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World Development Vol. xx, pp. xxx–xxx, 2017
0305-750X/© 2017 The Authors. Published by Elsevier Ltd.

http://dx.doi.org/10.1016/j.worlddev.2017.05.034

The Restructuring of South American Soy and Beef Production and Trade Under Changing Environmental Regulations

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Abstract. — In response to the extensive loss of forests caused by soy and cattle expansion in South America, several countries have increased their legal restrictions on deforestation, and stepped up their enforcement. In addition, in the Brazilian Amazon, new private agreements were initiated in 2006 and 2009 to limit the purchase of soy and cattle linked with deforestation. One concern is that such policies, because they are spatially heterogeneous or focus on a subset of relevant actors, might generate negative spillovers in the form of leakage of agricultural activities and deforestation to less-regulated areas, and/or a redistribution of non-compliant product sales to non-participants. In this study, we use panel data on soy and beef production and trade in agricultural frontiers of South America to examine how changes in deforestation regulations in South America have altered soy and cattle expansion and exports in this region, and to understand how these changes, if they have occurred, influence the overall effectiveness of deforestation regulations. We find no evidence of a change in soy or pasture area expansion patterns due to changes in regulations, except within the Amazon biome where pasture expansion slowed in response to more stringent regulations and coincided with pasture intensification. We do find, however, a decrease in beef imports from biomes with more stringent deforestation regulations. While this decrease may indicate the existence of leakage to countries outside the study area, it is likely offset by pasture intensification, continued opportunities for deforestation, and increasing domestic consumption from these biomes. These results point to the potential role of substitution effects between local and international consumer markets, and between different actors, in diminishing the overall effectiveness of deforestation regulations.

Key words — Soy, Cattle, Deforestation regulations, Leakage, South America, Amazon

1. INTRODUCTION

Over the last two decades, growing global demand for soy and livestock has driven rapid agricultural expansion throughout South America. This has resulted in substantial clearing of forest and savanna vegetation in the Amazon, Cerrado, and Chaco biomes, and subsequent losses of carbon and biodiversity, as well as changes in local to regional hydrological cycles (Silvério *et al.*, 2015). While this agricultural expansion has fueled economic growth and infrastructure development throughout the region, it has also led to numerous undesirable social impacts, such as land consolidation and violent conflict (Garrett & Rausch, 2015).

In response to these trends, many new environmental governance initiatives have emerged throughout South America to regulate deforestation, including on private lands. These initiatives include increasing the stringency and enforcement of national conservation policies pertaining to private property, developing new certification and market exclusion mechanisms, and expanding protected areas and indigenous lands (Nolte, le Polain de Waroux, Munger, Reis, & Lambin, 2017). While the interactions and effectiveness of these new policy mixes remain poorly understood (Lambin, Meyfroidt, & Rueda, 2014), both the Soy Moratorium and G4 cattle agreement — industry-led initiatives that established cut-off dates for deforestation and then excluded non-compliant suppliers — and increased enforcement of property-level conservation reserve requirements in Brazil have been shown by several recent studies as being effective mechanisms to reduce deforestation for major export commodities on private lands (Börner, Kis-Katos, Hargrave, & König, 2015; Gibbs *et al.*, 2014, 2015). In Argentina, a 2007 federal forest law that increased deforestation restrictions on private properties was also shown to have decreased deforestation in at least some provinces (Nolte *et al.*, 2017).

There is, however, growing concern that increasing public or private deforestation restrictions in some areas, or among a subset of relevant actors, might generate negative spillovers in the form of leakage of agricultural activities and deforestation to less-regulated areas, and/or a redistribution of non-compliant product sales to non-participants, offsetting carbon and biodiversity benefits of conservation actions (Ewers & Rodrigues, 2008; le Polain de Waroux, Garrett, Heilmayr, & Lambin, 2016). The objective of this study is to examine how changes in deforestation regulations in South America have altered soy and cattle expansion and exports in this region, and to understand how changes in expansion and exports, if they have occurred, are likely to influence the overall effectiveness of deforestation regulations.

Firstly, we use a panel model of municipality-level soy and pasture area change to test whether changes in environmental governance in the region have reduced agricultural expansion,

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* This work was supported by the Gordon and Betty Moore Foundation [grant GBMF #426]. We are grateful to the editors and two anonymous reviewers for their comments. We would also like to thank Javier Godar for his comments on previous versions of this paper.

and shifted it to less-restricted areas. Secondly, we utilize a panel model of bilateral trade in soy and beef to test whether increasing deforestation restrictions in some South American biomes have displaced soy and beef demand to other regions or whether certain importing countries have intensified trade with regions that have improved environmental governance. We then examine how changes in agricultural expansion in different South American biomes are linked to patterns of intensification and deforestation, and how changes in exports are linked to patterns of domestic consumption.

2. BACKGROUND

(a) *Changing land use policies in soy and cattle frontiers*

South America plays an important role in global markets for soy, grains, and cattle products in addition to meeting high domestic demand for soy and beef. Until the 1990s, most soy and cattle production was concentrated in Southern Brazil and Central and North-Eastern Argentina (the Pampas grasslands in both countries and the Brazilian Atlantic forest (Figure 1)). However, because of a substantial increase in global demand for meat and animal feed that began in the late 1990s and originated primarily in China, soy production began expanding more rapidly in the Cerrado tropical savanna in Brazil, and in other tropical forest biomes in the region — the Amazon forest in Bolivia and Brazil, and the Chaco and Chiquitano forests in Argentina, Bolivia, and Paraguay. In response to this uptick in agricultural expansion across South America, deforestation regulations evolved rapidly in the 2000s (Figure 2).

Brazil regulates deforestation on private properties through the federal Forest Code (Law 12.651/65), passed in 1965, which requires 80% of each property in forest areas of the Legal Amazon [1], 35% in *cerrado* areas of the Legal Amazon,

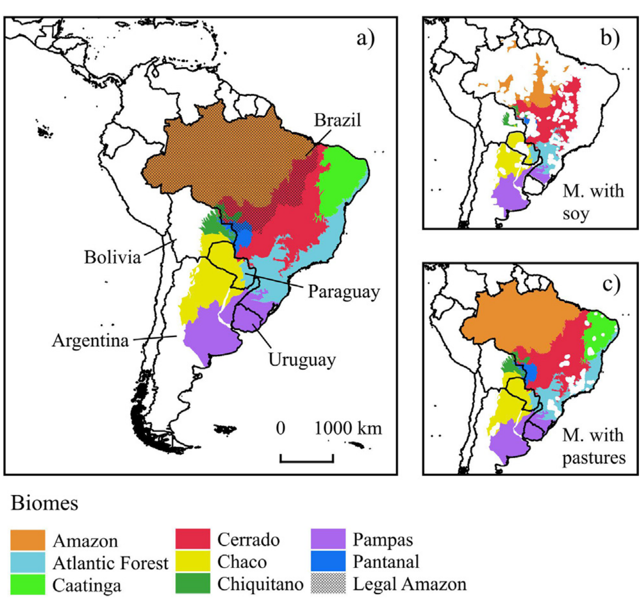

Figure 1. *Study area by biome (a) and municipalities (M.) with soy (b) and pasture (c) area during 2000–13. Biome boundaries are from WWF (Argentina, Bolivia, Paraguay, Uruguay) & Ministry of Environment (Brazil); soy area from ministries of agriculture (Argentina, Paraguay, Uruguay) & IBGE (Brazil); and pasture area are from Graesser et al. (2015). No below-national soy data was available for Uruguay. More on data in Table 1 and SM.*

and 20% in non-forest or cerrado areas of the Legal Amazon and all vegetation types in other biomes to be set aside in a Legal [conservation] Reserve. Riparian areas and steep slopes within properties must also be conserved in Permanent Preservation Areas. Historically, compliance with the Forest Code was low, with more than 80% of producers failing to meet Legal Reserve requirements in some regions (Stickler, Nepstad, Azevedo, & McGrath, 2013). However, enforcement in the Amazon biome was vastly improved in the 2000s through several mechanisms, including fines, increased field visits and field-based enforcement (Börner *et al.*, 2015), and confiscation of illegally acquired goods or assets. In 2008, the federal government also initiated a "black list" program that eliminated agricultural credit for properties in municipalities in the Amazon that had the highest deforestation rates. Together, these mechanisms made Brazil the country with the highest overall capacity for enforcement of public regulations in the region. In spite of this, significant differences persisted between biomes, particularly in terms of deforestation monitoring: while satellite images of the Amazon were readily available since the 1988 through the PRODES program (http://www.obt.inpe.br/prodes), this was not the case for the other biomes. The NGO SOS Mata Atlântica produced an atlas documenting changes in forest cover for the Atlantic forest in the 1990s and 2000s, but systematic, yearly monitoring began in 2011. Yearly monitoring in the Cerrado began in 2008, and was largely absent in other biomes.

In addition to the Forest Code's legal reserve requirements, Brazil imposed a zero-deforestation rule for the remaining Atlantic forest after 2006 (law 11.428/06). In 2013, the Federal Government also launched a program requiring all farmers in the country to become registered in a Rural Environmental Registry (CAR) by 2016 to identify compliance gaps with existing environmental regulations and develop plans to achieve compliance (Nepstad *et al.*, 2014). Finally, the government dramatically increased the number of protected areas and indigenous lands (100% during 2002–08 for the Amazon), which helped significantly slow down deforestation (C. Nolte, Agrawal, Silvius, & Soares-Filho, 2013).

In light of continued deforestation in the Amazon forest until the mid-2000s resulting from low enforcement of the Forest Code, and under heavy pressure from Greenpeace, private companies developed several new initiatives to avoid sourcing products associated with deforestation. In 2006, multinational soy traders, including ADM, Bunge, Cargill, Louis Dreyfus, and members of the Brazilian soy-processing industry signed the voluntary Soy Moratorium agreement (Gibbs *et al.*, 2014). These companies agreed not to purchase soy grown on Brazilian Amazon lands deforested after July 2006. Similarly, following intensive lobbying by civil society organizations and the public prosecutor, in 2009, individual meatpacking companies in several Amazonian states began signing legally binding Terms of Adjustment of Conduct ("MPF-TAC") agreements to stop purchasing cattle from properties that undertook illegal deforestation after July 2009. In 2009, Brazil's largest meatpacking companies (Marfrig, Minerva, JBS, and Bertin) also agreed not to purchase beef grown on lands deforested after October 2009 by signing the "G4" zero-deforestation agreement (Gibbs *et al.*, 2015). In 2010, the major Brazilian federal bank (Banco do Brasil) also signed onto this agreement, effectively limiting public credit to farmers who deforested after July 2006 (ABIOVE, 2010).

