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Abstract

Trade data are typically reported at the level of regions or countries and are therefore aggregates across space. In this paper, we investigate the sensitivity of standard gravity estimation to spatial aggregation. We build a model in which initially symmetric micro regions are combined to form aggregated macro regions. We then apply the model to the large literature on border effects in domestic and international trade. Our theory shows that larger countries are systematically associated with smaller border effects. The reason is that due to spatial frictions, aggregation across space increases the relative cost of trading within borders. The cost of trading across borders therefore appears relatively smaller. This mechanism leads to border effect heterogeneity and is independent of multilateral resistance effects in general equilibrium. Even if no border frictions exist at the micro level, gravity estimation on aggregate data can still produce large border effects. We test our theory on domestic and international trade flows at the level of U.S. states. Our results confirm the model's predictions, with quantitatively large effects.

JEL classification: F10, F15, R12
Keywords: Gravity, Geography, Borders, Trade Costs, Heterogeneity, Home Bias, Spatial Attenuation, Modifiable Areal Unit Problem (MAUP)

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1 Introduction

By how much do borders impede international trade? It has been a major objective of research in international trade to identify the frictions that hinder the international integration of markets, and many policy makers across the globe are keen on reducing them.

Ever since the seminal paper by McCallum (1995), many researchers have used the gravity equation as a workhorse model to estimate so-called border effects. In their simplest form, gravity equations with border dummies are estimated based on aggregate bilateral trade data. As aggregates, these data combine the trade flows of spatial sub-units such as boroughs, municipalities and counties into trade flows at a higher level of spatial aggregation such as regions, states and countries. The question we attempt to address in this paper is how this process of aggregation affects the estimation of border effects. How do border effects depend on the spatial units we find in any given data set? Put differently, how do border effects depend on the way we slice up the map?

To understand the effects of spatial aggregation, we build a theoretical framework based on a large number of 'micro' regions that trade with each other subject to spatial frictions. We then aggregate these regions into larger 'macro' regions. Due to the spatial frictions, the more micro regions we combine, the more we increase the costs of trading within the newly aggregated regions. As a result, aggregation increases the relative costs of trading within as opposed to across borders. Our theory shows how this shift in relative costs leads to heterogeneous border effect estimates: smaller regions are associated with strong border effects, and larger regions are associated with moderate border effects. We call this the spatial attenuation effect.

This heterogeneity has important implications for the estimation of border effects as typically found in the literature. First, since standard border effects are averages of the underlying individual border effects, we get sample composition effects. That is, samples that happen to include many large regions (or countries) tend to have moderate border effects, and vice versa. Second, given that samples inevitably vary across different studies, their border effects are not directly comparable to each other since each sample implies a different choice about the relevant spatial unit. We show how border effect estimates can be adjusted so that valid comparisons can be made.

In the empirical part of the paper, we test the predictions of our theory with a data set of domestic and international trade flows at the level of U.S. states. Our results confirm the model's predictions, in particular the systematic heterogeneity of border effects across states. For instance, we find that for a large state like California, removing the U.S. international border would lead to an increase of bilateral trade on average by only 13 percent, whereas for a small state like Wyoming trade would go up over four times as much (61 percent).

We also carry out a hypothetical scenario of aggregating U.S. states into larger spatial units, namely the nine Census divisions as defined by the U.S. Census Bureau. Consistent with our model, we obtain smaller estimated border effects at the level of Census divisions. Overall, we find that spatial aggregation has a strong, first-order quantitative impact on border effects.

It is important to note that our mechanism of spatial aggregation is separate from multilateral resistance effects in general equilibrium as highlighted by Anderson and van Wincoop (2003). Since small regions are typically more exposed to international trade, removing a border tends to have a stronger effect on their price index and hence their multilateral resistance, compared to large regions. In our model, due to symmetry at the level of micro regions, every location faces the same price index, and aggregation does not affect this equilibrium structure. We therefore obtain border effect heterogeneity without multilateral resistance effects at work. In the data, when we have to keep track of varying multilateral resistances across space, we find that the heterogeneity of border effects stemming from spatial aggregation dominates by a large margin the heterogeneity coming from multilateral resistance effects.

The fundamental problem with gravity estimation of border effects is that researchers attempt to identify a border friction that occurs at the micro level faced by individual economic agents. However, spatial aggregation systematically shifts the estimates that can be recovered through gravity. Our theory sheds light on the precise nature of this mismatch between micro frictions and macro data. We show that in fact, even if no friction exists at the border, standard gravity estimation will still give rise to border effects, and these can be very large.

Our theory and empirical results on spatial aggregation apply to both branches of the border effects literature: the international border effect and the domestic border effect. McCallum (1995) found that Canadian provinces trade up to 22 times more with each other than with U.S. states. This astounding result has led to a large literature on the trade impediments associated with international borders. Anderson and van Wincoop (2003) famously revisit the U.S.-Canadian border effect with new theory-consistent estimates. Although they are able to reduce the border effect considerably, the international border remains a large impediment to trade. Havránek and Iršová (2015) provide an overview of this extensive literature.[1]

[1] Anderson and van Wincoop (2004) report 74 percent as an estimate of representative international trade costs for industrialized countries (expressed as a tariff equivalent). Hillberry (2002) and Chen (2004) document significant but varying border effects at the industry level. Anderson and van Wincoop (2004, section 3.8) provide guidance and intuition for border effects in the case of aggregation across

A parallel and somewhat smaller literature has explored the existence of border effects within a country, known as the domestic border effect or intranational home bias. For example, Wolf (2000) and Millimet and Osang (2007) find that after controlling for economic size, distance and a number of additional determinants, trade within individual U.S. states is significantly larger than trade between U.S. states. Similarly, Nitsch (2000) finds that domestic trade within the average European Union country is about ten times larger than trade with another EU country.

Our approach is inspired by Hillberry and Hummels (2008) who find that counterfactual ZIP code border effects within the United States would be enormous, by far eclipsing the magnitude of traditional border effects typically found in the literature. Their results illustrate an issue known in the geography literature as the Modifiable Areal Unit Problem.[2] Briant, Combes, and Lafourcade (2010) systematically highlight this problem for empirical work in economic geography. Since spatial statistics are ultimately based on spatial units, empirical results depend on both the size and shape of these units. Our paper can be seen as an attempt to take the general notion of the Modifiable Areal Unit Problem and apply it to the specific context of gravity estimation of border effects. Our aim is to obtain precise analytical results for spatial aggregation. In addition, our paper is also related to the recent literature in international trade that explicitly models internal trade costs (Ramondo, Rodríguez-Clare and Saborío-Rodríguez 2016), or models space as a continuum (Allen and Arkolakis 2014).

The paper is organized as follows. In section 2 we briefly outline the typical estimation of border effects in the literature. In section 3 we present our formal model of spatial aggregation for domestic and international border effects. In section 4 we take the theory to the data and apply it to domestic and international trade flows at the level of U.S. states. In section 5 we discuss the implications of our analysis for the interpretation of border effects, in particular the relationship between border frictions at the micro level and estimation based on aggregate data. Section 6 concludes.

2 Border effects in gravity estimation

The seminal contribution of McCallum (1995) has led to a large number of papers that estimate border effects based on a gravity framework. For both the theoretical and empirical analysis of border effects in this paper, we follow the canonical structural gravity

industries with industry-specific elasticities of substitution and possibly also industry-specific border barriers. In this paper, we are concerned with spatial aggregation in the absence of industry variation. But we share the belief that industry aggregation is an important topic that has not received enough attention.

[2] See Fotheringham and Wong (1991).

model by Anderson and van Wincoop (2003). They derive their model from an endowment economy under the Armington assumption of goods differentiated by country of origin. It is well-known that an isomorphic gravity structure can be derived from different types of trade models.[3]

We first briefly review how domestic and international border effects are typically defined in the literature. We then proceed to the novel part, which is to explain how spatial aggregation systematically changes border effects.

2.1 The structural gravity framework

We adopt the widely used structural gravity framework by Anderson and van Wincoop (2003). They derive the following gravity equation for the value of exports x_{ij} from region i to region j:

$$x_{ij} = \frac{y_i y_j}{y^W} \left(\frac{t_{ij}}{P_i P_j} \right)^{1-\sigma}, \tag{1}$$

where y_i and y_j denote nominal income of regions i and j, and y^W denotes world income. The bilateral trade cost factor is given by $t_{ij} \geq 1$ (one plus the tariff equivalent). It is assumed symmetric for any given pair (i.e., $t_{ij} = t_{ji}$). P_i and P_j are the multilateral resistance terms, which can be interpreted as average trade barriers of regions i and j. The parameter $\sigma > 1$ is the elasticity of substitution across goods from different countries. There are N regions in the sample.

In the theory and the data, we will deal with three different tiers of trade flows: *international* trade flows that cross an international border, *national* bilateral trade flows between different regions of the same country, and *internal* trade flows within regions.[4]

2.2 The trade cost function

We follow McCallum (1995) and other authors by hypothesizing that trade costs t_{ij} are a log-linear function of bilateral geographic distance $dist_{ij}$, and an international border barrier represented by the dummy INT_{ij} that takes on the value 1 whenever regions i and j are located in different countries, and 0 otherwise. The INT_{ij} variable is therefore an *international border dummy.* We also include a dummy variable NAT_{ij} for bilateral national trade flows that takes on the value 1 whenever regions i and j are in the same country but distinct ($i \neq j$), and 0 otherwise. In a sample without international flows, we

[3] Those include the Ricardian model by Eaton and Kortum (2002) as well as the heterogeneous firms models by Chaney (2008) and Melitz and Ottaviano (2008). Head and Mayer (2014) discuss these similarities in more detail.

[4] Some authors use the expression *domestic* to describe trade flows within a region. We stick to *internal* here.

therefore refer to the NAT_{ij} dummy as the national border dummy, or *domestic border dummy*, since the case of $NAT_{ij} = 1$ implies that a domestic border has been crossed.[5]

We can express our trade cost function as

$$\ln\left(t_{ij}^{1-\sigma}\right) = \beta INT_{ij} + \gamma NAT_{ij} + \rho \ln\left(dist_{ij}\right), \tag{2}$$

where β and γ are dummy coefficients, and ρ is the distance elasticity of trade. We log-linearize gravity equation (1) and insert the trade cost function (2) to obtain

$$\ln\left(x_{ij}\right) = \ln\left(y_i\right) + \ln\left(y_j\right) - \ln\left(y^W\right) + \ln\left(P_i^{\sigma-1}\right) + \ln\left(P_j^{\sigma-1}\right) + \beta INT_{ij} + \gamma NAT_{ij} + \rho \ln\left(dist_{ij}\right). \tag{3}$$

In typical border effect gravity regressions, β and γ are the coefficients of interest. Both are typically found to be negative, and we will reproduce such standard estimates in the empirical section 4.

Expression (2) nests the most common trade cost functions in the literature. Wolf (2000) and Hillberry and Hummels (2003) only consider trade flows within the United States so that an international border effect cannot be estimated. This corresponds to $\beta = 0$ in trade cost function (2). Conversely, Anderson and van Wincoop (2003) follow McCallum's (1995) specification that does not allow for a domestic border effect ($\gamma = 0$).

3 A theory of spatial aggregation

We now explain formally how border dummy coefficients are affected when regions are spatially aggregated. We first turn to the domestic border effect and then to the international border effect.

3.1 The domestic border effect

Our aim is to formalize the effects of spatial aggregation. Our modeling strategy is to imagine a world of many 'micro' regions as the basic spatial units. We then aggregate these micro regions into larger 'macro' regions that more closely resemble those we observe in the data. The motivation is that we can think of large regions as a cluster of many micro regions combined. For instance, consider California and Vermont. We can imagine California as a cluster of many micro regions, but in comparison Vermont is a cluster of only a few micro regions.

[5] The NAT_{ij} dummy corresponds to the 'ownstate' dummy in Hillberry and Hummels (2003) and the 'home' dummy in Nitsch (2000), with the 0 and 1 coding swapped.

