioned in the Empirical Strategy and Identification Section, this may be due to concurrent inward shifts of demand and supply due to the “stamping out”, or culling, of animals that are suspected to be infected or vulnerable to infection.

It is important to note that the effect estimated in this paper is an average effect for a sample of municipalities in the Brazilian Amazon and *cerrado* regions that were or became FMD-free during the study period. Even if changes in FMD status result in increased or decreased deforestation within individual Brazilian municipalities, these results do not exclude the potential for leakage across municipality or country boundaries (in the case of deforestation reductions) or that a deforestation increase might correspond to reduced pressure on forests in other municipalities or outside of Brazil. To the extent that leakage exists across municipalities in this study, it is embedded in the results presented here. Possible future work could use matching methods (or others) to look more directly at the question of leakage across municipalities.

With respect to leakage across countries, this paper's estimation strategy relies on the fact that the Brazilian beef market is a major player in the global market, and does not operate in isolation. However, it is beyond the scope of this paper to look at how changes in beef production (or deforested area) in Brazil impact land use or beef production in areas outside of Brazil, but Cohn et al. (2014) investigate and discuss this issue at length. With respect to leakage both across municipalities

[13] While it might be possible to take a different estimation approach and use changes in FMD-status as an instrument for herd size and robustly examine the impact of herd size on deforestation, this would be complicated by at least two factors. First, if trying to estimate the impact of herd size on deforestation, a good instrument for herd size would be exogenous to herd size and deforestation, and correlated with herd size, but not with deforestation. Although exogenous, changes in FMD-status do not meet this criterion. This paper shows that FMD-status clearly impacts deforestation through channels other than herd size. Secondly, the temporal and functional relationships between deforestation and the size of the cattle herd complicate estimation. As a beef producer, I may clear land today with the intent to have cattle on it in two years. That is, land is an input into the beef production process, and the decision to clear land happens in a different (earlier) period. This presents issues of autocorrelation and potential reverse causality, among others, if deforestation is a dependent variable and herd size is included as a covariate.

and across countries, future research might consider approaches for dealing with regional and global demand for land and how different units of analysis (landowner, municipality, state, region, and country) can complement each other to help answer questions about the scale and scope of deforestation processes.

Do these results offer any insight for current and future deforestation and development policy in Brazil? Cattle ranching has a large footprint on the Brazilian landscape, is (on average) producing more beef on less land, and has potential for further intensification. Prompted by several influential reports critiquing the role of cattle ranching in deforesting the Amazon region and highlighting the potential for intensification (Steinfeld et al., 2006; Greenpeace International, 2009; de Gouvello et al., 2010), the Brazilian government developed a plan for the mitigation of greenhouse gas emissions that placed critical importance on intensifying cattle production to meet increased demand rather than expanding the land base dedicated to pasture, and contributing to deforestation. In their National Plan for Climate Change (Comitê Interministerial Sobre Mudança do Clima, 2008), Brazil proposed Nationally Appropriate Mitigation Actions (Embassy of Brazil, 2010) which focus on reducing emissions by constraining the land area occupied by extensive cattle ranching, and intensifying cattle ranching in areas already used for ranching. In doing so, they hope to achieve multiple objectives by conserving standing forests, expanding the area available for crop production, and reducing greenhouse gas emissions from ranching. Credit and international funding for cattle intensification have followed (Banco da Amazônia, 2011; Cohn et al., 2011).[14]