Enforcement of private moratoria occurs at the first point of sale for soy, or at the slaughterhouse for cattle, whereby farmers are excluded from selling to traders or slaughterhouses that are signatories of the moratoria (and prevented from accessing

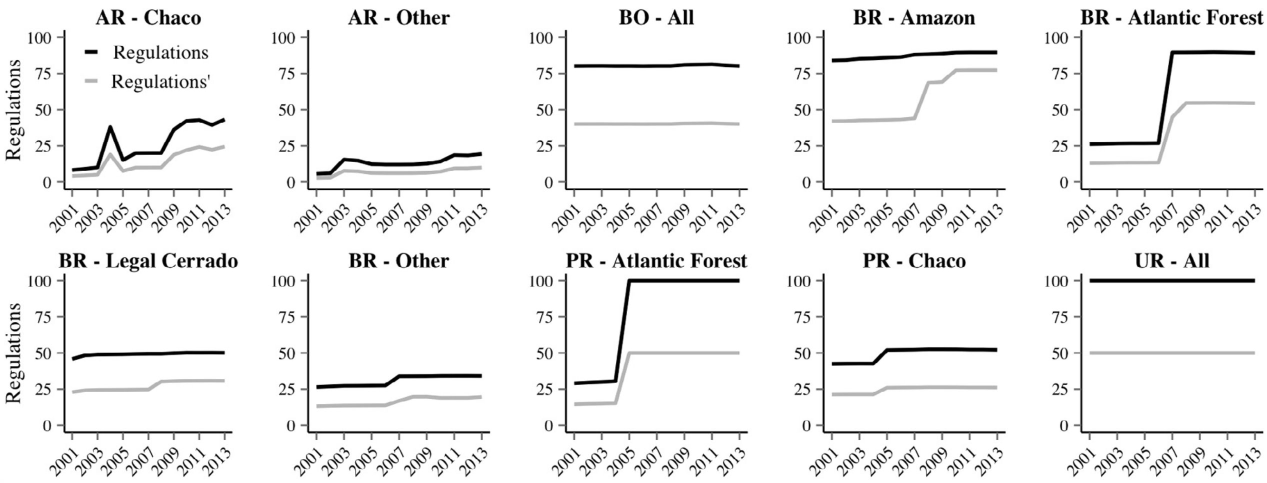

Figure 2. *Forest conservation regulations (% of forest protected) by biome in South America. Black lines represent the average % of forest protected for each biome (variable* $\text{Regulations}_{i,t}$ *in the models); the gray lines represent an alternative version of that variable (*$\text{Regulations}'_{i,t}$*), which takes into account deforestation monitoring, penalties for illegal deforestation, and enforcement capacity (see Section 4). The spike for the Argentine Chaco in 2004 is due to temporary moratoria on deforestation in the provinces of Santiago del Estero (law 6.657) and Santa Fe (law 12.366).*

credit when it is tied to sales contracts). The soy and cattle moratoria could therefore have a synergistic effect with existing public policies by increasing the penalties and the probability of enforcement of deforestation regulations for soy and cattle farmers (see Tables S1 & S2 for more details about changes in governance in the area).

In Argentina, the publication of the first national inventory of native forests in 2002 (Sectetaría del Ambiente y Desarrollo Sustentable, 2002) marked the beginning of a regular (every 2–4 years) satellite-based monitoring of native forests, which increased the visibility of the problem of deforestation, especially in the Gran Chaco. In 2003 and 2004, under mounting pressure from civil society organizations, the provincial governments of Entre Ríos, Santa Fe, and Santiago del Estero declared temporary moratoria on the clearing of native forests (the moratorium in Entre Ríos was originally not meant to be temporary, but it was retracted by a new government in 2004). The province of Córdoba followed with a 2005 open-ended moratorium of its own. In 2007, the national government passed the so-called "Ley de Bosques" (law 26.331), which required each province to design a zoning plan for native forests, based on three levels of land use restrictions. This zoning significantly reduced deforestation in Argentina, but its efficacy in doing so was variable across biomes due to the important differences between provinces in the levels of restrictions and enforcement thereof (Nolte, le Polain de Waroux, *et al.*, 2017; Nolte, Gobbi, *et al.*, 2017).

In 2004, Paraguay also established a "zero deforestation" law for the Atlantic forest. Deforestation rates decreased dramatically after that (Hansen *et al.*, 2013; WWF, 2014), but this decrease has not yet been formally attributed to the law, which environmental organizations say is poorly enforced (Soja y carne hacen perder bosques al país, 2013) in spite of improvements in monitoring capacity offered by quarterly reports of deforestation since 2007 (http://www.wwf.org.py). The Paraguayan ministry of the environment, in partnership with a local NGO and departmental governments, also developed an "environmental management plan" for the three departments of the Paraguayan Chaco. The plan, developed in 2007 and 2008, included non-legally binding recommendations against tree removal in certain areas. A "zero-deforestation law" for the Chaco was proposed and rejected by the chamber of deputies in 2009. Monitoring has greatly improved since 2010, with near-real-time, MODIS-based deforestation data for the whole Gran Chaco published by Guyra, a Paraguayan NGO. However, Paraguay had notably low enforcement of public regulations, with very low fines, low field-enforcement capacity, and very high levels of corruption (Paraguay ranked 150 out of 175 countries on Transparency International's Corruption Perception Index in 2013 (http://www.transparency.org)). Bolivia also had high corruption and insignificant fines (until the passing of law 337 in 2013, which raised fines to higher levels). Consequently, land use zoning plans, such as the one passed in 1996 in the department of Santa Cruz (where most of the Chaco and Chiquitano biomes lie) were largely ignored (le Polain de Waroux *et al.*, 2016).

Further up the soy and beef/leather supply chains, numerous countries and retailers have set aspirational goals and pledges to reduce deforestation from their supply chains that may complement these regional changes in governance. For example, the 2014 New York Declaration on Forests (NYDF), which was signed by 36 countries, including most of Western Europe, and over 100 companies, aims to at least halve the rate of natural forest loss by 2020 and end natural forest loss by 2030 (United Nations., 2014).

(b) *Spillover effects and the effectiveness of deforestation regulations*

For deforestation regulations to be effective in conserving forests locally they must reduce deforestation in the place where they are implemented beyond what was expected to occur in the absence of an intervention (i.e., additionality) (Andam, Ferraro, Pfaff, Sanchez-Azofeifa, & Robalino, 2008). A policy is most likely to be effective in meeting its local conservation goals when the disincentives (penalties) from not complying with the regulation exceed the costs of complying, or when the incentives (payments or rewards) for complying exceed the benefits of not-complying (Börner *et al.*, 2015). Reductions in additionality can occur when different policies

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are overlapping, creating redundancies (Garrett, Carlson, Rueda, & Noojipady, 2016), though the implementation of multiple conservation policies in the same region can also result in synergies (Lambin *et al.*, 2014).

Policies that effectively reduce deforestation for agricultural expansion at the local level may be compensated by intensification, which can take the form of increasing yields on the existing area and/or the replacement of lower productivity land uses with higher productivity ones, resulting in a decoupling of deforestation from growth in agricultural production. However, if increased yields are achieved as the result of a technological change that improves total factor productivity, then intensification can lead to rebound effects in area expansion and deforestation (i.e., Jevon's paradox, (Alcott, 2005)). Indirect land use change (whereby changes in one land use lead to unexpected changes in another land use), can also undermine the local effectiveness of deforestation regulations that target a single land use (Bregman *et al.*, 2015; Lambin & Meyfroidt, 2011; Meyfroidt, Lambin, Erb, & Hertel, 2013). Alternatively, deforestation regulations that pertain to a bounded geographical region can result in a displacement of deforestation-related activities to other areas, through land use leakage (Ewers & Rodrigues, 2008). In the remainder of this section, we discuss these three spillover mechanisms (rebound effects, indirect land use change, and leakage) in the context of South American soy and beef production. We focus in particular on land use leakage, which has received relatively less attention in the literature so far.

(i) *Rebound effects*

A rebound effect can occur when a technological change (e.g., agricultural intensification), which may or may not be induced by a policy change (e.g., restrictions on deforestation), leads to an increase in efficiency (a reduction in costs per unit of output), thereby increasing profits and leading to more agricultural expansion. For example, a policy that subsidizes intensification to ‘‘spare" land for nature may paradoxically lead to an expansion of agricultural area by increasing the profits associated with production in that region. Such an effect is more likely where price elasticity is high, which is typically the case of agricultural commodities such as soy and beef (Lambin & Meyfroidt, 2011). Aside from the provision of subsidized credit for certain forms of cattle intensification, which occurred in Brazil during the study period, most of the policies examined here focus on penalties for deforestation, rather than rewards for intensification, so there is limited potential for a policy-induced rebound effect. If intensification occurs on a large scale alongside effective deforestation restrictions, it should reduce the probability of leakage.