3.1.1 Micro and macro regions

As the basic framework, we model the world as consisting of an arbitrarily large number of small 'micro' regions denoted by the superscript S for 'small.' Each region is endowed with a differentiated good as in the Armington framework of Anderson and van Wincoop (2003). To be able to obtain analytical solutions, we impose symmetry across these basic spatial units. That is, we assume they have the same internal trade costs t_{ii}^S for all i and the same bilateral trade costs t_{ij}^S between each other such that $t_{ij}^S = t^S$ for all $i \neq j$. The bilateral costs are at least as high as the internal costs ($t^S \geq t_{ii}^S \geq 1$). The micro regions have uniform income and multilateral resistance terms y_i^S and P_i^S.[6]

As a consequence, the micro regions have the same internal and bilateral trade flows, x_{ii}^S and x_{ij}^S. The same gravity equation as (1) applies at the micro level, i.e.,

$$x_{ij}^S = \frac{y^S y^S}{y^W} \left(\frac{t_{ij}^S}{P^S P^S} \right)^{1-\sigma}, \tag{4}$$

where we drop the subscripts for all region-specific variables.

Aggregation

As the next step, we aggregate $n \geq 2$ micro regions into a 'macro' region denoted by the superscript L for 'large.' The income of this aggregated region follows as $y^L = ny^S$. Gravity is imposed to apply again at the macro level. For the internal trade of the macro region, we have the relationship

$$x_{ii}^L = \frac{y^L y^L}{y^W} \left(\frac{t_{ii}^L}{P^L P^L} \right)^{1-\sigma}. \tag{5}$$

This internal macro flow is the aggregate of the n internal flows of the original micro regions as well as their $n(n-1)$ bilateral flows:

$$x_{ii}^L = nx_{ii}^S + n(n-1)x_{ij}^S.$$

Combining the three previous equations we obtain

$$\underbrace{\frac{ny^S ny^S}{y^W} \left(\frac{t_{ii}^L}{P^L P^L} \right)^{1-\sigma}}_{x_{ii}^L} = n \underbrace{\frac{y^S y^S}{y^W} \left(\frac{t_{ii}^S}{P^S P^S} \right)^{1-\sigma}}_{x_{ii}^S} + n(n-1) \underbrace{\frac{y^S y^S}{y^W} \left(\frac{t^S}{P^S P^S} \right)^{1-\sigma}}_{x_{ij}^S}. \tag{6}$$

[6] Implicitly, if R is the number micro regions, then we have a space of dimension $R-1$. For a more complicated setting with asymmetric micro regions (characterized by different sizes and different trade costs), we generally have to resort to numerical methods. But qualitatively, the same insights go through as in the symmetric setting.

Multilateral resistance is unaffected by aggregation

In appendix A.1 we show that aggregation does not affect the multilateral resistance price index, i.e., $P^S = P^L$. The intuition is that due to the initial symmetry, aggregation does not change the underlying trade flow equilibrium and trade cost structure. The price index therefore preserves the incidence interpretation of carrying goods to and from the same hypothetical world market as in Anderson and Yotov (2010).

Aggregate internal and bilateral trade costs

Given that the price indices are the same across micro and macro regions, equation (6) simplifies to

$$\left(t_{ii}^L\right)^{1-\sigma} = \frac{1}{n}\left(t_{ii}^S\right)^{1-\sigma} + \frac{n-1}{n}\left(t^S\right)^{1-\sigma}. \tag{7}$$

If the economy faces higher bilateral than internal costs at the micro level ($t^S > t_{ii}^S$), then internal trade costs at the macro level grow in the number of aggregated micro regions ($\partial t_{ii}^L/\partial n > 0$).[7] The only exception is the limiting case of no spatial frictions in the sense of $t^S = t_{ii}^S$. In that case, internal trade costs at the macro level are the same as at the micro level ($t_{ii}^L = t_{ii}^S$). Thus, the frictionless world is the only case where aggregation is irrelevant since border effects are then by construction zero.[8]

In contrast to internal trade costs, *bilateral* trade costs are not affected by aggregation and remain the same for micro and macro regions. Suppose we observe two macro regions of different size, one comprising n_1 micro regions and the other n_2. Gravity commands the bilateral trade relationship

$$x_{n_1,n_2}^L = \frac{y_{n_1}^L y_{n_2}^L}{y^W}\left(\frac{t_{n_1,n_2}^L}{P^L P^L}\right)^{1-\sigma}, \tag{8}$$

where x_{n_1,n_2}^L denotes the trade flow from the first to the second region with bilateral costs t_{n_1,n_2}^L, and $y_{n_1}^L$ and $y_{n_2}^L$ are their respective incomes. This flow is the aggregate of $n_1 n_2$ bilateral micro flows:

$$x_{n_1,n_2}^L = n_1 n_2 x_{ij}^S.$$

We can therefore write

$$\underbrace{\frac{n_1 y^S n_2 y^S}{y^W}\left(\frac{t_{n_1,n_2}^L}{P^L P^L}\right)^{1-\sigma}}_{x_{n_1,n_2}^L} = n_1 n_2 \underbrace{\frac{y^S y^S}{y^W}\left(\frac{t^S}{P^S P^S}\right)^{1-\sigma}}_{x_{ij}^S}. \tag{9}$$

[7] See Ramondo, Rodríguez-Clare and Saborío-Rodríguez (2016, equation 11) for a similar derivation based on the Eaton and Kortum (2002) model for the special case of $t_{ii}^S = 1$.

[8] The frictionless world would correspond to $t_{ij}^S = t^S = 1$ for all i, j. But we could normalize trade costs to any other positive uniform level since this would lead to the same trade flows in general equilibrium.

Given $P^S = P^L$, it follows

$$t^L_{n_1,n_2} = t^S \tag{10}$$

such that bilateral trade costs between any two regions are the same regardless of the degree of aggregation. Thus, while the bilateral friction t^S is specified at the lowest level of spatial aggregation (i.e., at the level of micro regions), no additional friction appears by crossing the border from one macro region and another.

3.1.2 Estimating the traditional border effect

Having characterized the full set of aggregate internal and bilateral trade costs for macro regions in equations (7) and (10), we now formally derive the estimated border effect coefficient. That is, if the above model is true but we use standard gravity estimation in combination with the traditional trade cost function, what result do we get?

To keep the exposition as clear as possible, we use a simplified version of the traditional trade cost function (2) that only consists of the dummy variable for bilateral national trade flows NAT_{ij}:

$$\ln\left(t_{ij}^{1-\sigma}\right) = \gamma NAT_{ij}, \tag{11}$$

where we revert to the standard notation with i denoting an exporting region and j denoting an importing region. We deliberately ignore other trade cost components.[9] The simplified trade cost function (11) implies that internal trade costs within regions are zero with $NAT_{ii} = 0$ and hence $t_{ii} = 1$. Most important for our purposes, this condition holds for *all* regions i. The trade cost function (11) therefore imposes a one-size-fits-all restriction on internal trade costs. It goes beyond a normalization whereby internal trade costs are set to a particular value for *one* region.

We use the log-linearized form of gravity equation (1)

$$\begin{aligned}\ln\left(\frac{x_{ij}}{y_i y_j}\right) &= c + (1-\sigma)\ln(t_{ij}) \\ &= c + \gamma NAT_{ij},\end{aligned}$$

where we take the income terms onto the left-hand side. Since the multilateral resistance terms do not vary across regions, they are absorbed by the constant $c = -\ln\left(y^W\right) + \ln\left(P_i^{\sigma-1}\right) + \ln\left(P_j^{\sigma-1}\right)$. This simple regression model with a constant and single explana-

[9] In appendix A.5 we show that our results go through for a more conventional specification that includes bilateral distance as an additional trade cost component.

tory variable leads to the OLS estimate

$$\widehat{\gamma} = \frac{\operatorname{Cov}\left(\ln\left(\frac{x_{ij}}{y_i y_j}\right), NAT_{ij}\right)}{\operatorname{Var}\left(NAT_{ij}\right)}. \tag{12}$$

As shown in appendix A.2, we can derive the coefficient estimate as

$$\widehat{\gamma} = \gamma + \underbrace{\ln\left(\prod_{i=1}^{N}\left(t_{ii}^{\sigma-1}\right)^{\frac{1}{N}}\right)}_{\text{bias}}. \tag{13}$$

We therefore obtain a biased estimate. The bias is the logarithm of the geometric average of internal trade cost factors scaled by the elasticity of substitution. To be more specific, given that γ is typically negative and given that internal trade costs are typically positive in the data (i.e., $t_{ii} > 1$), we have an upward bias: the larger internal trade costs are in the sample, the closer the γ estimate will be pushed towards zero.

Once we acknowledge positive internal trade frictions, we need to adjust our interpretation of border coefficients estimated with the traditional dummy variable. We highlight three important implications that follow from the result in (13) and that we will explore in the empirical section:

1. **Interpretation relative to a zero-internal-frictions benchmark:** As the one exception, the bias would disappear only if internal trade costs were on average zero.[10] For the interpretation of trade cost function (11) we therefore have to adopt the implicit normalization of zero average internal trade costs.[11] The correct interpretation based on the traditional trade cost function would be: "All else being equal, trade flows across national borders are estimated to be only the fraction $\exp(\gamma)$ of internal trade flows *under the assumption* that internal trade costs are zero on average."

2. **No direct comparability across samples:** Border effect coefficients are generally not directly comparable across different samples because of the heterogeneity of internal trade costs. For example, suppose we obtain a coefficient of $\gamma_1 = -1$ in one sample and a coefficient of $\gamma_2 = -0.5$ in another, and the two coefficients are significantly different. This difference does not necessarily imply that the domestic border is more detrimental to trade flows in the first sample than in the second.

[10] Formally, only if $\prod_{i=1}^{N} t_{ii}^{1/N} = 1$.

[11] If other controls such as distance are added to the trade cost function, the bias generally does not disappear (see appendix A.5).

3. **Systematic sample composition effects:** Related to the second implication, border effect coefficients are sensitive to sample composition in a systematic way. More specifically, adding regions to the sample with relatively large internal trade costs pushes the border coefficient towards zero. Vice versa, adding countries with relatively small internal trade costs renders the border coefficient more negative. In the empirical section we show that these sample composition effects are substantial from a quantitative point of view.

3.1.3 A heterogeneous trade cost function

Once we aggregate across space as implied by equation (7), internal trade costs become heterogeneous across regions with $t_{ii} \neq t_{jj}$ for all $i \neq j$ in general. The one-size-fits-all restriction implicit in the simple NAT_{ij} dummy then renders trade cost function (11) misspecified. As shown by equation (13) and in appendix A.4, this tension generates an omitted variable bias in standard gravity estimation of border effects. Trade cost function (11) with a simple dummy is therefore unsuitable for spatial aggregation as it does not accommodate the heterogeneous nature of internal trade costs.

This problem can be addressed by augmenting the function with an interaction term to obtain a heterogeneous trade cost function:

$$\ln\left(t_{ij}^{1-\sigma}\right) = \gamma NAT_{ij} + \psi\left(1 - NAT_{ij}\right)\ln\left(t_{ii}^{1-\sigma}t_{jj}^{1-\sigma}\right)^{\frac{1}{2}} \tag{14}$$

with $\psi = 1$. The trade cost function (14) reduces to equation (11) for $i \neq j$. But unlike (11), it allows for heterogeneous internal trade costs in the case of $i = j$. It nests the simple trade cost function (11) for $\psi = 0$. This parameter restriction on ψ comes down to a straightforward testable hypothesis of border effect heterogeneity that we consider in the empirical section.