At the same time as the Brazilian government has emphasized sustainable intensification of cattle production, they have also invested in policies to increase the costs of deforestation. These include the establishment and enforcement of a revised version of the Forest Code and a federal property registry (Cadastro Ambiental Rural, or CAR), the implementation of the DETER monitoring system, the expansion of a vast network of protected areas, and the “priority municipality” approach taken by MMA during the last several years of this analysis. As mentioned elsewhere in this paper, these formal policies have been reinforced by supply chain initiatives that pressure companies operating in the Amazon to source from properties that are not deforesting more land to produce soybeans or raise cattle. The research question asked in this paper does not allow me to evaluate the effectiveness of these changes in federal policies or market initiatives.[15] Nor does this work offer direct insight on how improving the productivity of cattle ranching in Brazil will impact deforestation through expansion at the extensive margin. Improving the productivity of cattle ranching in Brazil may well reduce pressure on forests over the long term relative to an alternative of extensive ranching, but changes in global market conditions and increasing demand for beef do not guarantee that production will expand only at the intensive margin (see Angelsen, 2010 for a discussion of how various types of policies may impact deforestation, and Hardie et al., 2004 for a discussion of land use and policy decisions at the intensive and extensive margins). Investing money in policies to encourage intensification in the cattle industry (a structural change that is already underway) may not necessarily be a first-best policy option to curb deforestation.

This work does provide evidence of what the deforestation trajectory looked like in municipalities that became FMD-free relative to other municipalities during a 10 year period. Results suggest that there was a short-term spike in deforestation in these municipalities, followed by reduced deforestation. Even if the overall impact on deforestation of this shift in demand at the municipality level were negative, these results have important implications for policy. Because they illustrate a short-term spike in deforestation in response to becoming FMD-free, they emphasize the critical importance of policies designed to directly increase the cost of deforestation—such as establishment and enforcement of a revised version of the Forest Code, implementation of the DETER monitoring system, and the “priority municipality” approach taken by MMA during the last several years of this analysis—to continuing to reduce deforestation rates in Brazil.

This short-term spike in deforestation also suggests that there may also be a role for timely spatial targeting of policy initiatives and resources in anticipation of or in response to changing local and regional market conditions. Too often, deforestation policies focus on setting aside protected areas that are already likely to remain in forest, or, figuratively, on fighting fires rather than preventing them. The priority municipality approach adopted by MMA in 2008 is one such policy. While it is widely considered to be successful in reducing deforestation in listed municipalities (a result supported by this paper), the municipalities targeted are those that already meet criteria that place them among the top deforesters in the Amazon. Thus, in order to be targeted by that particular initiative, a municipality needed to be 1) within the legal Amazon and 2) to have already had very high deforestation rates relative to other municipalities. What about municipalities not within the legal Amazon, or municipalities where deforestation rates are increasing, or are expected to increase?

The real policy questions raised by this paper are, first: do governments know enough about regional economies and changing global market conditions to anticipate when and where pressure on forests might occur, and to target resources to strengthening local institutions and enforcement capabilities *prior* to a deforestation spike? Second, economic theory suggested that we might see a spike in deforestation in FMD-free municipalities if beef prices increased, but this paper

[14] The success of this policy approach hinges on the “Borlaug hypothesis” (see, e.g. Angelsen and Kaimowitz, 2001) which implies that the demand for land for cattle ranching will decrease as productivity improves in the sector, thereby sparing forests. Other theories of land use change, based on work by Ricardo and von Thünen suggest that improvements in productivity could have the opposite effect. Kaimowitz and Angelsen (2008) summarize these theories as they apply to cattle ranching and deforestation in Latin America, and conclude that improvements in the productivity of cattle ranching are unlikely to lead to lower prices, and thus will continue to drive deforestation—particularly in regions where land is not a limiting factor of production. Cattaneo (2008) argues that improving the productivity of beef production outside the Amazon (by expanding grain-fed beef operations) could be an effective way to reduce the incentives to clear forests.

[15] Others have tried to isolate to what degree these factors vs. macroeconomic forces (currency fluctuations, commodity prices, and a global economic downturn) are responsible for reductions in deforestation in the Brazilian Amazon during the period of this study (e.g. Soares-Filho et al., 2010; Assunção et al., 2012; Richards et al., 2012; Hargrave and Kis-Katos, 2013).

showed that this was also followed by reduced deforestation. If a short-term spike could have been anticipated, when is deforestation and expansion of the agricultural land base an inevitable and acceptable phenomenon, especially in light of reduced deforestation in the long-run? Even if Brazil and other countries were able to predict short- and long-run deforestation trends, they must still decide how much they care about short-term spikes relative to long term trends, and where, when, and how resources are best targeted to meet conservation and development goals.

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