(ii) *Indirect land use change*

Indirect land use change can occur when a policy differentially affects land uses or users, leading to a cascade of events that rearranges the proximate causes of deforestation. Notably, in South America, where soy and cattle production is suitable in many of the same regions, the expansion of soy has been shown to lead to a displacement of cattle pastures into forest (Arima, Richards, Walker, & Caldas, 2011). While most public regulations examined in this study theoretically apply equally to both soy and cattle properties [2] and to different sizes of farms, there are differences across the soy and beef sectors in the way private regulations in the Brazilian Amazon (the Soy Moratorium and G4 cattle agreement) were designed and implemented. First, the Soy Moratorium preceded the cattle agreement and, from the start, covered a large proportion of the soy market. A majority of Brazilian soy production (73%) goes to international markets, and all major international traders, as well as the domestic Brazilian Vegetable Oil Industry, were signatories to the Soy Moratorium in 2006. In contrast, roughly 80% of Brazilian beef production goes to domestic markets, and while the first G4 zero-deforestation agreement was signed by the four largest meatpacking companies in 2009, it was not until 2013 that the Brazilian Association of Supermarkets (ABRAS) signed a similar agreement (Butler, 2013). Secondly, there are significantly more opportunities for ranchers to evade private regulations, due to the lower capacity of small and midsize processors to monitor deforestation among their suppliers, opportunities for laundering between compliant and non-compliant ranchers, and loopholes in the tracking system (Datu Research, 2014; Gibbs *et al.*, 2015). Additionally, compliance with deforestation regulations may be lower on smaller properties, since the fixed costs associated with obtaining the paperwork showing compliance are high, and because it is more difficult to monitor deforestation or identify laundering on smaller properties (Gibbs *et al.*, 2015; Godar, Gardner, Tizado, & Pacheco, 2014). Under these circumstances, increases in deforestation regulations may induce a redistribution of land uses toward cattle ranching and small-sized farms, which would limit the overall local effectiveness of these regulations. Note that this would also reduce the potential for cross-biome leakage.

(iii) *Land use leakage*

Leakage, i.e., the displacement of an environmental impact due to a policy intervention, can be driven by two interconnected mechanisms, both the consequence of a negative effect of regulations on agricultural rents. The introduction of more stringent regulations is expected to reduce agricultural rents in the frontier by: (i) increasing prices for unregulated arable land, and (ii) increasing costs associated with production, primarily by increasing transaction costs associated with both legal and illegal area expansion, e.g., fines for illegal activities, administrative costs related to verifying environmental compliance, or opportunity costs associated with authorization delays.

In the first mechanism, called ‘‘activity leakage" (Atmadja & Verchot, 2012; Henders & Ostwald, 2012), unused capital is displaced directly out of the frontier affected by the new deforestation regulations, and redirected to areas with higher rents (Angelsen, 2007). This redirection of capital to other agricultural regions may occur when specialized machinery, labor, and knowledge cannot be easily transferred to other, local economic sectors. In the second mechanism, called ‘‘market leakage", changes in the location of production are induced by changes in the price of agricultural commodities. An increase in *global or regional* commodity prices can occur, provided demand is not perfectly elastic, when regulations cause a substantial decrease in production volumes that affects a large share of the market. Higher commodity prices will then incentivize farming in new areas where it was not profitable before. An increase in *local* commodity prices, on the other hand, can occur as a result of changes in costs associated with production, as described above, resulting in a loss of competitive advantage relative to other potential suppliers of the same good. If consumers in this market source mainly based on price, they will then adjust their sourcing practices to purchase more of that good from an alternative region that now costs less (Villoria & Hertel, 2011).

Given the existence of these potential mechanisms, we suggest that leakage is most likely to occur in the context of a particular commodity and set of regions when: (i) new regulations are sufficiently stringent and enforced to increase the costs of

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production for that commodity; (ii) alternative production areas for the commodity exist, with low competition from alternative land uses; (iii) capital is mobile across suitable production regions; (iv) markets for that commodity are fully integrated, with trade that is based primarily on price rather than quality differentiation (particularly quality attributes that are influenced by the region of production) (Atmadja & Verchot, 2012); and (v) the market share covered by the region where regulations occur is large for the commodity in question.

Soy and cattle frontiers in South America largely fulfill these conditions. Recent changes in forest conservation policies and enforcement across South America have created large differentials in environmental governance within cattle- and soy-producing regions (Figure 2), although it is not known whether these translate into significant differences in land prices or in the cost of production. Regulations increased significantly in the Brazilian Legal Amazon (including parts of the Cerrado) and Atlantic Forest, the Argentinian Chaco, and the Paraguayan Atlantic Forest, which collectively represent 36% of South American soy production and 38% of South American beef production (Figure 3). These policy changes occurred amidst continued incentives to expand agricultural area in all regions due to growing global demand for meat products. Furthermore, there is a large degree of integration between cattle and soy companies in the region, and high mobility of some major companies across country borders,

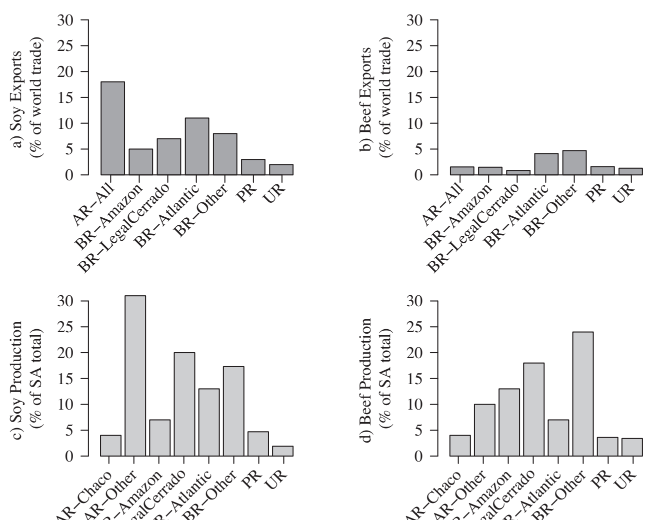

Figure 3. *Market shares of South American soy and beef as a proportion of world trade (a,b) and South American (SA) production (c,d). AR = Argentina, BO = Bolivia, BR = Brazil, PR = Paraguay, UR = Uruguay. Brazil is further delimited by biome for both trade and production, while Argentina is delimited by biome for just production since the SEI-PCS model data did not include Argentina. For Brazil, the term Legal Cerrado*[2] *is a combination of both an ecological and political designation. Soy production and trade data are from 2012, beef production and trade data are from 2011. World trade totals and export volumes for Argentina, Paraguay, and Uruguay and production volumes for Paraguay and Uruguay are from FAOStat. Export volumes for Brazilian biomes are from SEI-PCS. Production volumes for Argentinian and Brazilian biomes are from domestic agricultural surveys. Soy and beef exports and production in biomes/countries with higher forest restrictions (BR-Amazon, BR-Legal Cerrado, BR-Atlantic, PR, and UR) each comprise a relatively small proportion of total world trade and South American production, but together account for roughly 38% of South American production.*

in contrast to smallholders, who are typically more constrained (Gasparri & le Polain de Waroux, 2015; Glauser, 2009; le Polain de Waroux *et al.*, 2016; Piñeiro, 2012; Urioste, 2012). Finally, the global market for soybeans and beef is largely based on price although, in some cases, quality preferences can offset price-based differentiation (Garrett, Rueda, & Lambin, 2013; Villoria & Hertel, 2011). For all of these reasons, the soy and cattle frontiers of South America may be susceptible to policy-induced leakage (see Figure 4).

If deforestation regulations affect agricultural rents, then reductions in the rates of soy and pasture expansion (beyond what would have occurred otherwise) should be observed in the biomes that have experienced the greatest strengthening of regulations. If changes in expansion are observed, then there is some reason to expect that leakage may have also occurred. Additionally, we may expect a reduction in soy and beef exports from these regions if they have lost competitive advantage due to increased costs. The association of these two conditions with increases in the rate of soy and pasture expansion in the less regulated biomes, such as the Cerrado or the Pampas, would suggest that restrictions to soy and pasture expansion in the more regulated biomes may be leading to activity and market leakage to less regulated biomes.

3. DATA

To test for the influence of deforestation regulations on the rate of agricultural expansion and on import patterns, we develop models of soy and pasture area expansion (hereafter "area models") and of soy and beef imports (hereafter "trade models") against control variables (see Section 4). When variables overlap (e.g., agricultural production), the same data sources are used in the area and trade models, unless otherwise indicated.

For the area models, our scale of analysis is *municipios* in Brazil, *departamentos* in Argentina, Paraguay, and Uruguay, and *provincias* in Bolivia, hereafter referred to as "municipalities" for simplicity. These units of analysis have an average area of 200,000 ha (sd = 640,000 ha). Pasture, cropland, and forest area for 2001–14 are derived from MODIS images (see Graesser, Aide, Grau, & Ramankutty, 2015) and averaged to the municipality. Soy area, soy yields, cattle heads, and producer prices were obtained from the local Ministries of Agriculture, FAOSTAT, and various other sources (see SM). We obtained population data from national censuses, soy and pasture suitability indexes from the FAO GAEZ, and climatic data from the Climate Research Unit, CRU TS3.23 (Harris, Jones, Osborn, & Lister, 2014). We calculated transport costs using port and slaughterhouse data from various sources (Table 1), and roads data from the Global Roads Inventory Project.

We obtained data on national trade flows for soybeans, soy oil, and beef from FAOSTAT's trade matrix tool. One limitation of the trade data is that imports and exports are self-reported and countries may purposefully or mistakenly misrepresent trade levels in official data. Furthermore, import data may not account for re-exports. Data on biome-level exports (within Brazil) was obtained from the SEI-PCS model ((Godar, Persson, Tizado, & Meyfroidt, 2015; Godar, Suavet, Gardner, Dawkins, & Meyfroidt, 2016)). We obtained biome-level soy and cattle production from annual Brazilian Municipal Agricultural Surveys and aggregated to biomes using the same coding as the trade flow data (IBGE., 2013). We derived total consumption in each country and biome by summing production and imports and subtracting exports.