If the heterogeneous trade cost function (14) is used in a gravity equation such as (1), then the border effect (defined here as the trade-impeding effect of the border on bilateral trade, ignoring the general equilibrium multilateral resistance effects) is given by

$$\frac{\mathrm{d}\ln\left(x_{ij}\right)}{\mathrm{d}\,NAT_{ij}} = \gamma + \psi\ln\left(t_{ii}^{\sigma-1}t_{jj}^{\sigma-1}\right)^{\frac{1}{2}}. \tag{15}$$

As we show in appendix A.3, this border effect is invariant to the specific normalization chosen for trade costs.[12] That is, suppose we renormalize trade costs by setting $t_{kl} = 1$ for trade costs between regions k and l. The border effect (15) remains unchanged.

[12] In the Anderson and van Wincoop (2003) model, trade flows are homogeneous of degree zero in trade costs t_{ij} for all i, j (including internal trade costs). Therefore, trade costs can be arbitrarily normalized.

The key insight is that all else equal, larger internal trade costs lead to a smaller border effect. That is, the second term $\psi \ln \left(t_{ii}^{\sigma-1} t_{jj}^{\sigma-1}\right)^{1/2}$ increases in t_{ii} and t_{jj} and thus counteracts the negative effect stemming from $\gamma < 0$.[13] Ceteris paribus border effects are therefore mechanically driven by internal trade costs and inherently heterogeneous, in contrast to the traditional trade cost function (11). We call this the spatial attenuation effect. In the empirical part of the paper, we illustrate the heterogeneity by reporting the full range of border effects.

The intuition is that due to aggregation, larger regions have larger internal trade frictions. This increases 'internal resistance', leading to relatively less internal trade and relatively more bilateral trade. As a result, the domestic border effect appears smaller. In section 4.7 we show that this mechanism is entirely separate from general equilibrium multilateral resistance effects as highlighted by Anderson and van Wincoop (2003).

3.1.4 Estimating heterogeneous domestic border effects

The right-hand side variables of the heterogeneous trade cost function (14) do not only include the national border dummy NAT_{ij} but also the internal trade costs of the two regions in each pair, t_{ii} and t_{jj}. Internal trade costs are typically not directly observable, but this does not pose a problem since we can use appropriate fixed effects to control for them.[14]

More specifically, we can break down trade cost function (14) into region-specific terms as

$$\ln\left(t_{ij}^{1-\sigma}\right) = \underbrace{\gamma NAT_{ij} - \left\{\psi NAT_{ij} \ln\left(t_{ii}^{1-\sigma}\right)^{\frac{1}{2}} + \psi NAT_{ij} \ln\left(t_{jj}^{1-\sigma}\right)^{\frac{1}{2}}\right\}}_{\frac{\gamma_k}{2} NAT_{ij}\alpha_k \;=\; \frac{\gamma_k}{2} NAT_{ij}^k} + \underbrace{\psi \ln\left(t_{ii}^{1-\sigma}\right)^{\frac{1}{2}}}_{\alpha_i} + \underbrace{\psi \ln\left(t_{jj}^{1-\sigma}\right)^{\frac{1}{2}}}_{\alpha_j}. \tag{16}$$

In a standard log-linearized regression based on gravity equation (1), the last two terms would be absorbed by *exporter* and *importer* fixed effects α_i and α_j that also capture income and multilateral resistance terms. At first glance it would seem that the terms in curly brackets could be estimated by interacting the national border dummy NAT_{ij} with α_i and α_j. However, this would lead to perfect collinearity with the last two terms, α_i and α_j.[15] Instead, the first three terms can be estimated through an interaction of the

[13] Note that $\sigma - 1 > 0$. For sufficiently large t_{ii} and t_{jj} the border effect can even become positive in total. See the empirical section for examples.

[14] An alternative would be to use internal distance as a proxy for internal trade costs. But we prefer the fixed effects approach due to its simplicity and because it is not clear how to measure internal distances (see Head and Mayer 2009).

[15] The collinearity would arise because adding up the two interaction effects with the exporter and importer fixed effects would yield twice the constant term. That is, $NAT_{ij}\alpha_i + NAT_{ij}\alpha_j + \alpha_i + \alpha_j = 2$ for each observation.

NAT_{ij} dummy with *region* fixed effects α_k that equal unity whenever k is an exporter ($k = i$) or an importer ($k = j$) with $k = 1, ..., N$. This is equivalent to region-specific NAT_{ij}^k dummies with coefficients γ_k.[16] A simple test of border effect heterogeneity comes down to the hypothesis that the γ_k coefficients differ from each other. We note that the common γ coefficient in (16) cannot be identified since it would be collinear with the γ_k's.

3.2 The international border effect

We proceed in two steps. First, we model trade flows at the level of small geographical units, which we call 'micro' regions, based on a standard gravity setting. Second, as in the model for the domestic border effect, we aggregate these micro regions into larger 'macro' regions. We assume that a gravity setting also holds at the macro level, and we map the trade flows and trade costs of the micro regions onto the larger spatial units of macro regions. Our purpose is to explore the implications of this aggregation for gravity estimates of the international border effect.

The global economy consists of two symmetric countries, Home and Foreign. We first describe the trade flows within one country and then across countries.

3.2.1 Micro and macro regions on a circle

As in section 3.1 the world is based on symmetric micro regions denoted by superscript S. Each region is endowed with a differentiated good and has uniform income and multilateral resistance terms y_i^S and P_i^S. Gravity equation (4) holds at the micro level.

As will become apparent shortly, to deal with the international border effect it is no longer sufficient to just have a binary difference between domestic trade costs t_{ii}^S and bilateral trade costs t^S at the micro level as in section 3.1. Instead, we need to introduce a spatial topography such that frictions increase between more distant micro regions. At the same time, we would like to preserve symmetry to be able to obtain analytical solutions.

Therefore, as the simplest case of such a topography, we model the domestic economy as a circle. Micro regions are symmetric segments of the circle, each surrounded by two neighbors. Bilateral trade costs t_h^S are equal to δ^h, where $\delta \geq 1$ represents a spatial distance friction with $h \geq 1$ denoting the number of 'steps' between micro regions. Adjacent regions are one step apart with $h = 1$, and so on. Thus, bilateral trade costs between

[16] Since the region-specific dummies capture every national trade flow twice (once on the exporter side and once on the importer side), the γ_k coefficients must be divided by 2 to obtain estimates that are comparable to the standard border coefficient.

micro regions increase in distance as long as $\delta > 1$. Internal trade costs within a micro region are lower than or equal to bilateral costs, i.e., $t_{ii}^S \leq t_h^S$ for any h.[17]

Aggregate bilateral trade costs

We aggregate $n \geq 2$ micro regions into a macro region denoted by superscript L with income $y^L = ny^S$, and we impose gravity at the macro level. The aggregated micro regions are adjacent on the circle such that the macro region has no 'holes.' Here we focus on bilateral trade between macro regions both within and across borders. Those are the relevant flows for the international border effect. But for completeness, in appendix B.1 we also derive the internal trade flows of an aggregated macro region and the associated internal trade costs.

In contrast to the domestic border setting in section 3.1, bilateral trade costs at the macro level are sensitive to aggregation. Suppose we observe two macro regions of different size, one comprising n_1 micro regions and the other n_2. Gravity commands the bilateral trade relationship (8). The bilateral macro flow from the first to the second region is the aggregate of $n_1 n_2$ bilateral micro flows:

$$x_{n_1,n_2,h}^L = \sum_{v=1}^{n_1} \sum_{w=1}^{n_2} x_{h+v+w-2}^S,$$

where the subscript h in $x_{n_1,n_2,h}^L$ indicates the number of steps that the two macro regions are apart. For instance, $x_{n_1,n_2,1}^L$ for $h = 1$ means that the two macro regions are adjacent (i.e., one step apart), and $x_{n_1,n_2,2}^L$ for $h = 2$ means the two macro regions are two steps apart etc. This means we have to add the micro flows $x_{h+v+w-2}^S$ with step length $h + v + w - 2$, summed over v and w, to yield the bilateral macro flow.

As in the model for the domestic border effect, it turns out that aggregation does not change the multilateral resistance price indices, i.e., $P^S = P^L$. In appendix B.2, we show this result formally. The intuition is that aggregation does not affect the underlying trade cost structure and equilibrium of trade flows.

Using a relationship as in equation (9) and given that multilateral resistances are the same across micro and macro regions, we can derive the expression for bilateral trade costs at the macro level as

$$\left(t_{n_1,n_2,h}^L\right)^{1-\sigma} = \frac{1}{n_1 n_2} \sum_{v=1}^{n_1} \sum_{w=1}^{n_2} \left(t_{h+v+w-2}^S\right)^{1-\sigma}. \tag{17}$$

[17] The theory for the domestic border effect in section 3.1 can be seen as a one-country special case. The simple binary difference between bilateral and domestic trade costs at the micro level can be achieved by setting $\delta = 1$ such that all bilateral trade costs become unity ($t_h^S = t^S = 1$) and by normalizing domestic trade costs to a smaller value $t_{ii}^S < 1$.

A key result is that these bilateral macro trade costs rise in the number of aggregated micro regions, i.e., $\partial t^L_{n_1,n_2,h}/\partial n_1 > 0$ and $\partial t^L_{n_1,n_2,h}/\partial n_2 > 0$. That is, all else equal, larger regions tend to have larger trade costs with other regions in that country. The only exception would be the special case of no spatial gradient when bilateral trade costs between micro regions are the same regardless of distance, i.e., when $\delta = 1$ such that $t^S_h = t^S$ for all h. In that case, bilateral trade costs would be the same at the micro and macro levels as in equation (10).

To see more clearly how bilateral trade costs depend on region size n_1 and n_2, we substitute the spatial friction $t^S_{h+v+w-2} = \delta^{h+v+w-2}$.[18] We can then decompose bilateral trade costs at the macro level into three elements as

$$t^L_{n_1,n_2,h} = \underbrace{\delta^h}_{\text{bilateral distance}} \underbrace{\left(\frac{1}{n_1}\sum_{v=1}^{n_1}\left(\delta^{v-1}\right)^{1-\sigma}\right)^{\frac{1}{1-\sigma}}}_{\alpha_{n_1}} \underbrace{\left(\frac{1}{n_2}\sum_{w=1}^{n_2}\left(\delta^{w-1}\right)^{1-\sigma}\right)^{\frac{1}{1-\sigma}}}_{\alpha_{n_2}}. \tag{18}$$

The first element δ^h denotes the bilateral distance between the two macro regions. The remaining elements α_{n_1} and α_{n_2} are region-specific, and more importantly they rise in the sizes n_1 and n_2 of the macro regions.[19] These terms can be interpreted as the costs of reaching the domestic borders of macro regions. For instance, suppose the first macro region consists of only one micro region ($n_1 = 1$). It follows $\alpha_{n_1} = 1$, meaning that no distance has to be incurred to reach the domestic border. But for a macro region consisting of several micro regions ($n_1 > 1$), we get $\alpha_{n_1} > 1$ as long as $\delta > 1$ because of the rising average internal distances of individual micro regions to the domestic border.

In summary, bilateral trade costs at the macro level increase in the size of the underlying regions because more spatial frictions within the macro regions have to be overcome. Only in the limiting case where the macro regions are micro regions ($n_1 = n_2 = 1$) does the bilateral distance δ^h fully represent the bilateral trade costs.

International trade costs

Both countries have the same internal structure of micro regions, and we therefore have two circles. We assume that bilateral international trade costs between micro regions t^S_{int} consist of a common international distance δ_{int}. The common distance can be motivated by a central port for international trade in each country. Then for each micro region the distance to the port is the same.[20] In addition, we assume a cost for crossing the

[18] We assume that the two macro regions are in the same semi-circle so that the shortest direction of trade is always either clockwise or counterclockwise. If the two regions straddled different semi-circles, the same argument would go through qualitatively but the resulting expression for $t^L_{n_1,n_2,h}$ would be more complicated.

[19] Formally, $\partial\alpha_{n_1}/\partial n_1 > 0$ and $\partial\alpha_{n_2}/\partial n_2 > 0$.