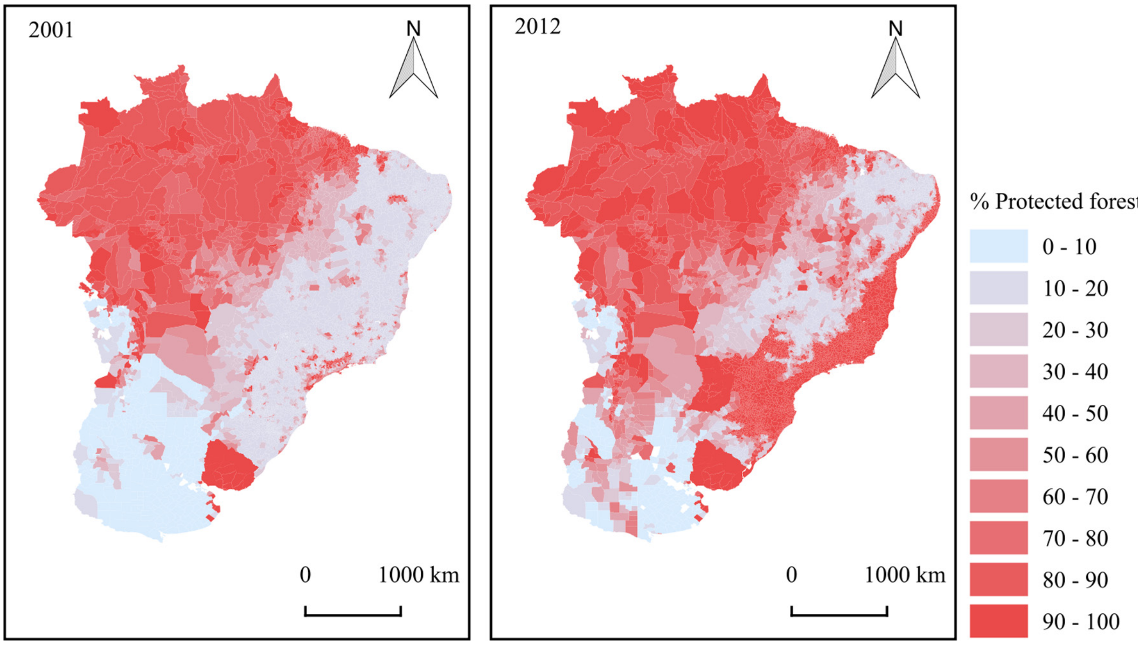

Figure 4. *Percent of municipal-level forest area that cannot be legally deforested (average of the values of variable* $\text{Regulations}_{i,t}$ *for soy and cattle; includes on-property regulations and protected areas; Argentinian Patagonia is excluded from the sample).*

Table 1. *Data*

Data	Scale	Source
Contours of administrative units	n/a	IGN (Argentina); CDRN (Bolivia); IBGE (Brazil); GADM (Paraguay, Uruguay)
Contours of biomes	n/a	WWF (Argentina, Bolivia, Paraguay, Uruguay); IBGE & Ministry of Environment (Brazil)
Roads	n/a	Global Roads Inventory Project
Ports	n/a	Literature review
Slaughterhouses	n/a	Literature review; SENASA (Argentina); SENACSA (Paraguay); SENASAG (Bolivia); ACG (Uruguay); MAPA (Brazil)
Deforestation regulations	Municipality	Literature review
Soy area & yield	Municipality	Ministry of Agriculture (Argentina, Paraguay, Uruguay); IBGE (Brazil)
Cattle heads	Municipality	SENASA (Argentina); CAO & MDRyT (Bolivia); Ministry of Agriculture (Paraguay, Uruguay); IBGE (Brazil)
Soy & grass suitability	Municipality	FAO GAEZ
Rainfall & temperature	Municipality	Climate Research Unit
Population	Municipality	National censuses; DGEEC (Paraguay); IBGE (Brazil)
Pasture, cropland & forest area	Municipality	Graesser et al. (2015)
Soy prices	National	FAOSTAT
Beef prices	National	FAOSTAT (Argentina, Bolivia, Uruguay); SENACSA (Paraguay); Fundação Getulio Vargas (Brazil)
Exchange rates	National	International Monetary Fund
Export taxes	National	Literature review
Property conservation regulations	Biome	Literature review
Protected areas	n/a	World Database on Protected Areas
Trade data	National	FAOSTAT trade matrix
	Municipality aggregated to biome (Brazil)	SEI-PCS
GM soy area	National	International Service for the Acquisition of Agri-biotech Applications
	State aggregated to biome (Brazil)	Celeres
Soy & beef production	National	FAOSTAT production
	Municipality aggregated to biome	IBGE

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Table 2. *Regulation variables*

Variable	Value	Meaning
Regulations	0–100	Percentage of the municipality's forest area that cannot be deforested legally (variable multiplied by a soy or pasture suitability index)
Penalties	0	Fines for illegal deforestation are <\$100/ha
	0.5	Fines for illegal deforestation are \$100/ha to \$1000/ha
	1	Fines for illegal deforestation are >\$1000/ha
Monitoring	0	No satellite monitoring
	0.33	Sporadic or incomplete monitoring
	0.66	Systematic monitoring at low temporal resolution (over a year)
	1	Systematic monitoring at high temporal resolution (under a year)
Enforcement	0	No enforcement mechanism applied consistently
	0.33	One enforcement mechanism applied consistently
	0.66	Two enforcement mechanism applied consistently (regular application of fines + blacklisting)
	1	Several enforcement mechanisms applied consistently (regular application of fines + blacklisting + moratorium)

For all metrics soybean and soy oil were combined into a single measure based on the weight contribution of soy oil in soybeans (see SM). Beef products and live cattle were similarly combined, this time based on carcass weight and life cycle length (for annual production equivalents) (see SM). We obtained exchange rates per US$ for all countries from the IMF and converted these exchange rates into ratios of exchange between the exporting country and importing country (www.imf.org). We compiled data on export taxes through an extensive literature review including official sources (e.g., ministries) and newspaper articles. Table 1 summarizes all the data used, and additional details on the data are available in the Supplementary Material.

4. METHODS

(a) *Area models: estimating the impact of regulations on agricultural expansion*

In order to estimate the effect of deforestation regulations on agricultural expansion, we use a multivariate panel regression on year-to-year difference in soy and pasture area during 2002–13, with time and individual fixed effects. The area model takes the general form:

$$\Delta(Area_{i,t}, Area_{i,t+1}) = Regulations_{i,t} + Controls_{i,t} + \alpha_i + \delta_t * Biome_i + u_{it} \quad (1)$$

where $Regulations_{i,t}$ corresponds to the percentage of the forest-land within each municipality that must be kept as forest legally according to public regulations (% protected forest, Figure 2; this includes on-property regulations as well as protected areas and non-agricultural zoning laws, see SM), multiplied by a soy or pasture suitability index in order to give less weight to municipalities not suitable for these activities, and where regulations therefore should not matter. For legal limits on deforestation to have an effect, they must be enforced. This implies: (i) the ability to detect and monitor changes in land use, (ii) the existence of penalties for illegal deforestation, and (iii) the existence of clear mechanisms to enforce penalties. Therefore, we also test models with an alternative regulations variable $Regulations'_{i,t}$ that incorporates governance, and is defined as the product of $Regulations_{i,t} * [0.5 + 0.5 * (Penalties_{i,t} * Monitoring_{i,t} * Enforcement_{i,t})]$ with $Penalties_{i,t}$ representing the level of fines for illegal deforestation, $Monitoring_{i,t}$ representing the frequency of satellite monitoring, and $Enforcement_{i,t}$ representing the number of mechanisms used for enforcement (see Table 2). We run models with a 1- and 2-year lag on $Regulations_{i,t}$ and $Regulations'_{i,t}$ to test for potential endogeneity. Figure 2 shows the evolution of these variables over time for the main biomes in the region. The term α_i is a fixed effect for municipalities, and $\delta_t * Biome_i$ is a biome-specific time fixed effect. We exclude municipalities that had no soy or pastures during the whole study period, or with an altitude higher than 1000 m, from the analysis. All variables are mean centered and scaled.

The full soy area model is specified as follows:

$$\begin{aligned}\Delta(Soy_Area_{i,t}, Soy_Area_{i,t+1}) = {} & Regulations_{i,t} \\ & + \Delta(Soy\_Area_{i,t-1}, Soy\_Area_{i,t}) \\ & + Neighborhood\_Effect_{i,t} \\ & + Soy\_Price_{c,t} + Soy\_Yields_{i,t} \\ & + Population_{i,t} + Cost\_to\_Ports_{i,t} \\ & + Rainfall_{i,t} + Temperature_{i,t} \\ & + Suitable\_Cropland\_Area_{i,t} \\ & + Suitable\_Pasture\_Area_{i,t} \\ & + Suitable\_Forest\_Area_{i,t} + \alpha_i + \delta_t \\ & * Biome_i + u_{it} \quad (2)\end{aligned}$$

where i is the municipality and c the country. The term $\Delta(Soy\_Area_{i,t-1}, Soy\_Area_{i,t})$ captures path dependence in the dependent variable, and $Neighborhod\_Effect_{i,t}$ reflects the influence of contiguous municipalities, calculated as the difference between the average percent change in soy area of contiguous municipalities within the same country, and the percent change in soy area for the municipality under consideration, multiplied by the total area. The variables $Suitable\_Cropland\_Area_{i,t}$, and $Suitable\_Pasture\_Area_{i,t}$ represent land that is potentially available for soy expansion, calculated as the area of cropland or pasture multiplied by the index of suitability for soy cultivation (excluding the area already cultivated in soy at time t). The remaining variables control for spatial and temporal variations in agricultural rent. For $Rainfall_{i,t}$ and $Temperature_{i,t}$, we tested the raw values and

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deviation from mean value for all seasons and the year total. We used the variables that were most significant and yielded the best AIC (Akaike Information Criterion) and BIC (Bayesian Information Criterion) for the models (here average monthly rainfall and average spring temperature).

The pasture area model is specified as follows:

$$\begin{aligned}\Delta(Pasture\_Area_{i,t}, Pasture\_Area_{i,t+1}) \\ = Regulations_{i,t} + \Delta(Pasture\_Area_{i,t-1}, Pasture\_Area_{i,t}) \\ + Neighborhod\_Effect_{i,t} + Beef\_Price_{c,t} \\ + \ln(Cattle\_Density)_{i,t} + Population_{i,t} \\ + Cost\_to\_Slaughterhouse_{i,t} + Rainfall_{i,t} \\ + Temperature_{i,t} + Suitable\_Cropland\_Area_{i,t} \\ + Suitable\_Forest\_Area_{i,t} + \alpha_i + \delta_t * Biome_i + u_{it}\end{aligned} \tag{3}$$

where $Cattle\_Density_{i,t}$ is the number of cattle heads per hectare, taken as a proxy for pasture productivity, $Rainfall_{i,t}$ and $Temperature_{i,t}$ are average fall rainfall and average summer temperature, and $Suitable\_Cropland\_Area_{i,t}$ is the area of cropland multiplied by a grass productivity index (see SM for more information on the variables). We test additional models with an interaction term $Regulations_{i,t} * Forest\_Area_{i,t}/(Area_i - Soy\_Area_{i,t})$, for the soy model, and $Regulations_{i,t} * Forest\_Area_{i,t}/(Area_i - Pasture\_Area_{i,t})$, for the pasture model, to see if the effect of regulations is moderated by the proportion of forestland in the land available for expansion (we expect regulations to matter more where a large proportion of the land on which soy or cattle can potentially expand is covered in forests). We also run models on a sample restricted to the Amazon biome, in order to see to what extent our models reproduce the results of existing studies (e.g., Hargrave & Kis-Katos, 2013).

(b) *Trade model: testing trade and price differentiation*

To examine how changes in environmental governance (regulations, monitoring, penalties, and enforcement) influence soy and cattle trade, we specify a multivariate panel regression with time and individual fixed effects spanning from 2000 to 2013. The model is a standard partial equilibrium integrated world market model, with an *Armington assumption* (Villoria

Table 3. *Soy area models results*

	I	II	III	IV	V	VI	VII
Regulations	–	0.11***	0.05*	0.01	0.12***	0.06*	0.02
Lagged soy area	−0.12**	−0.12**	−0.12**	−0.14***	−0.12**	−0.12**	−0.14***
Neighborhood	0.69***	0.68***	0.69***	0.74***	0.68***	0.69***	0.74***
Population	−0.20	−0.19	−0.19	−0.21	−0.19	−0.19	−0.21
Transport cost to port	0.05*	0.06*	0.06*	0.05†	0.06*	0.06*	0.05†
Soy yield	0.03***	0.03**	0.03***	0.04***	0.03**	0.03***	0.04***
Soy price	0.34	0.26	0.26	−0.03	0.24	0.25	−0.04
Average monthly rainfall	0.02*	0.02*	0.03*	0.02†	0.02*	0.03*	0.02†
Average spring temperature	−0.26**	−0.28***	−0.28***	−0.32***	−0.28***	−0.28***	−0.32***
Suitable cropland	0.51**	0.52**	0.50**	0.50**	0.52**	0.50**	0.50**
Suitable pastureland	0.53	0.53	0.50	0.58	0.52	0.50	0.58
Suitable forestland	1.32†	1.33†	1.28†	1.36†	1.33†	1.28†	1.36†
Constant	0.04	0.12	0.09	0.15	0.12	0.09	0.16
R-squared	0.20	0.20	0.20	0.21	0.20	0.20	0.21
Lag	n/a	None	1 year	2 years	None	1 year	2 years
Regulation variable	n/a	Regulations	Regulation	Regulations	Regulations'	Regulations'	Regulations'

Notes: † = 0.90. *0.95. **0.99. ***0.999. Includes municipality and year * biome fixed effects.

Table 4. *Pasture area models results*

	I	II	III	IV	V	VI	VII
Regulations	–	0.00	0.01	0.02	0.01	0.02	0.04†
Lagged pasture area difference	0.03	0.04	0.04	0.04	0.04	0.04	0.04
Neighborhood	1.16*	1.14*	1.14*	1.15†	1.14*	1.13*	1.15†
Population	−0.07	−0.08	−0.08	−0.06	−0.08	−0.08	−0.06
Transport cost to slaughterhouse	0.13	0.12	0.12	0.27	0.12	0.12	0.26
ln(cattle density)	0.10***	0.10***	0.10***	0.09***	0.10***	0.10***	0.09***
Beef price	1.28	1.28	1.28	1.28	1.28	1.28	1.29
Average fall rainfall	−0.05***	−0.05***	−0.05***	−0.06***	−0.05***	−0.05***	−0.06***
Average summer temperature	−0.15***	−0.14***	−0.14***	−0.18***	−0.14***	−0.14***	−0.18***
Suitable cropland	0.31*	0.32*	0.32*	0.42*	0.32*	0.32*	0.42*
Suitable forestland	7.07**	7.21**	7.21**	7.50*	7.21**	7.22**	7.52*
Constant	−0.17*	−0.17*	−0.17*	−0.23†	−0.17*	−0.16*	−0.23†
R-squared	0.17	0.17	0.17	0.17	0.17	0.17	0.17
Lag	n/a	None	1 year	2 years	None	1 year	2 years
Regulation variable	n/a	Regulations	Regulation	Regulations	Regulations'	Regulations'	Regulations'

Notes: † = 0.90. *0.95. **0.99. ***0.999. Includes municipality and year * biome fixed effects.

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& Hertel, 2011), which states that seemingly identical exports from different countries are not perfectly substitutable. Instead, an importer's rate of substitution between different exporters in response to price changes depends on existing trade infrastructure and the perceived quality of different exporters. Here we allow for the possibility that changing environmental governance in the exporting region could differentially influence the perceived quality of that exporter within importing countries.

We use the following logistic model to estimate annual imports:

$$Imports_{i,e,t} = Regulations_{e,t} * Europe_i + GM_{e,t} * Europe + Prices_{i,e,t} + Consumption_{e,t} + Production_{e,t} + \alpha_{i,e} + \delta_t + u_{i,e,t} \quad (4)$$

where the dependent variable $Imports_{i,e,t}$ is the proportion of country i's processed and unprocessed soy imports from country e in time t and is bounded by 0 to 1, which allows us to assess factors that influence substitution between export partners. As with the area models above, we test models with $Regulations_{e,t}$ as the average percentage of the forestland within each exporting country or biome that must be kept as forest (i.e., that may not be cleared), and as the product of $Regulations_{e,t} * [0.5 + 0.5 * (Penalties_{e,t} * Monitoring_{e,t} * Enforcement_{e,t})]$ (variable $Regulations'_{e,t}$). The variable $GM_{e,t}$ is the proportion of the soy area in each exporting country (or in the case of Brazil, each biome), that is planted with genetically modified seeds (included only in the soy trade model), which has been shown to be a predictor of import behavior (Garrett *et al.*, 2013). With $Regulations_{e,t}$ and $Regulations'_{i,t}$, we include a binary interaction term, $Europe_i$, to represent all of the European countries in our study, (France, Germany, Italy, Netherlands Portugal, Spain, United Kingdom), since as a group European soy and beef retailers and processers have made the greatest number of commitments to eliminating deforestation in their supply chains, which might lead to a structural difference in the way that these importing countries respond to changes in deforestation regulations in the exporting country. We conduct robustness tests with New York Declaration signatories [3] as a group, since these countries have made public commitments to reducing deforestation, which may be an indication of preferences for more sustainable products (McCarthy, 2016). We also include an interaction term with $GM_{e,t}$ to represent Europe's preference for non-GM soy (Garrett *et al.*, 2013). The vector

Table 5. *Soy trade model results*

	I	II	III	IV	V	VI
Regulations	-1.21^{***}	-0.42	-2.01^{***}	-0.63	0.15	0.03
Regulations:Importer Group	1.98^{***}	–	3.19^{***}	–	-1.51^{***}	-1.83^{***}
GM Percent	-0.01^{*}	-0.01^{*}	$-0.01^{\dagger}$	$-0.01^{\dagger}$	-0.01^{*}	-0.01^{*}
GM Percent:Europe	-0.02^{***}	-0.02^{***}	-0.02^{***}	-0.02^{***}	-0.02^{***}	-0.02^{***}
Europe	0.13	1.15^{***}	0.29	1.15^{***}	1.42^{***}	1.36^{***}
NY Declaration	–	–	–	–	–	0.17
Production	0.36	0.33	0.37	0.32	0.29	0.32
Exchange Rate	-0.32^{**}	-0.28^{*}	-0.31^{**}	-0.28^{*}	0.32	-0.28^{*}
Export Tax	-0.31^{***}	-0.34^{***}	-0.31^{***}	-0.34^{***}	-0.28^{*}	-0.34^{***}
Constant	−0.06	−0.23	−0.26	−0.3	−0.38	−0.41
R-squared	0.36	0.35	0.37	0.35	0.36	0.35
Importer Group	Europe		Europe		NY Declaration	NY Declaration
Regulation variable	Regulations	Regulations	Regulations'	Regulations'	Regulations	Regulations'

Notes: † = 0.90. *0.95. **0.99. ***0.999. Includes year, importer, and exporter fixed effects. Europe = France, Germany, Italy, United Kingdom, Spain, Netherlands, Portugal. Non-Europe = China (mainland), Egypt, Indonesia, Japan, Malaysia, Mexico, Republic of Korea, Russian Federation, Saudi Arabia, Thailand, Tunisia, Turkey, USA, and Viet Nam. NY Declaration = France, Germany, Indonesia, Japan, Mexico, Netherlands, United Kingdom, USA. Non-NY Declaration = China (mainland), Egypt, Italy, Portugal, Malaysia, Republic of Korea, Russian Federation, Saudi Arabia, Spain, Thailand, Tunisia, Turkey, and Viet Nam.