[20] As a generalization, we could allow for bilateral distance gradients between micro regions at the

international border so that we can write

$$t^S_{int} = \delta_{int} \exp\left(\frac{\beta}{1-\sigma}\right), \tag{19}$$

where $\beta \leq 0$ captures the international border barrier. This structure translates into the same level of international trade costs at the aggregate level between two macro regions of size n_1 and n_2, i.e., $t^S_{int} = t^L_{n_1,n_2,int}$. The intuition is that identical trade costs are aggregated such that the appropriate theoretical average is the same. This stands in contrast to aggregate bilateral trade costs within countries as in equation (18) that do vary by region size.

We should briefly comment on a possible generalization. As an alternative modeling strategy, instead of just two circles representing two countries we could assume multiple circles representing multiple countries. To preserve symmetry we could have a 'pearl necklace' of countries where each pearl represents a circular economy. That is, we could arrange countries in a circular fashion similar to the way micro regions are arranged within countries. International distances would then vary by country pair in contrast to our simple common distance δ_{int}. However, this expanded model would not yield any qualitatively new insights. We therefore work with the simpler two-country setting.

The trade cost function

Comparing expressions (18) and (19) for bilateral trade costs at the national and international levels, we can see that region-specific terms only appear for national trade costs. In logarithmic form and scaled by the elasticity of substitution, we can therefore write the overall trade cost function that arises from our model as

$$\ln\left(t^{1-\sigma}_{ij}\right) = \ln\left(\delta^{1-\sigma}_{ij}\right) + \beta INT_{ij} + (1 - INT_{ij})\left\{\ln(\alpha^{1-\sigma}_i) + \ln(\alpha^{1-\sigma}_j)\right\}, \tag{20}$$

where i denotes an exporter and j is an importer. If ij is a domestic pair, then δ_{ij} equals δ^h, and δ_{int} otherwise.

3.2.2 Heterogeneous international border effects

The key feature of trade cost function (20) is the interaction term between the international border dummy and the region-specific terms $\ln(\alpha^{1-\sigma}_i)$ and $\ln(\alpha^{1-\sigma}_j)$. This interaction is absent in standard trade cost functions such as (2). It implies that in a gravity equation such as (1), the impact of the border on bilateral trade becomes heterogeneous.

international level. The relevant case would be a friction parameter that differs from the corresponding parameter δ for domestic flows.

More specifically, the direct effect of INT_{ij} on bilateral trade follows as

$$\frac{\mathrm{d}\ln\left(x_{ij}\right)}{\mathrm{d}\,INT_{ij}} = \beta + \left\{\ln(\alpha_i^{\sigma-1}) + \ln(\alpha_j^{\sigma-1})\right\}, \tag{21}$$

where for the moment we ignore the general equilibrium multilateral resistance effects operating through the price indices.

The literature typically finds a negative and significant border dummy coefficient β. In the limiting case when regions i and j are micro regions with no aggregated spatial frictions, we have $\alpha_i = \alpha_j = 1$ and the second term disappears. This would also happen if the domestic economies were frictionless in the sense of $\delta = 1$. But in the more realistic case when i and j are aggregates and spatial frictions are present, the second term becomes positive and counteracts the negative effect stemming from β.[21] Thus, larger regions have weaker (i.e., less negative) border effects. We call this the spatial attenuation effect.

We note that this form of heterogeneity operates independently and in addition to heterogeneity induced by multilateral resistance effects. We discuss general equilibrium effects in more detail in section 4.7.

Ceteris paribus the effect of an international border dummy is therefore driven by the 'internal resistance' of the regions in question, inducing systematic heterogeneity. In the empirical part of the paper, we illustrate the heterogeneity by reporting the full range of border effects. We find that the heterogeneity is quantitatively substantial.

Estimating heterogeneous international border effects

Estimation of trade cost function (20) is straightforward. Due to symmetry, the α_i and α_j terms are region-specific, not exporter- and importer-specific. We can therefore capture them with region fixed effects α_k that equal unity whenever $i = k$ or $j = k$ regardless of the direction of trade.[22] As the empirical specification we obtain

$$\ln\left(t_{ij}^{1-\sigma}\right) = \underbrace{INT_{ij}\left(\beta + \left\{\ln(\alpha_i^{\sigma-1}) + \ln(\alpha_j^{\sigma-1})\right\}\right)}_{\beta_k INT_{ij}\alpha_k} + \ln\left(\delta_{ij}^{1-\sigma}\right) - \underbrace{\ln(\alpha_i^{\sigma-1}) + \ln(\alpha_j^{\sigma-1})}_{\alpha_k}, \tag{22}$$

where β_k indicates region-specific international border coefficients. A simple test of border effect heterogeneity comes down to the hypothesis that the β_k coefficients differ from each other. We note that the β parameter cannot be identified due to collinearity with the fixed effects.

[21] In appendix B.3 we show that only if the α_i and α_j terms are unity can we obtain an unbiased estimate of β in a gravity regression with a standard international border effect.

[22] We do not use internal trade flows in the estimation where $i = j$.

4 Empirical results

4.1 Data

Our two main data sources are the Commodity Flow Survey and the Origin of Movement series provided by the U.S. Census Bureau. To obtain results that are comparable to the literature, we use the same data sets as Wolf (2000) and Anderson and van Wincoop (2003) for domestic trade flows within the United States, based on the Commodity Flow Survey. The novelty of our approach is to combine these domestic trade flows with international trade flows from individual U.S. states to the 50 largest U.S. export destinations, based on the Origin of Movement series. Thus, our data set comprises, for instance, trade flows within Minnesota, exports from Minnesota to Texas as well as exports from Minnesota to France. We also employ trade data between foreign countries in our sample. In appendix C we describe our sources in detail.

We form a balanced sample over the years 1993, 1997, 2002 and 2007. We drop Alaska, Hawaii and Washington, D.C. due to data quality concerns raised in the Commodity Flow Survey so that we are left with the 48 contiguous states. This yields 1,726 trade observations per cross-section within the U.S., including 48 intra-state observations and 1,678 state-to-state observations per cross-section.[23] The observations that involve the 50 foreign countries are made up of 2,338 export flows from U.S. states to foreign countries as well as 2,233 exports flows amongst foreign countries per cross-section.[24]

4.2 Overview

We first show in section 4.3 that our data exhibit a substantial domestic border effect, as established by Wolf (2000). We also show that the data exhibit a significant international border effect, as established by McCallum (1995). In a second step in section 4.4, we move away from border effects that are common across states, as typically imposed in the literature. Instead, we estimate individual border effects that are allowed to vary across states, thus uncovering a large degree of underlying heterogeneity. In section 4.5, we systematically alter our estimation sample to understand how sample composition

[23] The maximum possible number of U.S. observations would be $48{*}48 = 2,304$ per cross-section. The missing observations are due to the fact that a number of Commodity Flow Survey estimates did not meet publication standards because of high sampling variability or poor response quality. To generate a balanced sample, we drop pairs if at least one year is missing.

[24] Our entire sample thus comprises $6,297$ observations per cross-section, or $25,188$ in total. The maximum possible number of international exports from U.S. states would be $48{*}50 = 2,400$ per year. We have 62 missing observations mainly because exports to Malaysia were generally not reported in 1993. Only 18 of these observations not included in our sample are most likely zeros (as opposed to missing). The maximum possible number of exports between foreign countries would be $49{*}50 = 2,450$ per cross-section. To generate a balanced sample, we drop pairs if least one year is missing.

effects change border effect estimates. In section 4.6, we aggregate the 48 U.S. states into larger spatial units. Finally, we show in section 4.7 that quantitatively, border effect heterogeneity is substantially more important than heterogeneity induced by multilateral resistance effects.

4.3 Estimating common border effects

In columns 1 and 2 of Table 1, we replicate well-known results on the domestic border effect, estimated with a national border dummy. We only use trade flows within the U.S. International trade flows are not included. As our estimating equation we use the log-linear version of gravity equation (1). As typical in the literature (for instance Hillberry and Hummels 2003), we use exporter and importer fixed effects to control for multilateral resistance and all other country-specific variables such as income. As in Wolf (2000), in column 1 we only use data for 1993. In column 2 we add the data for 1997, 2002 and 2007. Our estimate of $\widehat{\gamma} = -1.48$ in column 2 is the same as Wolf's baseline coefficient.[25]

The interpretation of our coefficient is that given distance and economic size, trade between U.S. states is 77 percent lower compared to trade within U.S. states ($\exp(-1.48) = 0.23$). Assuming a value for the elasticity of substitution of $\sigma = 5$, we can translate this into a tariff equivalent of the national border of 45 percent.[26] As we show in section 3.1.2, this interpretation would only be valid under the assumption that domestic trade costs within U.S. states were zero on average. For positive domestic trade costs (which is the realistic scenario), according to expression (13) the underlying tariff equivalent is even higher. Put differently, the $\widehat{\gamma}$ estimate only captures the national border barrier net of internal trade costs.

In columns 3 and 4 of Table 1 we replicate standard results for the international border effect. As is customary, we do not include trade flows within U.S. states, and the national border dummy is dropped as a regressor. To be able to identify the international border dummy coefficient we follow Anderson and van Wincoop (2003) and others by using state and country fixed effects instead of exporter and importer fixed effects. As the output regressors are collinear with these fixed effects, they are dropped from the estimation. In column 3 we estimate an international border coefficient of $\widehat{\beta} = -1.25$ for the year 1993, implying that after we control for distance and economic size, exports from U.S.

[25] Wolf's coefficient has a positive sign because his domestic border dummy is coded in the opposite way. Hillberry and Hummels (2003) reduce the magnitude of the national border coefficient by about a third when excluding wholesale shipments from the Commodity Flow Survey data. The reason is that wholesale shipments are predominantly local so that their removal disproportionately reduces the extent of intra-state trade. However, Nitsch (2000) reports higher coefficients in the range of -1.8 to -2.9 by comparing trade within European Union countries to trade between EU countries.

[26] For $\ln\left(t_{ij}^{1-\sigma}\right) = -1.48$, it follows $t_{ij} = 1.45$. This is a partial equilibrium calculation in the sense that we ignore price index effects for simplicity. For general equilibrium effects, see section 4.7.

states to foreign countries are about 71 percent lower than trade between U.S. states ($\exp(-1.25) = 0.29$). The corresponding tariff equivalent is 37 percent. When we pool the data over the years 1993, 1997, 2002 and 2007 in column 4, we obtain a similar coefficient of -1.21. These estimates are somewhat smaller in absolute magnitude but nevertheless roughly fall in the same ballpark range as the estimates of around -1.6 reported by Anderson and van Wincoop (2003, Table 2) in their sample involving trade flows of U.S. states and Canadian provinces.

Overall, we have replicated national and international border coefficient estimates as typically found in the literature. In fact, our national point estimate exceeds the international point estimate in absolute magnitude, a finding which is consistent with Fally, Paillacar and Terra (2010) in their study of Brazilian trade data as well as Coughlin and Novy (2013).

4.4 Estimating individual border effects

We run the same regression specifications with panel data as in columns 2 and 4 of Table 1, but now allowing the domestic and international border coefficients to vary across states. That is, we estimate individual, state-specific border effects. This approach is consistent with the theory in sections 3.1.4 and 3.2.2, respectively. Expressions (15) and (21) predict that for larger states, the border coefficients should be closer to zero due to spatial attenuation.

4.4.1 Individual domestic border effects

We first estimate national border dummy coefficients for the 48 U.S. states in our sample. We obtain the corresponding γ_k coefficients by using trade cost function (16) in otherwise standard gravity estimation. As equation (15) shows, theory predicts that for a given U.S. state, all else being equal we should expect a smaller trade effect of the national border dummy in absolute magnitude (i.e., less negative) if the state has larger (logarithmic) internal trade costs.