Table 6. *Beef trade model results*

	I	II	III	IV	V	VI
Regulations	-1.41^{***}	-0.93^{**}	-2.09^{***}	-1.29^{*}	-1.16^{**}	-1.69^{**}
Regulations:Importer Group	0.98^{***}	–	1.61^{***}	–	0.58^{*}	0.99^{*}
Importer Group	−0.22	–	−0.20	–	−0.13	−0.12
Production	0.10	0.10	0.10	0.10	0.10	0.10
Exchange Rate	-0.55^{*}	-0.48^{*}	-0.54^{*}	-0.48^{*}	-0.49^{*}	-0.49^{*}
Export Tax	−0.07	−0.08	−0.08	−0.08	−0.07	−0.08
Constant	-2.6^{***}	-2.69^{***}	-2.64^{***}	-2.72^{***}	-2.64^{***}	-2.67^{***}
R-squared	0.26	0.25	0.26	0.25	0.25	0.25
Importer Group	Europe	Europe	Europe	Europe	NY Declaration	NY Declaration
Regulation variable	Regulations	Regulations	Regulations'	Regulations'	Regulations	Regulations'

Notes: † = 0.90. *0.95. **0.99. ***0.999. Includes year, importer, and exporter fixed effects. Europe = France, Germany, Italy, Netherlands, Spain, and United Kingdom. Non-Europe = Canada, Egypt, Japan, Malaysia, Republic of Korea, Russia, Saudi Arabia, and USA. NY Declaration = Canada, France, Germany, Japan, Netherlands, and United Kingdom. Non-NY Declaration = Egypt, Italy, Russia, Spain, Malaysia, Republic of Korea, and Saudi Arabia.

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$Prices_{i,e,t}$ represents soy or beef prices, and includes the exchange rate between the exporting country's currency and the importing country's currency ($Exchange\_Rate_{i,t}$), i.e., the value of the exporter's currency per unit of the importer's currency, and export taxes in each exporting country ($Export\_Tax_{e,t}$). $Consumption_{e,t}$ and $Production_{e,t}$ include the volume of soy or beef consumption and production, respectively, in the exporting country. We include year (δ_t) and country ($\alpha_{i,e}$) fixed effects for all importers and exporters to control for any other price or quality variable that is place-dependent but not captured in our model. We test the robustness of the models to one year lags for all of our explanatory variables and find no difference in the results.

For soy, we include the 6 largest global exporters as of 2012—Argentina, Brazil, Canada, Paraguay, Uruguay, and USA—and the 21 largest importers (see Table 5). Together, this group of exporters and importers accounts for 90% of global soy trade. For cattle, we include the 10 largest exporters — Argentina, Australia, Brazil, Canada, France Mexico, New Zealand, Paraguay, United States, and Uruguay and the 14 largest importers (see Table 6). Together, this group of exporters and importers accounts for 90% of global beef exports and 60% of imports. To capture differences in public and private regulations across Brazil, this exporter is further broken into the Amazon, Legal Cerrado, Atlantic Forest, and "Other", corresponding to the Caatinga, Chiquitano, Pampas and Pantanal biomes (Figure 1).

(c) *Patterns of deforestation, intensification, and domestic consumption*

In order to provide context for the results of the area and trade models, and understand their significance for the effectiveness of deforestation regulations, we conduct additional analyses. First, we estimate the correlation coefficients (Pearson) of forest area change with soy and pasture area change for each biome in the region, using municipality-level land use data (Table 1). Second, we use FAOSTAT and SEI-PCS

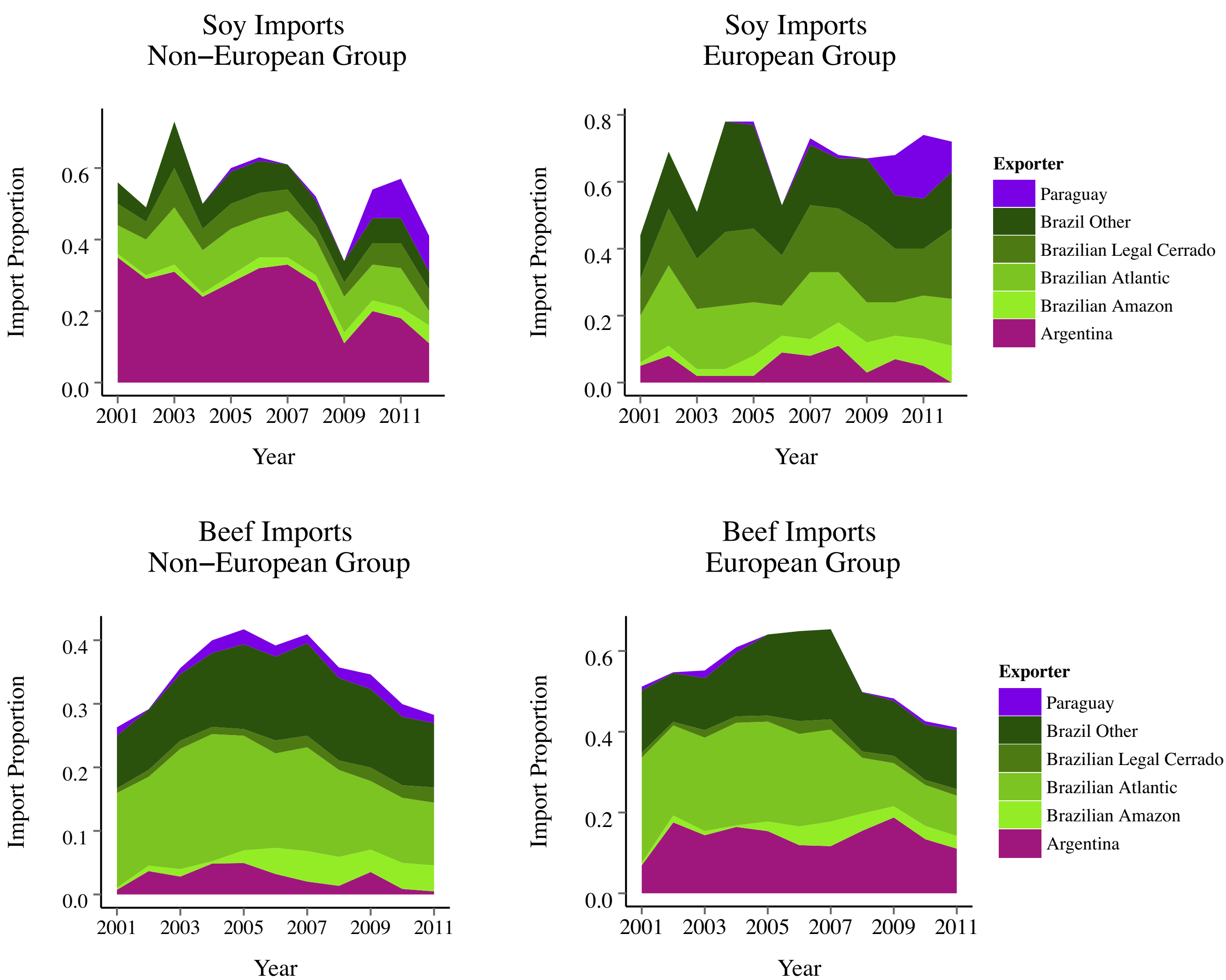

Figure 5. *Average soy and beef import proportions from European and non-European countries. Data from FAOSTAT & SEI-PCS (Table 1). Import proportions are the average proportion of imports comprised by each exporting region, for countries in the import group (European or Non-European). On average, imports of soy produced in biomes/countries with higher forest restrictions (Brazilian Amazon, Atlantic, Legal Cerrado, and Paraguay) to non-European countries decreased during the study period, but were offset by increases in imports to European countries from these same regions. Imports of beef from regions with higher forest restrictions decreased to all countries over the study period.*

data to examine how changes in exports relate to patterns of domestic consumption of soy and beef.

5. RESULTS

(a) *Area change model results*

For the entire study region, we find no significant reduction in the rate of soy and pasture area expansion due to increased regulations and governance in our models (Tables 3 and 4). Instead, the soy area models show a significant positive sign for $Regulations_{i,t}$ and $Regulations'_{i,t}$ that decreases with a 1-year lag and disappears with a 2-year lag. However, when restricting the sample to the Brazilian Amazon only, we find a significant reduction of pasture expansion with increasing regulations, although we find no such effect for soy area (Tables S3 and S4). In robustness tests that include an interaction effect for forest availability, the coefficient for the interaction term $Regulations_{i,t} * Forest\_Area_{i,t}/(Area_i - Pasture\_Area_{i,t})$ is significant and negative in the non-lagged pasture model, but this effect disappears in the lagged models and it is absent for $Regulations'_{i,t}$. The coefficient for the term $Regulations_{i,t} * Forest\_Area_{i,t}/(Area_i - Soy\_Area_{i,t})$ is not significant for the soy area models except for the interaction with $Regulations'_{i,t}$, where it is positive (Tables S5 and S6).

Control variables mostly have expected effects on soy and pasture area expansion rates. For soy area, high yields, high rainfall, a large difference in soy area with neighboring municipalities, and large amounts of available cropland (and, less significantly, forestland) all increase rates of soy area expansion, while high spring temperatures and high expansion in the previous year have the opposite effect. However, the effect of soy yields disappears when lagged. The positive sign of transport cost to the nearest port, while less intuitive, may be due to the absence of land prices from the model (see Section 6). Population, soy price and suitable pastures all have no effect on soy expansion.

For pastures, high cattle density, high amounts of suitable cropland and forestland, and large differences in pasture area with neighboring municipalities were all positively associated with pasture expansion. High fall rainfall and summer temperatures have the opposite effect, and past year expansion, beef prices, transport cost to slaughterhouses, and population have no effect. The effect of available forestland is especially large compared to that of other variables. The neighborhood effect is also relatively large, for both the soy and pasture area models.

For both models, we test for non-stationarity of the dependent variable by means of a Fisher-type ADF unit root test with 1, 2, and 3 lags, and find the variable to be stationary. All the variance inflation factors are equal or inferior to 2, indicating no collinearity issue. A modified Wald test for group-wise heteroscedasticity test indicates the presence of heteroscedasticity in the models, so we specify heteroscedasticity-robust standard errors.

(b) *Trade model results*

We find that all countries imported less beef from exporters with more stringent environmental regulations, all else equal, as well as more stringent overall governance (penalties, monitoring, and enforcement) (Table 6, Figure 5). However, the shift in response to environmental regulations was less pronounced among European and NY Declaration beef importers. Non-European and NY Declaration countries imported less soy from exporters with more stringent environmental governance, including places with more stringent regulations, while European countries imported more soy from exporters with more stringent governance (Table 5). The difference in soy import behavior by the European and NY Declaration groups is due to Japan and Indonesia (NY Declaration signatories), who substantially reduced their imports from more regulated regions.