How can we obtain a measure of internal trade costs that is consistent with the theory? Equation (7) describes how t_{ii}^L depends on the number of aggregated micro regions n and the micro frictions t_{ii}^S and t^S. But since these micro frictions are unobservable, instead we resort to gravity equation (5) to obtain a theory-consistent measure of internal trade costs. Given that multilateral resistance terms are the same across macro regions, it follows that $\left(t_{ii}^L\right)^{\sigma-1}$ is proportional to the ratio $y^L y^L / x_{ii}^L$. We therefore proxy $\ln\left(t_{ii}\right)$ with $\ln\left(y^L y^L / x_{ii}^L\right)$.

As an illustration, in Figure 1 we plot the national border coefficients γ_k against our proxy of internal trade costs. Two main observations can be made. First, there is a large degree of heterogeneity across the estimates. While the mean of the coefficients is -1.32 and thus close to the point estimates reported in columns 1 and 2 of Table 1, the individual border coefficients span a range of more than six log points. They are tightly estimated, with standard errors of 0.13 on average (not plotted in the figure).

Second, as predicted by our theory, the individual coefficients are positively related to internal trade costs. Given a correlation of 0.92 between internal trade costs and state GDP, this means the coefficients are also positively related to the economic size of states. That is, the smaller the state, the more detrimental the effect of crossing a national border appears to be. For example, the five states with the smallest state GDPs (Wyoming, Vermont, North Dakota, Montana, South Dakota) have border coefficients in the vicinity of -4. The back-of-the-envelope interpretation would be that for those states, crossing a border with another state reduces trade by 98 percent.[27] At the other extreme, a few economically large states such as New Jersey and California are associated with positive border coefficients.[28] These results are clearly implausible. They underline the nature of the domestic border effect as a statistical artefact.

4.4.2 Individual international border effects

We also estimate individual coefficients for the international border dummies. We obtain these β_k estimates by using trade cost function (22) in otherwise standard gravity estimation, substituting bilateral distance for δ_{ij}.[29] As equation (21) shows, all else equal theory predicts a smaller trade effect of the international border dummy in absolute value (i.e., less negative) for regions of larger economic size.

Figure 2 illustrates the individual coefficients plotted against our proxy of internal trade costs. As a more direct measure of economic size, Figure 3 plots the coefficients against logarithmic state GDP. Overall, the figures demonstrate a clear positive relationship. As with the national border coefficients, the individual estimates display a large degree of heterogeneity, falling into a range of -2.7 to 0.9. The mean estimate is -0.64.[30]

[27] As $\exp(-4) = 0.02$, all else equal in partial equilibrium the border reduces trade by 98 percent relative to within-state trade. For general equilibrium effects see section 4.7.

[28] The coefficients for California, Illinois, Minnesota, Nevada, New Jersey and Virginia are positive and significant at the five percent level. Despite these empirical outliers, in the theory the upper bound for state-specific national border coefficients is actually zero. In equation (7) t_{ii}^L approaches t^S for $n \to \infty$, which is the same as t_{n_1,n_2}^L through equation (10). Therefore, in equation (16) it follows $\gamma_k = 0$ since $\psi = 1$.

[29] Behrens, Ertur and Koch (2012) also estimate heterogeneous international border dummy coefficients based on a framework that allows for spatial correlation of trade flows.

[30] The corresponding common international border coefficient that captures international trade flows of U.S. states only is -0.60 and thus very close to the mean estimate underlying Figures 2 and 3. See section 4.7 for details.

The coefficients are tightly estimated with an average standard error of 0.13. The larger the state, the closer the individual international border coefficient tends to be to zero. For example, Wyoming as the smallest state is associated with an international border coefficient of -1.53, whereas the value for California as the largest state is -0.34. Under the assumption of $\sigma = 5$, the corresponding tariff equivalents would be 47 percent and 9 percent.

We stress that in our model, the international border barrier at the micro level, β, is common across all regions (see equation 19). The substantial difference between the above tariff equivalents can therefore be attributed to spatial aggregation as a primary driving force behind border effect estimates.

4.5 Sample composition effects

As shown above, border dummy coefficients can vary substantially across regions. They tend to be large in absolute magnitude for small states, and vice versa. It follows that when we estimate common border effects, our estimates should be sensitive to the distribution of state economic size in the sample. We perform a simple check of this sample composition effect.

In order to systematically change the composition of economic size in our sample, we run rolling regressions where we keep dropping states and their associated trade flows from the sample. More specifically, we start out with the domestic border effect regression as in column 1 of Table 1 for the year 1993 where we obtained a coefficient on the national border dummy of -1.47. We then drop the largest state from the sample in terms of GDP (California) and re-estimate the border coefficient. We then drop the second largest state from the sample (New York) and re-estimate, and so on, such that the smallest states are remaining. To obtain comparable estimates we keep the distance coefficient at its initial value but we allow the exporter and importer fixed effects to adjust freely. The black dots in Figure 4 illustrate the national border coefficients. As predicted by our theory, we yield the following pattern: the more big states we drop from the sample, the larger the coefficients tend to become in absolute value. Although their movement is not strictly monotonic, the downward trend is reasonably clear.

The grey diamonds in Figure 4 illustrate the coefficients obtained when we drop the smallest state first (Wyoming), then the second smallest state (Vermont), and so on. As expected, we yield the opposite pattern: the national border coefficients move upwards towards zero. Overall in Figure 4, we obtain coefficients ranging from around -2 to -0.5.

In Figure 5, we repeat the rolling regressions for the international border effect, starting out with the same regression as in column 3 of Table 1 where the obtained a coefficient of -1.25. We find the same pattern as in Figure 4. That is, the smaller the average economic size of states in the sample, the further the estimated border effect tends to get pushed away from zero, and vice versa. The coefficients roughly fall in the range from -3.5 to 0.[31]

Therefore, in summary we find strong sample composition effects in Figures 4 and 5. We interpret these as further evidence corroborating the impact of state size on border effects. The figures demonstrate that this impact is quantitatively strong.

4.6 Aggregating to U.S. Census divisions

The individual border effects illustrated in Figures 1-3 demonstrate that larger states tend to exhibit smaller border effects in absolute magnitude. We now trace this relationship between economic size and the magnitude of border effects in a different way. We aggregate U.S. states and thus enlarge the size of the underlying spatial units.

To be specific, we aggregate the 48 contiguous U.S. states into the nine Census divisions as defined by the U.S. Census Bureau. We choose Census divisions because their borders conveniently coincide with state borders (this would not be the case with Federal Reserve Districts, for instance). But any alternative clustering of adjacent states would in principle be equally suitable for this aggregation exercise. Figure 6 provides a map of the Census divisions.

Trade flows within a division are taken to equal the sum of the internal trade flows of its states plus the flows between these states. Trade flows between divisions are given by the sum of trade flows between their respective states. Similarly, trade flows from a division to a foreign country are given as the sum of exports from the states in the division to the foreign country.

Table 2 reports regression results that correspond to Table 1. We use the simple average of distances associated with the underlying individual trade flows. The division-based national border dummy coefficients are -1.17 and -1.25 and thus smaller in magnitude than the corresponding state-based estimates of -1.47 and -1.48 in Table 1, albeit not statistically different. The division-based international border dummy coefficients are -0.36 and -0.39 and thus considerably smaller in magnitude and significantly different from the corresponding state-based estimates of -1.25 and -1.21 in Table 1. The distance coefficients are very similar between Tables 1 and 2.

Overall, a common pattern arises: the border coefficients are further away from zero

[31] Balistreri and Hillberry (2007) show that the reduction of the border effect by Anderson and van Wincoop (2003) relies on the addition of trade flows between U.S. states to the sample. Since U.S. states are on average considerably larger than Canadian provinces, we expect the addition of such flows to push the common border dummy estimate towards zero according to our result in Figure 5.

when states are the underlying spatial units, and the border coefficients are closer to zero when we use divisions as the larger underlying spatial units. This pattern mirrors the cross-sectional heterogeneity apparent in the individual border coefficients depicted in Figures 1-3.

4.7 Multilateral resistance effects in general equilibrium

In their seminal paper, Anderson and van Wincoop (2003) highlight the role of general equilibrium. They show that small and large countries react differently to changes in international border barriers. Intuitively, removing the border leads to a reallocation of trade away from domestic towards international partners. But since a small country is more exposed to international trade and thus more exposed to the border barrier, this reallocation is relatively stronger for the small country.[32] This differential response between small and large countries is entirely driven by price index or 'multilateral resistance' effects.

In our theoretical framework, however, multilateral resistance is symmetric across countries (see appendix B.2). The differential trade response is instead driven by heterogeneity in the border effect itself due to spatial aggregation, as shown in equation (21).

While multilateral resistance is the same across countries in our theory, we cannot assume this to be the case with actual trade flows. In Table 3 we explore the general equilibrium counterfactuals implied by removed international border barriers, accounting for both heterogeneous border effects as well as heterogeneous multilateral resistance effects. We use the same balanced sample as for column 4 of Table 1 based on 24,996 observations for the years 1993, 1997, 2002 and 2007 (6,249 observations per year).

In panel 1 we report counterfactuals based on removing a common international border barrier as in the standard Anderson and van Wincoop (2003) model. As in column 4 of Table 1, we estimate this border barrier based on the logarithmic version of the standard gravity equation (1) with logarithmic bilateral distance and country fixed effects as additional controls. The border dummy captures the U.S. international border only.[33] We then remove the U.S. international border and recompute the associated general

[32] To be precise, the ratio of bilateral international trade to bilateral domestic trade increases more strongly for a country consisting of smaller regions such as Canada. Anderson and van Wincoop (2003, section IV.C) discuss "the relatively small size of the Canadian economy" in the context of their data set of trade flows between Canadian provinces and U.S. states.

[33] The distance and border dummy coefficients are -1.21 and -0.60, respectively, both highly significant at the 1 percent level. As the border dummy only captures the U.S. border, its coefficient is directly comparable to the individual border coefficients for U.S. states plotted in Figures 2 and 3. Their average is -0.64 and thus about the same.

equilibrium.[34]

Panel 1 presents the logarithmic differences between the counterfactual and initial equilibria. Removing the U.S. border leads to an increase in bilateral trade flows by 23 percent on average (see the top row of panel 1). Trade would have increased by 31 percent just through the direct (partial equilibrium) effect of reducing bilateral trade costs.[35] This direct effect is the same for all U.S. states by construction because we impose a common border barrier. The offsetting general equilibrium effect through falling multilateral resistance is 10 percent on average but varies somewhat across states, while the increase in incomes pushes up trade by 2 percent. In sum, there is a modest degree of variation across states due to the heterogeneous general equilibrium effects. For instance, the bilateral trade of California goes up by 24 percent on average, whereas the trade of Wyoming goes up by 21 percent.

In panel 2 we report counterfactuals based on our framework with heterogeneous border barriers. We estimate state-specific border coefficients as described in section 4.4.2. Those are plotted in Figures 2 and 3. We also account for multilateral resistance effects when computing the counterfactual equilibrium. Removing the heterogeneous border barriers leads to average effects that are almost identical (see the top row of panel 2). However, the underlying effects for individual states exhibit much more variation. The key insight is that this variation is primarily driven by the heterogeneous direct effects (see column 2b), not multilateral resistance effects. The overall differences across states can be quite substantial. For instance, here the bilateral trade of California goes up by 13 percent on average, whereas the trade of Wyoming goes up over four times as much (61 percent). Consistent with our theory, small states are more affected by the removal of the border.[36]

Overall, we conclude that heterogeneous border barriers translate into heterogeneous trade effects. Quantitatively, this form of heterogeneity is considerably more important than heterogeneity associated with multilateral resistance effects.

[34] For the initial equilibrium we take the income data for the 48 U.S. states and 50 large foreign countries in our sample for the year 1993, thus capturing the vast majority of global economic activity. Using our estimated distance and border dummy coefficients, we use numerical methods to compute the multilateral resistance variables and construct the associated bilateral trade flows based on gravity equation (1). For the counterfactual we set the border dummy coefficient to zero and recompute the full equilibrium, assuming that the endowment quantities are fixed.

[35] Assuming $\sigma = 5$ this corresponds to a cut in trade costs by 7.75 percent since $0.31/(1-\sigma) = -0.0775$.

[36] For some states the overall trade effect shows up as slightly negative (e.g., -7 percent for Connecticut). This happens because some individual border coefficients were estimated to have a positive sign (see Figures 2 and 3). Most of these positive coefficients are not significant, but we report the associated results in Table 3 nevertheless.

5 Discussion

The aim of much of the empirical literature on border effects is to identify γ (for the national border effect) and β (for the international border effect). However, as we have shown in the context of equations (16) and (22), these parameters cannot be identified empirically in gravity regressions based on aggregate data. This is similar in spirit to the result by Gorodnichenko and Tesar (2009) based on price data who show that border effects cannot be identified by comparing price dispersion across countries.

For the national border effect, there is no domestic border friction to begin with because t^S is a bilateral friction that appears between any two micro regions, regardless of whether they happen to be in the same state or not. In that sense, the domestic border effect is a pure statistical artefact.

For the international border effect, there is a friction of crossing an international border as long as we have $\beta < 0$. But to the extent that it exists, this friction cannot be identified from traditional gravity estimation.[37] Equation (21) shows how β could be recovered once $\alpha_i^{\sigma-1}$ and $\alpha_j^{\sigma-1}$ have been constructed. But from equation (18) it is clear that $\alpha_i^{\sigma-1}$ and $\alpha_j^{\sigma-1}$ will depend on the choice of spatial unit for a micro region and thus parameters such as the distance friction δ. They will also depend on the choice for the underlying topography (be it a circle or an alternative spatial structure).

Overall, the insight is that a trade cost function with a border dummy can mechanically lead to large estimated border effects depending on the choice of spatial unit – even if individual economic agents at the micro level do not face any border friction. Due to spatial aggregation, the border effects estimated with aggregate data systematically vary by country characteristics, in particular economic size. In that light, traditional border effects could be seen as statistical artefacts in the sense that their variation is not driven by underlying border frictions at the micro level faced by individual economic agents.

6 Conclusion

We build a model of spatial aggregation. Initially symmetric micro regions are aggregated to larger macro regions. Our theory shows how spatial aggregation affects the internal and bilateral trade costs of aggregated regions, and in turn their estimated border effects. The main result of the theory is that aggregation leads to border effect heterogeneity in that larger regions or countries are associated with border effects closer to zero, and vice

[37] If $\beta = 0$, the international border friction does not exist. But as equation (21) demonstrates, estimation based on aggregate would data would still yield heterogeneous coefficients. Those would be *positive*.

versa. The intuition is that due to spatial frictions, aggregation across space increases the relative trade costs of trading within as opposed to across borders.

We collect a data set of U.S. exports that combines three types of trade flows: trade within an individual state (Minnesota-Minnesota), trade between U.S. states (Minnesota-Texas) as well as trade flows from an individual U.S. state to a foreign country (Minnesota-France). This data set allows us to estimate the effect on trade of crossing the domestic state border and the effect of crossing the U.S. international border. Moreover, it allows us to estimate these effects individually by state.

We find that the larger the state, the smaller its international border effect and the smaller its domestic border effect. In addition, both border effects decline in magnitude when states are aggregated into larger U.S. Census divisions. We also find substantial sample composition effects when small and large states are systematically dropped from the sample.

Overall, we conclude that border effects are inherently heterogeneous. This underlying heterogeneity drives the magnitude of standard, common border dummy coefficients estimated in the literature. To the extent that there exist frictions of crossing domestic or international borders at the micro level of firms and households, standard gravity estimation based on aggregate trade flows is unable to recover them. We surmise that structural estimation or natural experiments involving micro data may be the way forward to achieve that objective.

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Appendix A: The domestic border effect

This appendix contains a number of derivations referred to in the main text.

A.1 Aggregation and multilateral resistance

We exploit our symmetric setting to characterize the multilateral resistance price indices. As in Anderson and van Wincoop (2003), the general equilibrium price index for each micro region is given by

$$\left(P_i^S\right)^{1-\sigma} = \sum_{j=1}^{R} \frac{y_j^S}{y^W} \left(\frac{t_{ji}^S}{P_j^S}\right)^{1-\sigma},$$

where R is the number of micro regions. Due to symmetry we have $t_{ji}^S = t_{ij}^S = t^S$ for all $j \neq i$ as well as $y_j^S / y^W = 1/R$ and $P_j^S = P^S$, and therefore

$$\left(P^S\right)^{1-\sigma} = \frac{1}{R} \left(\frac{t_{ii}^S}{P^S}\right)^{1-\sigma} + \frac{R-1}{R} \left(\frac{t^S}{P^S}\right)^{1-\sigma}, \tag{23}$$

where the first term reflects the internal part, and the second term captures the relationships with all other micro regions. We can solve for P^S as

$$\left(P^S\right)^{1-\sigma} = \left(\frac{1}{R} \left(t_{ii}^S\right)^{1-\sigma} + \frac{R-1}{R} \left(t^S\right)^{1-\sigma}\right)^{\frac{1}{2}} \tag{24}$$

so that the price index is pinned down by the number of micro regions and their trade costs.

Now suppose n micro regions are aggregated into a macro region. Analogous to (23), we can then write the micro price index from the perspective of a remaining micro region as

$$\left(P^S\right)^{1-\sigma} = \frac{1}{R} \left(\frac{t_{ii}^S}{P^S}\right)^{1-\sigma} + \frac{R-1-n}{R} \left(\frac{t^S}{P^S}\right)^{1-\sigma} + \frac{n}{R} \left(\frac{t^S}{P^L}\right)^{1-\sigma}, \tag{25}$$

where the first term reflects the internal part. The second term captures the remaining $R-1-n$ micro regions. The third term captures the relationship with the macro region, weighted by its share n/R of the global economy. The macro price index P^L appears here.

From gravity equation (5) at the macro level, we can solve for the macro price index as

$$\left(P^L\right)^{1-\sigma} = \left(\frac{y_i^L y_i^L}{x_{ii}^L y^W} \left(t_{ii}^L\right)^{1-\sigma}\right)^{\frac{1}{2}}.$$

We use (6) to replace x_{ii}^L as well as $y_i^L = n y_i^S$ to obtain

$$\left(P^L\right)^{1-\sigma} = \left(P^S\right)^{1-\sigma} \left(\frac{\left(t_{ii}^L\right)^{1-\sigma}}{\frac{1}{n}\left(t_{ii}^S\right)^{1-\sigma} + \frac{n-1}{n}\left(t^S\right)^{1-\sigma}}\right)^{\frac{1}{2}}.$$

For brevity, we set

$$\lambda^{1-\sigma} \equiv \left(\frac{\left(t_{ii}^L\right)^{1-\sigma}}{\frac{1}{n}\left(t_{ii}^S\right)^{1-\sigma} + \frac{n-1}{n}\left(t^S\right)^{1-\sigma}}\right)^{\frac{1}{2}}$$

so that we have

$$\left(P^{L}\right)^{1-\sigma}=\left(\lambda P^{S}\right)^{1-\sigma}. \tag{26}$$

We insert this result back into expression (25) and solve for the micro price index as

$$\left(P^{S}\right)^{1-\sigma}=\left(\frac{1}{R}\left(t_{ii}^{S}\right)^{1-\sigma}+\frac{R-1-n}{R}\left(t^{S}\right)^{1-\sigma}+\frac{n}{R}\left(\frac{t^{S}}{\lambda}\right)^{1-\sigma}\right)^{\frac{1}{2}}.$$

Setting this result equal to expression (24), we obtain

$$\frac{1}{R}\left(t_{ii}^{S}\right)^{1-\sigma}+\frac{R-1}{R}\left(t^{S}\right)^{1-\sigma}=\frac{1}{R}\left(t_{ii}^{S}\right)^{1-\sigma}+\frac{R-1-n}{R}\left(t^{S}\right)^{1-\sigma}+\frac{n}{R}\left(\frac{t^{S}}{\lambda}\right)^{1-\sigma},$$

which implies $\lambda^{1-\sigma}=1$. Inserting this into (26), we arrive at the result that the price index is unaffected by the aggregation of symmetric regions, i.e., $P^{L}=P^{S}$. Note that $\lambda^{1-\sigma}=1$ also implies the expression in equation (7) for domestic trade costs in the macro region.

A.2 Estimating the border effect

As expressed in equation (12), the coefficient estimate for γ is given by

$$\widehat{\gamma}=\frac{\operatorname{Cov}\left(\ln\left(\frac{x_{ij}}{y_i y_j}\right),NAT_{ij}\right)}{\operatorname{Var}\left(NAT_{ij}\right)}.$$

Our aim is to derive an analytical solution for this expression. Since $x_{ij}/\left(y_i y_j\right)$ and $t_{ij}^{1-\sigma}$ are proportional, it can be rewritten as

$$\widehat{\gamma}=\frac{\operatorname{Cov}\left(\ln\left(t_{ij}^{1-\sigma}\right),NAT_{ij}\right)}{\operatorname{Var}\left(NAT_{ij}\right)}. \tag{27}$$

We assume a sample with K internal trade observations with $NAT_{ij}=0$ and M other observations with $NAT_{ij}=1$ such that we have $K+M$ total observations. To simplify notation let $A_{ij}=NAT_{ij}$. Then the denominator is

$$\begin{aligned}\operatorname{Var}\left(NAT_{ij}\right) &= \frac{1}{K+M}\sum_{ij}\left(A_{ij}-\overline{A}\right)\left(A_{ij}-\overline{A}\right)\\ &= \frac{1}{K+M}\left[\sum_{ij,NAT_{ij}=0}\left(-\overline{A}\right)^{2}+\sum_{ij,NAT_{ij}=1}\left(1-\overline{A}\right)^{2}\right],\end{aligned}$$

where the first term in the brackets reflects the K internal observations. Using $\overline{A}=M/\left(K+M\right)$ for the average of the A_{ij}'s we then obtain the solution

$$\operatorname{Var}\left(NAT_{ij}\right)=\frac{KM}{\left(K+M\right)^{2}}.$$

Setting $B_{ij} = \ln\left(t_{ij}^{1-\sigma}\right)$, we can write the numerator of (27) as

$$\begin{aligned}
& \operatorname{Cov}\left(\ln\left(t_{ij}^{1-\sigma}\right), NAT_{ij}\right) \\
= \; & \frac{1}{K+M} \sum_{ij} \left(B_{ij} - \overline{B}\right)\left(A_{ij} - \overline{A}\right) \\
= \; & \frac{1}{K+M} \left[\sum_{i=1, NAT_{ij}=0}^{K} \left(\ln\left(t_{ii}^{1-\sigma}\right) - \overline{B}\right)\left(-\overline{A}\right) + \sum_{ij, NAT_{ij}=1} \left(\gamma - \overline{B}\right)\left(1 - \overline{A}\right) \right],
\end{aligned}$$

where the first term in the brackets reflects the K internal observations. Using

$$\overline{B} = \gamma \overline{A} + \frac{1}{K+M} \sum_{k=1}^{K} \ln\left(t_{kk}^{1-\sigma}\right)$$

we can rewrite the expression as

$$\begin{aligned}
& \operatorname{Cov}\left(\ln\left(t_{ij}^{1-\sigma}\right), NAT_{ij}\right) \\
= \; & \gamma \operatorname{Var}(NAT_{ij}) + \frac{1}{K+M} \left[\begin{array}{c} \sum_{i=1, NAT_{ij}=0}^{K} \left(\ln\left(t_{ii}^{1-\sigma}\right) - \frac{1}{K+M} \sum_{k=1}^{K} \ln\left(t_{kk}^{1-\sigma}\right)\right)\left(-\overline{A}\right) \\ + \sum_{ij, NAT_{ij}=1} \left(-\frac{1}{K+M} \sum_{k=1}^{K} \ln\left(t_{kk}^{1-\sigma}\right)\right)\left(1 - \overline{A}\right) \end{array} \right] \\
= \; & \gamma \operatorname{Var}(NAT_{ij}) + \frac{1}{K+M} \left[-\left(\frac{M}{K+M}\right)^2 \sum_{k=1}^{K} \ln\left(t_{kk}^{1-\sigma}\right) - \frac{KM}{(K+M)^2} \sum_{k=1}^{K} \ln\left(t_{kk}^{1-\sigma}\right) \right] \\
= \; & \gamma \operatorname{Var}(NAT_{ij}) + \frac{KM}{(K+M)^2} \ln\left(\prod_{k=1}^{K} \left(t_{kk}^{\sigma-1}\right)^{\frac{1}{K}} \right),
\end{aligned}$$

where the last term in parentheses is the geometric average of internal trade costs in the sample. Inserting this result into (27) we obtain

$$\widehat{\gamma} = \gamma + \ln\left(\prod_{k=1}^{K} \left(t_{kk}^{\sigma-1}\right)^{\frac{1}{K}} \right).$$

Let us consider a sample that is 'balanced' in the sense that no internal or bilateral observations are missing. We have N^2 total observations with $K = N$ internal and $M = N(N-1)$ bilateral flows. We then get the result in equation (13).