Other determinants of trade functioned largely as predicted for the soy models. European countries imported less from countries with low availability of non-GM soy. Imports were lower from exporters whose currency increased in value relative to the importer. For soy, increases in the export tax in the exporter had a significant (negative) influence on imports. Production levels in the exporter were not a significant determinant of trade. We tested for non-stationarity of the dependent variable by means of a Fisher-type ADF unit root test with 1, 2, and 3 lags, and found the variable to be stationary. We did not identify any multicollinearity problems — all the variance inflation factors in the model without fixed effects were less than 1.7.

(c) *Additional analyzes*

(i) *Agricultural expansion and deforestation*

We find higher correlations between pasture expansion and deforestation than between soy expansion and deforestation,

Table 7. *Correlations of forest area change with soy and pasture area change*

Country	Biome	Soy			Pastures		
		2001–13	2001–06	2007–13	2001–13	2001–06	2007–13
Argentina	Chaco	−0.02	−0.02	0.02	-0.69^{***}	-0.57^{***}	-0.84^{***}
	Other	−0.02	−0.03	−0.02	-0.77^{***}	-0.72^{***}	-0.84^{***}
Bolivia	All	-0.24^{*}	$-0.29^{\dagger}$	−0.24	-0.63^{***}	-0.98^{***}	-0.52^{***}
Brazil	Amazon	-0.08^{**}	-0.11^{**}	−0.01	-0.55^{***}	-0.83^{***}	-0.36^{***}
	Atlantic Forest	-0.07^{***}	-0.11^{***}	0.01	-0.22^{***}	-0.36^{***}	-0.2^{***}
	Cerrado	-0.14^{***}	-0.15^{***}	-0.08^{*}	-0.79^{***}	-0.69^{***}	-0.89^{***}
	Other	-0.08^{***}	-0.04^{*}	-0.13^{***}	-0.84^{***}	-0.86^{***}	-0.83^{***}
Paraguay	Atlantic Forest	-0.25^{**}	-0.29^{*}	−0.14	-0.42^{***}	-0.42^{**}	-0.38^{**}
	Chaco	0.01^{*}	−0.07	0.05	-1^{***}	-1^{***}	-1^{***}
Uruguay	All	n/a	n/a	n/a	-0.18^{**}	-0.23^{**}	0.04

Notes: † = 0.90. *0.95. **0.99. ***0.999. All correlations are Pearson's correlations. Due to absent sub-national data for soy area in Uruguay, correlation coefficients are not provided.

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for all regions (Table 7). In most regions, the association between soy expansion and deforestation is stronger in the first period (2001–06) than in the second (2007–13), in which most correlations are non-significant. A similar but weaker decoupling is observed for pasture expansion and deforestation in several biomes, but in Argentina and the Brazilian Cerrado, the correlation actually increases during the second period.

(ii) *Domestic consumption of soy and beef*

We find a large increase in beef supply to Brazilian markets from the Amazon (+117%), Legal Cerrado (+73%), and Atlantic (+73%) biomes during 2001–11 (Figure 6), while consumption from other regions of Brazil increased by 13%. Brazil's domestic soy consumption from more regulated biomes also increased substantially during the study period (+26% for the Amazon, +113% for the Legal Cerrado, and +264% for the Atlantic during 2001–12). In contrast, domestic soy consumption from other regions of Brazil (primarily the "non-Legal" Cerrado) increased by 46%. For the beef sector, these increases in consumption from less regulated regions constituted a shift in the distribution of consumption, since domestic consumption levels remained relatively flat, while for soy it is an artifact of rapidly increasing consumption from all regions. In Argentina and Paraguay, beef consumption also remained fairly constant, while soy consumption grew steadily alongside exports (Figure S1, Table S7). In Uruguay, beef consumption was strongly, inversely correlated with exports (Figure S1, Table S6). In Argentina, Brazil, and Paraguay, domestic beef consumption was consistently higher than exports, while soy exports were generally much larger than domestic soy consumption (Figure S1).

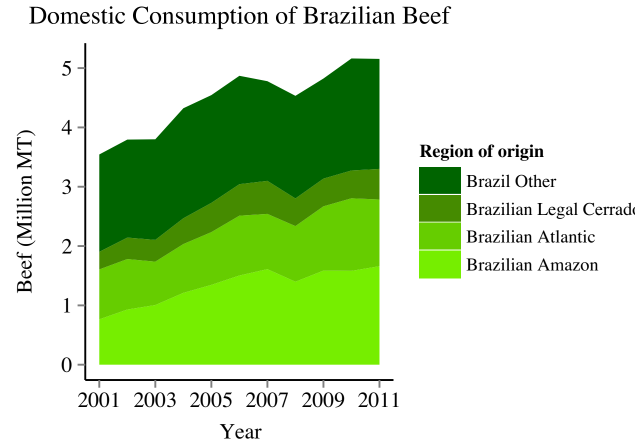

Figure 6. *Domestic consumption of Brazilian beef. Data from FAOSTAT & SEI-PCS (Table 1). Domestic consumption of beef produced in Brazilian biomes with higher forest restrictions (the Amazon, Atlantic, Legal Cerrado) increased during the study period.*

6. DISCUSSION

(a) *Deforestation regulations, agricultural expansion, and commodity trade*

We do not find evidence that soy and cattle producers decrease their investments in regions with higher deforestation regulations and shift to less-restricted regions, except for cattle producers within the Amazon. Instead, we find a positive relationship between regulation stringency and rates of soy expansion. As the positive effect between regulation stringency and soy and pasture expansion decreases with a 1-year time lag and disappears with a two-year time lag on the regulations variable, it is likely not picking up differences between regions, but rather differences over time that may be endogenous to land use change: regulations increase where expansion rates are high.

The absence of an effect of regulations on pasture expansion outside the Amazon seems to contradict a recent analysis in Argentina, Bolivia, and Paraguay, which showed that cattle ranchers in the Chaco and Chiquitano biomes tend to purchase land for expansion in areas with laxer regulations (le Polain de Waroux *et al.*, 2016). However, that analysis relied on different methods (interviews with individual land owners) and focused on large-scale producers, who are particularly mobile and potentially more responsive to deforestation regulations (see below). In contrast, this analysis relies on aggregate data and encompasses all types of actors, including small-scale farmers, who are more constrained in terms of their mobility and may have fewer incentives to move in response to changing regulations (due to lower deforestation monitoring on their properties and lower enforcement of violations) (Godar *et al.*, 2014; Richards & VanWey, 2015).

The trade model results, on the other hand, indicate that deforestation regulations did influence both soy and beef exports, but did so in a heterogeneous manner. All countries decreased their beef imports from exporters with more stringent deforestation regulations (relative to what would have occurred, all else equal), although that effect was less pronounced for European countries. This result, combined with a reduction of pasture expansion in the Brazilian Amazon, could indicate some level of market leakage of beef demand to countries outside of the study region.

Non-European countries also reduced their soy imports from more regulated regions, but this effect was largely offset by increasing imports by European countries. This may indicate that in general, while deforestation regulations reduce the price competitiveness of exporting regions (by increasing costs), in some cases they provide an advantage in terms of quality and reputation. That is, non-genetically modified soy grown in places with more stringent deforestation regulations may be preferred by certain importers, even if it is slightly more expensive, because it meets consumers' expectations for more sustainable products (Garrett *et al.*, 2013). It is also possible that increases in deforestation regulations coincided with other unaccounted-for changes in those regions that improved the price competitiveness of production, such as transportation infrastructure and improved logistics.

In light of growing global demand for soy and cattle products, there are two potential reasons why deforestation regulations may have failed to influence rates of cropland and pasture expansion within South America (though some leakage outside the study region is still possible): (i) deforestation regulations may have not been effective in reducing deforestation for cropland and pasture expansion or (ii) regulations may have stimulated intensification, such that more intensive land uses expanded into less-intensive ones and yields increased. Where regulations did influence area expansion (e.g., in the Amazon), reduced expansion may have been offset by higher yields on the existing area, preventing a market leakage effect.

(i) *Continued opportunities for deforestation*

While rates of deforestation decreased in the more regulated South American biomes during the second half of the study period, deforestation did not stop altogether, and since 2012 rates of deforestation have increased again in the Amazon (http://www.obt.inpe.br/prodes). In this light, the absence of an effect of deforestation regulations could be interpreted as evidence that unregulated forestland (or other forms of native vegetation) that is suitable for agriculture is still sufficiently abundant in most areas. In this case, regulations had a minimal impact overall because opportunities for legal deforestation and vegetation clearing still existed. Indeed, the large coefficient for available forestland in our results, particularly for pastureland expansion, suggests that the presence of forestland remains a major determinant of expansion.

Additionally, it is possible that, despite important differences in regulations over time and between regions, the expectation of enforcement still remains too low for legal limits on deforestation to have a discernible effect on agricultural expansion at the regional level. In this case deforestation is continuing to occur because the disincentives to deforest are not sufficiently high. Theoretically, variations of the expectation of enforcement should be captured in our models, but it is possible that we have not adequately measured monitoring, penalties, and enforcement capacity.

In fact, recent analyses suggest that there are many alternative pathways by which soy and cattle farmers can continue to evade increasing deforestation regulations in South America, even though improved environmental governance appears to be effective in some limited circumstances. For example, the Soy Moratorium has helped reduce direct deforestation for soy in the Brazilian Amazon on monitored properties (Gibbs *et al.*, 2014; Rudorff *et al.*, 2011), but soy farmers with multiple properties are still able to sell soy from deforested land that is not as closely monitored (Rausch & Gibbs, 2016). The Brazilian Amazon cattle agreements have helped to change the sourcing behavior of certain meatpackers toward farms that are compliant with deforestation regulations, but non-compliant farmers can still launder their cattle through compliant farms (Gibbs *et al.*, 2015; Rausch & Gibbs, 2016).

For both industries, but particularly for cattle, domestic markets provide farmers with the opportunity to sell to smaller companies that are either not signatories of the voluntary zero-deforestation agreements or are under less pressure to implement their commitments. For smaller producers these domestic buyers may be the only viable marketing option, as the cost of proving they are compliant with forest regulations or moratoria (in terms of documentation and property mapping) to international buyers can be substantial (Datu Research, 2014). Small producers are also generally less likely to be targeted directly by enforcement agencies (Garcia-Drigo *et al.*, 2016), and sometimes benefit from lower restrictions (e.g., the native forest zoning in Argentina does not apply to farms smaller than 10 hectares). In fact, a recent analysis shows that smallholders increased their share of Amazon deforestation by 69% during 2004–11, and concludes that the effectiveness of current environmental governance efforts to reach these actors is substantially more limited in comparison to large land owners (Godar *et al.*, 2014), although another study concentrating on Mato Grosso showed that large landowners remained the principal agents of deforestation there in absolute terms (Richards & VanWey, 2015).

Our trade model and consumption results support this reasoning, particularly, for the beef sector. While soy imports from more regulated regions by non-European countries were partially offset by increasing imports by European importers, beef imports from more regulated regions were lower among all countries. For the beef sector, changing regulations appear to have led to a rearrangement of trade patterns in a way that accommodated continued deforestation. As importers shifted some of their beef imports away from exporters with more stringent deforestation regulations and toward other regions, domestic markets took up more of the beef supply from the Brazilian Amazon and Legal Cerrado (Figure 6). In fact, domestic beef consumption is so much higher than exports in the study region (Figure S1), that it is highly unlikely that cattle agreements could be effective in reducing deforestation without the full participation of both major and minor domestic buyers. This may prove particularly challenging, as the domestic cattle markets are highly diffuse, with many small-scale slaughterhouses and local transactions operating in tandem with larger and more concentrated multi-national buyers (Datu Research, 2014).

(ii) *Increased opportunities for intensification*

While some continued deforestation for agricultural expansion is a reality, recent analyses have also documented a large increase in the intensification of South American agriculture (Dias, Pimenta, Santos, Costa, & Ladle, 2016; Lapola *et al.*, 2013; Martha, Alves, & Contini, 2012; Oesterheld, 2008), via two primary mechanisms. First, pastureland is being replaced by cropland. A continental-scale study of cropland and pastureland dynamics showed that cropland expansion during 2001–13 for the whole of South America occurred predominantly at the expense of pastures — in Argentina, 40% of new cropland came from pastureland (Graesser *et al.*, 2015). In the Amazon and Legal Cerrado, new soy area expanded primarily into cattle pastures after 2005 (Macedo *et al.*, 2012), and in the Atlantic forest, new sugarcane area has also expanded largely into cattle pastures (Rudorff *et al.*, 2010). Secondly, stocking rates and daily weight gain of cattle have increased on some of the remaining area (Martha *et al.*, 2012). For example, the median number of cattle per hectare of pasture increased by 19.5% in the Amazon and 14% in the Atlantic forest during 2001–13, due in part to several new agricultural programs and policies in Brazil aimed at intensification, at the inception of the effort to increase governance of deforestation (Garrett *et al.*, 2017). Increase in cattle per hectare was more modest in the Cerrado (10%), and while it was high during 2001–10 for the Chaco (25%), the number of cattle per hectare decreased back to 2001 levels after 2010 in the Argentine part of the biome, reflecting the crisis traversed by the beef sector in Argentina following several years of price controls, export quotas, and drought. The very slight negative effect of the interaction term of regulations with the proportion of available land under forest cover in the pasture model might be seen as tentative evidence of the impact of intensification: regulations start to matter only when alternative land areas are no longer available for expansion.

(b) *Other drivers of land use change*

The positive effect of soy yields and cattle density in the area models, particularly for cattle, for which the coefficient remains significant when lagged, could suggest the existence of a rebound effect. Thus, while intensification may explain, in part, why we don't see leakage from the Amazon, it may also have caused further expansion where not accompanied by tight deforestation restrictions. Such rebound effects would further reduce the likelihood of leakage to other regions, by offsetting some of the increase in costs caused by increased regulations. The significance of soy yields and cattle density, however, might also be due to endogeneity (i.e., yields improve faster in rapidly developing agricultural frontiers because the availability of agricultural inputs is increasing (Garrett, Lambin, & Naylor, 2013)).

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The absent or positive effect of transport costs to ports and slaughterhouses for the area models suggests that they are not a major hindrance for agricultural expansion. This supports recent findings in the region that proximity to agricultural clusters can be more important than distance to port in driving expansion, particularly when more distant regions have a greater abundance of cheap land (Garrett *et al.*, 2013; Gasparri, Grau, & Sacchi, 2015). To the extent that these clusters were stable during the study period, this effect is captured by the municipality fixed effect in our models, although the positive coefficient in the soy model might be due to a failure to account for land prices, which are generally lower away from ports (but for which we lack data at this scale). The magnitude and significance of the neighborhood effect in the area models suggest it may also capture some of this agglomeration effect. Similarly, deforestation activities (road building, migration, etc.) often beget more deforestation, as highlighted by several studies that have found distance to prior deforestation to be a major determinant of the probability of new deforestation (Müller, Müller, Schierhorn, & Gerold, 2011; Volante, Mosciaro, Gavier-Pizarro, & Paruelo, 2016).

(c) *Policy implications*

Evidence of geographic leakage would suggest a need for supply chain actors to consider the indirect impacts of their sourcing behaviors on other regions, even if local deforestation regulations are very stringent. Yet, our results suggest that, thus far, the changes in deforestation regulations that have occurred in certain provinces and biomes may not be resulting in the widespread displacement of deforestation-causing land uses across South American borders. Instead, leakage, if it is occurring, is more likely taking place between actors locally or being directed to countries outside of South America, as suggested by our trade model results. To help avoid future leakage it will be imperative to couple increasing restrictions on deforestation with incentives for intensification on the existing land base. Such incentives may help maintain investments in agriculture within regulated regions that can promote economic development.

We do find evidence that changes in deforestation regulations are restructuring domestic sourcing patterns for beef. Namely, domestic markets appear to be sourcing more beef from regions with more stringent regulations as international importers decrease their imports from these regions. The existence of these market and actor substitution effects underscore the need for public and private actors to focus on closing loopholes and broadening the reach of their existing conservation measures to cover all segments of the supply chain, e.g., calf producers and small, local slaughterhouses, and distributors. Progress has already been made on this front since the end of our study period. In 2015, public prosecutors in Brazil took action to force signatories of the Amazonian zero-deforestation cattle agreements (i.e., TAC and G-4), including major domestic beef retailers, to audit their supply chains and verify their compliance with the agreements (Garcia-Drigo *et al.*, 2016).

Meanwhile, the number of commitments to reduce deforestation in food supply chains is increasing rapidly, with more than 350 companies having made such commitments by 2016 (McCarthy, 2016). As these agreements spread to more regions, affecting large proportions of the global supply (and prices) for beef, soy, and other commodities, the likelihood that they could lead to deforestation leakage to unregulated biomes will increase, making it increasingly important to harmonize corporate commitments across regions. This is particularly true for commitments related to soy and palm oil, which are linked to each other through demand markets for vegetable oils, yet grown in very different geographical areas, enabling leakage across a wider area.

(d) *Limitations and future research*

This study examines the statistical relationship between production and import trends and changing public and private deforestation regulations. It leaves many questions unanswered with respect to the impacts of deforestation regulations on the incentives of producers and traders to invest in, or source from a particular region. For example, we find that European importers source more soy from regions with more stringent deforestation regulations. But it remains unclear whether certain regions evolved more stringent deforestation regulations precisely because of their interest in maintaining trade with certain importers. Understanding of these causal mechanisms will require complementary research methods, such as interviews with primary actors involved and longitudinal tracking of land investment decisions over time and space. It will also require better measures of agricultural intensification and enforcement. Furthermore, our study looks only at partial equilibrium outcomes, and the area model is limited to South America. As such it fails to control for the influence that deforestation regulations may have on world prices through changes in supply and how these price impacts are influencing decisions in other parts of the world.

7. CONCLUSION

The design of conservation policies that reduce deforestation both locally and globally is challenged by a number of implementation barriers and spillover effects. In this study, we examined how soy and beef production and trade responded to changing regulations in agricultural frontiers of South America to see whether there is evidence of spillover effects outside the target region that would offset local effectiveness. After reviewing the potential for activity and market leakage, we find scarce evidence that deforestation regulations have impacted agricultural production in a way that would generate significant leakage of either soy or beef production across South American borders. However, we do find a redistribution of beef consumption and trade patterns that create deforestation loopholes and may lead to leakage outside the study region. As beef importers shifted away from exporters with the most stringent deforestation regulations, supply from these regions was taken up by domestic markets. We also find high levels of intensification that may have further reduced leakage.

These results highlight the complexity of production and trade responses to changing environmental regulations and the need for more sophisticated and comprehensive global modeling to understand the global impacts of local changes in regulations. From a policy perspective, our results highlight the need to reduce loopholes in both private and public regulations that allow for a restructuring of marketing channels to accommodate continued deforestation. Closing these loopholes will require greater cooperation between public and private, as well as domestic and international environmental governance efforts to better synchronize regulation stringency and enforcement across all commodities, actors, and regions.

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NOTES

1. The Argentinian forest law (federal law 26.331 and it provincial adaptations) is an exception, in the sense that it provincial zoning plans often specify lower percentages of forest reserve requirements for cattle ranching than for crop farming, because it is considered that silvopastoral use (cattle herding under trees) are a partial substitute for forest reserves.

2. The Legal Amazon is a political boundary that includes "areas of forest", "cerrado", and "campos gerais", and has different conservation requirements for each designation (Lei 12,651). The Legal Cerrado includes municipalities that are predominantly *cerrado* vegetation, yet are located within the political boundary of the Legal Amazon. In contrast, the "Amazon" includes all municipalities classified as *forest* vegetation within the Legal Amazon.

3. Signatories included in this analysis are France, Germany, Indonesia, Italy, Japan, Mexico, Netherlands, Portugal, Spain, Viet Nam, United Kingdom, and United States.

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APPENDIX A. SUPPLEMENTARY DATA

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.worlddev.2017.05.034.