A.3 Invariance of the border effect to normalization

A key feature of the generalized trade cost function (14) introduced in section 3.1.3 is that its implied border effect (15) is invariant to the specific normalization chosen for trade costs. For instance, suppose we choose the new normalization $t_{kl} = 1$ for trade costs between regions k and l. This normalization implies that trade costs $t_{ij}^{1-\sigma}$ for all i, j get multiplied by a constant $q \equiv 1/t_{kl}^{1-\sigma} > 0$ such that

$$\begin{aligned}
\ln\left(t_{ij}^{1-\sigma} q\right) &= \gamma NAT_{ij} + \psi\left(1 - NAT_{ij}\right) \ln\left(t_{ii}^{1-\sigma} t_{jj}^{1-\sigma}\right)^{\frac{1}{2}} + \ln(q) \\
&= \gamma NAT_{ij} + \psi\left(1 - NAT_{ij}\right) \ln\left(\left(t_{ii}^{1-\sigma} q\right)\left(t_{jj}^{1-\sigma} q\right)\right)^{\frac{1}{2}} + \left(1 - \psi\left(1 - NAT_{ij}\right)\right) \ln(q).
\end{aligned}$$

The border effect follows as

$$\begin{aligned}\frac{\mathrm{d}\ln(x_{ij})}{\mathrm{d}\,NAT_{ij}} &= \gamma - \psi\ln\left(\left(t_{ii}^{1-\sigma}q\right)\left(t_{jj}^{1-\sigma}q\right)\right)^{\frac{1}{2}} + \psi\ln(q)\\ &= \gamma - \psi\ln\left(t_{ii}^{1-\sigma}t_{jj}^{1-\sigma}\right)^{\frac{1}{2}},\end{aligned}$$

where the latter equation gives the same result as in (15). Note that the traditional trade cost function (11) is also invariant to renormalization since

$$\ln\left(t_{ij}^{1-\sigma}q\right) = \gamma NAT_{ij} + \ln(q)$$

such that

$$\frac{\mathrm{d}\ln(x_{ij})}{\mathrm{d}\,NAT_{ij}} = \gamma$$

irrespective of q.

A.4 The bias of omitting internal trade costs

We show that ignoring the interaction term between the border dummy and internal trade costs leads to omitted variable bias unless internal trade costs are zero on average. The proof is as follows.

The heterogeneous trade cost function (14) can be expanded as

$$\ln\left(t_{ij}^{1-\sigma}\right) = \gamma NAT_{ij} + \psi\ln\left(t_{ii}^{1-\sigma}t_{jj}^{1-\sigma}\right)^{\frac{1}{2}} - \psi NAT_{ij}\ln\left(t_{ii}^{1-\sigma}t_{jj}^{1-\sigma}\right)^{\frac{1}{2}}.$$

The last term, $\psi NAT_{ij}\ln\left(t_{ii}^{1-\sigma}t_{jj}^{1-\sigma}\right)^{1/2}$, introduces an interaction between the domestic border dummy NAT_{ij} and internal trade costs that vary across regions.

Imagine a researcher imposes the traditional trade cost function (11), thus omitting the interaction term. The γ domestic border coefficient in the traditional function is then unbiased only in the special case of a zero covariance between the border dummy and the interaction term. Formally, we can state this condition as

$$\mathrm{Cov}\left(NAT_{ij}, NAT_{ij}\ln\left(t_{ii}^{1-\sigma}t_{jj}^{1-\sigma}\right)^{\frac{1}{2}}\right) = 0. \tag{28}$$

To simplify notation let

$$\begin{aligned}A_{ij} &= NAT_{ij},\\ B_{ij} &= NAT_{ij}\ln\left(t_{ii}^{1-\sigma}t_{jj}^{1-\sigma}\right)^{\frac{1}{2}}.\end{aligned}$$

so that condition (28) becomes

$$\begin{aligned}&\mathrm{Cov}\left(A_{ij}, B_{ij}\right) = 0\\ \Leftrightarrow &\sum_{ij}\left(A_{ij} - \overline{A}\right)\left(B_{ij} - \overline{B}\right) = 0,\end{aligned}$$

where $\overline{A}$ and $\overline{B}$ denote the arithmetic averages of A_{ij} and B_{ij}.

Assume a sample with K internal trade observations with $NAT_{ij} = 0$ as well as M

other observations with $NAT_{ij} = 1$ such that we have $K + M$ total observations. We can rewrite the previous equation as

$$\begin{aligned} K\left(-\overline{A}\right)\left(-\overline{B}\right) + \sum_{ij, NAT_{ij}=1} \left(1-\overline{A}\right)\left(B_{ij} - \overline{B}\right) &= 0 \\ \Leftrightarrow K\overline{AB} + \left(1-\overline{A}\right) \sum_{ij, NAT_{ij}=1} \left(B_{ij} - \overline{B}\right) &= 0, \end{aligned}$$

where the first term reflects the K internal observations. We can rearrange the last equation as

$$\begin{aligned} K\overline{AB} - \left(1-\overline{A}\right) M\overline{B} + \left(1-\overline{A}\right) \sum_{ij, NAT_{ij}=1} B_{ij} &= 0 \\ \Leftrightarrow (K+M)\,\overline{AB} - M\overline{B} + \left(1-\overline{A}\right) \sum_{ij, NAT_{ij}=1} B_{ij} &= 0. \end{aligned}$$

Note that $\overline{A} = M/(K+M)$. The last equation thus simplifies to

$$\begin{aligned} \left(1-\overline{A}\right) \sum_{ij, NAT_{ij}=1} B_{ij} &= 0 \\ \Leftrightarrow \sum_{ij, NAT_{ij}=1} \ln\left(t_{ii}^{1-\sigma} t_{jj}^{1-\sigma}\right)^{\frac{1}{2}} &= 0 \\ \Leftrightarrow \sum_{ij, NAT_{ij}=1} \left[\ln\left(t_{ii}\right) + \ln\left(t_{jj}\right)\right] &= 0. \end{aligned}$$

There are two partner regions (one exporter i and one exporter j) for each of the M non-internal observations. Let m_i denote the relative frequency with which region i appears as a partner in those observations (either as an exporter or as an importer). Then we can rewrite the last expression as

$$\begin{aligned} \sum_{i=1}^{N} m_i \ln\left(t_{ii}\right) &= 0 \\ \Leftrightarrow \prod_{i=1}^{N} t_{ii}^{m_i} &= 1, \end{aligned}$$

where N is the number of regions in the sample. That is, the geometric average of internal trade cost factors, weighted by the frequency of appearance in bilateral observations, is equal to 1.

In a 'balanced' sample with no missing internal or bilateral observations, we have N^2 total observations with $K = N$ internal and $M = N(N-1)$ bilateral flows. The frequency of observations per region is therefore uniform with $m_i = 1/N \; \forall i$. As a special case, we then have

$$\prod_{i=1}^{N} t_{ii}^{\frac{1}{N}} = 1.$$

That is, the unweighted geometric average of internal trade cost factors is equal to 1.

A.5 A trade cost function with distance

In section 3.1 we use a model without spatial distance frictions. As a result, the trade cost function (11) only contains a dummy variable for national trade flows.

In this appendix, we generalize the trade cost function to the more conventional and realistic case that includes distance. In particular, we abandon the assumption that all bilateral trade costs at the micro level are the same. Instead, in addition to a domestic border dummy NAT_{ij}, we introduce a distance friction δ^h as in the model for the international border effect. To preserve symmetry, we model the economy as a circle as in section 3.2. But since we focus on the domestic border effect, we only need to consider one country and can ignore all international flows. We therefore have the following trade cost function at the micro level:

$$\ln\left(t_h^S\right)^{1-\sigma} = \gamma NAT_h + \ln\left(\delta^h\right)^{1-\sigma},$$

where as in section 3.2 h denotes the number of steps between micro regions, with adjacent regions one step ($h = 1$) apart and so on. We have $NAT_h = 1$ for all bilateral flows ($h \geq 1$) and $NAT_h = 0$ for internal flows ($h = 0$).

Given the above micro structure of trade costs, bilateral trade costs between two aggregated regions at the macro level follow from equations (17) and (18) as

$$\left(t_{n_1,n_2,h}^L\right)^{1-\sigma} = \exp\left(\gamma NAT_h\right)\left(\delta^h\right)^{1-\sigma}\left(\alpha_{n_1}\right)^{1-\sigma}\left(\alpha_{n_2}\right)^{1-\sigma}.$$

For internal trade costs of a macro region m of aggregated size n we have from equation (32)

$$\begin{aligned}\left(t_{mm}^L\right)^{1-\sigma} &= \frac{1}{n}\left(t_{ii}^S\right)^{1-\sigma} + 2\sum_{h=1}^{n-1}\frac{n-h}{n^2}\left(t_h^S\right)^{1-\sigma} \\ &= \frac{1}{n}\left(t_{ii}^S\right)^{1-\sigma} + \exp\left(\gamma NAT_h\right)\underbrace{2\sum_{h=1}^{n-1}\frac{n-h}{n^2}\left(\delta^h\right)^{1-\sigma}}_{\left(\delta_{mm}\right)^{1-\sigma}},\end{aligned} \tag{29}$$

where we define the last term as the internal distance friction δ_{mm}, scaled by $(1-\sigma)$, since it represents the appropriately weighted underlying frictions δ^h within region m. It is multiplied by the term $\exp\left(\gamma NAT_h\right)$ with $h \geq 1$.

Assuming the distance relationship $\left(\delta^h\right)^{1-\sigma} = dist_h^\rho$, we obtain bilateral trade costs

$$\ln\left(t_{n_1,n_2,h}^L\right)^{1-\sigma} = \gamma NAT_h + \rho\ln\left(dist_h\right) + \ln\left(\alpha_{n_1}\right)^{1-\sigma} + \ln\left(\alpha_{n_2}\right)^{1-\sigma}.$$

For internal trade costs, $\ln\left(t_{mm}^L\right)^{1-\sigma}$ cannot be written as a log-linear function of NAT_h and $dist_{mm}$ because expression (29) is not multiplicative.

Overall, to combine bilateral and domestic trade costs we set up a heterogeneous trade cost function similar to (14)

$$\ln\left(t_{ij}^{1-\sigma}\right) = \gamma NAT_{ij} + \rho\ln\left(dist_{ij}\right) + \ln\left(\alpha_i\right)^{1-\sigma} + \ln\left(\alpha_j\right)^{1-\sigma} + \left(1 - NAT_{ij}\right)\ln\left(\kappa_i\kappa_j\right)^{\frac{1-\sigma}{2}}. \tag{30}$$

Trade cost function (30) captures bilateral trade costs when $NAT_{ij} = 1$ for $i \neq j$ and internal trade costs when $NAT_{ij} = 0$ for $i = j$ with

$$\ln(\kappa_i)^{1-\sigma} = -\rho \ln(dist_{ii}) - \ln(\alpha_i)^{(1-\sigma)2} + \ln(t_{ii})^{1-\sigma}$$

and where we now use i and j to denote the exporter and importer. Crucially, this trade cost function features an interaction effect as in equation (14). It can be estimated as outlined in section 3.1.4 and equation (16). That is, exporter and importer fixed effects are used in combination with region-specific domestic border dummies. The only difference is the addition of the standard bilateral distance regressor.

Appendix B: The international border effect

This appendix contains a number of derivations referred to in the main text.

B.1 Aggregate internal trade costs

We impose gravity at the macro level so that relationship (5) holds for the internal trade of the macro region x_{mm}^L, where m denotes the set of n aggregated micro regions. This internal macro flow consists of the n internal flows of the original micro regions and their $n(n-1)$ bilateral flows:

$$\begin{aligned} x_{mm}^L &= \sum_{i\epsilon m} x_{ii}^S + \sum_{i\epsilon m} \sum_{j\epsilon m, j\neq i} x_{ij}^S \\ &= \sum_{i\epsilon m} x_{ii}^S + 2\sum_{h=1}^{n-1} (n-h) x_h^S, \end{aligned}$$

where the second term on the right-hand side captures all bilateral micro flows and x_h^S denotes trade between micro regions that are h steps apart.

Combining the corresponding gravity relationships at the macro and micro levels, we obtain an expression similar to equation (6)

$$\underbrace{\frac{ny^S ny^S}{y^W}\left(\frac{t_{mm}^L}{P^L P^L}\right)^{1-\sigma}}_{x_{mm}^L} = \sum_{i\epsilon m} \underbrace{\frac{y^S y^S}{y^W}\left(\frac{t_{ii}^S}{P^S P^S}\right)^{1-\sigma}}_{x_{ii}^S} + 2\sum_{h=1}^{n-1}(n-h)\underbrace{\frac{y^S y^S}{y^W}\left(\frac{t_h^S}{P^S P^S}\right)^{1-\sigma}}_{x_h^S}. \quad (31)$$

Given that multilateral resistance is unaffected by aggregation, the internal trade costs of the macro region therefore follow from equation (31) as

$$\left(t_{mm}^L\right)^{1-\sigma} = \frac{1}{n}\left(t_{ii}^S\right)^{1-\sigma} + 2\sum_{h=1}^{n-1} \frac{n-h}{n^2}\left(t_h^S\right)^{1-\sigma}. \quad (32)$$

If bilateral costs are higher than internal costs at the micro level ($t_h^S > t_{ii}^S$), then internal trade costs at the macro level grow in the number of aggregated micro regions ($\partial t_{mm}^L/\partial n > 0$). The only exception is the limiting case of no spatial frictions in the sense of $t_h^S = t_{ii}^S$. In that case, internal trade costs at the macro level are the same as micro-level costs ($t_{mm}^L = t_h^S = t_{ii}^S$).

B.2 Aggregation and multilateral resistance

It is also the case for the model of the international border effect that aggregation leaves the multilateral resistance price indices unaffected. The proof is as follows.

As in Anderson and van Wincoop (2003), the general equilibrium price index for each micro region is given by

$$\left(P_i^S\right)^{1-\sigma} = \sum_{j=1}^{2R} \frac{y_j^S}{y^W}\left(\frac{t_{ji}^S}{P_j^S}\right)^{1-\sigma},$$

where R is the number of Home micro regions and $R^* = R$ is the number of Foreign micro regions. Thus, the price index aggregates trade costs over $R + R^* = 2R$ micro regions. The bilateral trade cost term t^S_{ji} refers to t^S_h for trade with other micro regions in the same country that are h steps away, and to t^S_{int} for trade with micro regions in the other country. Due to symmetry we have $y^S_j / y^W = 1/(2R)$ and $P^S_j = P^S$. Therefore we can write the price index for a Home region as

$$\left(P^S\right)^{1-\sigma} = \frac{1}{2R}\left(\frac{t^S_{ii}}{P^S}\right)^{1-\sigma} + \frac{1}{2R}\sum_{j\epsilon R, j\neq i}\left(\frac{t^S_{ji}}{P^S}\right)^{1-\sigma} + \frac{1}{2}\left(\frac{t^S_{int}}{P^S}\right)^{1-\sigma}, \tag{33}$$

where the first term reflects the trade of the micro region with itself, the second term captures the relationships with all other Home micro regions, and the third term captures the relationships with all Foreign micro regions. We can solve for P^S as

$$\left(P^S\right)^{1-\sigma} = \left(\frac{1}{2R}\left(t^S_{ii}\right)^{1-\sigma} + \frac{1}{2R}\sum_{j\epsilon R, j\neq i}\left(t^S_{ji}\right)^{1-\sigma} + \frac{1}{2}\left(t^S_{int}\right)^{1-\sigma}\right)^{\frac{1}{2}} \tag{34}$$

so that the price index is pinned down by the number of micro regions and their trade costs. The analogous steps apply for the price index of a Foreign micro region.

Now suppose n micro regions in the Home country are aggregated into a macro region denoted by the subscript m. Analogous to (33), we can then write the micro price index from the perspective of a remaining Home micro region as

$$\left(P^S\right)^{1-\sigma} = \frac{1}{2R}\left(\frac{t^S_{ii}}{P^S}\right)^{1-\sigma} + \frac{1}{2R}\sum_{j\epsilon R, j\neq i,m}\left(\frac{t^S_{ji}}{P^S}\right)^{1-\sigma} + \frac{n}{2R}\left(\frac{t^L_{mi}}{P^L}\right)^{1-\sigma} + \frac{1}{2}\left(\frac{t^S_{int}}{P^S}\right)^{1-\sigma}, \tag{35}$$

where the first term reflects the internal part. The second term captures the remaining Home micro regions. The third term captures the relationship with the macro region, weighted by its share $n/(2R)$ of the global economy. The macro price index P^L appears here together with the bilateral trade costs t^L_{mi} between the macro region and the micro region. The fourth term captures the international relationships.

From gravity equation (5) at the macro level, we can solve for the macro price index as

$$\left(P^L\right)^{1-\sigma} = \left(\frac{y^L_m y^L_m}{x^L_{mm} y^W}\left(t^L_{mm}\right)^{1-\sigma}\right)^{\frac{1}{2}}.$$

We use (31) to replace x^L_{mm} as well as $y^L_m = n y^S_m$ to obtain

$$\left(P^L\right)^{1-\sigma} = \left(P^S\right)^{1-\sigma}\left(\frac{\left(t^L_{mm}\right)^{1-\sigma}}{\frac{1}{n}\left(t^S_{ii}\right)^{1-\sigma} + \frac{2}{n^2}\sum_{h=1}^{n-1}(n-h)\left(t^S_h\right)^{1-\sigma}}\right)^{\frac{1}{2}}.$$

For brevity, we set

$$\lambda^{1-\sigma} \equiv \left(\frac{\left(t^L_{mm}\right)^{1-\sigma}}{\frac{1}{n}\left(t^S_{ii}\right)^{1-\sigma} + \frac{2}{n^2}\sum_{h=1}^{n-1}(n-h)\left(t^S_h\right)^{1-\sigma}}\right)^{\frac{1}{2}} \tag{36}$$

so that we have

$$\left(P^L\right)^{1-\sigma} = \left(\lambda P^S\right)^{1-\sigma}. \tag{37}$$

We insert this result back into expression (35) and solve for the micro price index as

$$\left(P^S\right)^{1-\sigma} = \left(\frac{1}{2R}\left(t_{ii}^S\right)^{1-\sigma} + \frac{1}{2R}\sum_{j\epsilon R, j\neq i,m}\left(t_{ji}^S\right)^{1-\sigma} + \frac{n}{2R}\left(\frac{t_{mi}^L}{\lambda}\right)^{1-\sigma} + \frac{1}{2}\left(t_{int}^S\right)^{1-\sigma}\right)^{\frac{1}{2}}. \quad (38)$$

Setting this result equal to expression (34), we obtain

$$n\left(\frac{t_{mi}^L}{\lambda}\right)^{1-\sigma} + \sum_{j\epsilon R, j\neq i,m}\left(t_{ji}^S\right)^{1-\sigma} = \sum_{j\epsilon R, j\neq i}\left(t_{ji}^S\right)^{1-\sigma}.$$

The t_{ji}^S terms between i and those micro regions j that were not aggregated are the same on both sides of the equation. We therefore have

$$n\left(\frac{t_{mi}^L}{\lambda}\right)^{1-\sigma} = \sum_{j\epsilon m}\left(t_{ji}^S\right)^{1-\sigma}, \quad (39)$$

where the right-hand side only sums over those micro regions j that were aggregated.

In equation (35) we write down the post-aggregation price index of a micro region. Analogously, the post-aggregation price index for the macro region in the Home country is given by

$$\left(P^L\right)^{1-\sigma} = \frac{n}{2R}\left(\frac{t_{mm}^L}{P^L}\right)^{1-\sigma} + \frac{1}{2R}\sum_{j\epsilon R, j\neq m}\left(\frac{t_{jm}^L}{P^S}\right)^{1-\sigma} + \frac{1}{2}\left(\frac{t_{int}^S}{P^S}\right)^{1-\sigma},$$

where the first term reflects trade within the macro region. The second term captures the relationships with the remaining micro regions. The third term captures the international relationships, where we use the result surrounding equation (19) that international trade costs are unaffected by aggregation and thus equal to t_{int}^S.

We then substitute the relationship (37) and solve for the micro price index as

$$\left(P^S\right)^{1-\sigma} = \left(\frac{1}{\lambda^{1-\sigma}}\right)^{\frac{1}{2}}\left(\frac{n}{2R}\left(\frac{t_{mm}^L}{\lambda}\right)^{1-\sigma} + \frac{1}{2R}\sum_{j\epsilon R, j\neq m}\left(t_{jm}^L\right)^{1-\sigma} + \frac{1}{2}\left(t_{int}^S\right)^{1-\sigma}\right)^{\frac{1}{2}}.$$

We set this result equal to equation (38). To replace the $\left(t_{mm}^L\right)^{1-\sigma}$ term, we use the definition of λ in equation (36). To replace the $\left(t_{mi}^L/\lambda\right)^{1-\sigma}$ term in equation (38), we use the result in (39). We also note that due to symmetry, we have $\left(t_{jm}^L\right)^{1-\sigma} = \left(t_{mj}^L\right)^{1-\sigma}$. Through equation (39) this is the same as

$$\left(t_{jm}^L\right)^{1-\sigma} = \left(t_{mj}^L\right)^{1-\sigma} = \frac{\lambda^{1-\sigma}}{n}\sum_{i\epsilon m}\left(t_{ij}^S\right)^{1-\sigma}.$$

Collecting terms and simplifying, we obtain

$$\begin{aligned} & \left(t_{ii}^S\right)^{1-\sigma} + \frac{2}{n}\sum_{h=1}^{n-1}(n-h)\left(t_h^S\right)^{1-\sigma} + \frac{1}{n}\sum_{j\epsilon R, j\neq m}\sum_{i\epsilon m}\left(t_{ij}^S\right)^{1-\sigma} + \frac{1}{\lambda^{1-\sigma}}R\left(t_{int}^S\right)^{1-\sigma} \\ = & \left(t_{ii}^S\right)^{1-\sigma} + \sum_{j\epsilon R, j\neq i}\left(t_{ji}^S\right)^{1-\sigma} + R\left(t_{int}^S\right)^{1-\sigma}. \end{aligned}$$

We note that the second term on the left-hand side of the last equation captures all bilateral trade costs amongst the micro regions that were aggregated. We can write this as

$$\frac{2}{n}\sum_{h=1}^{n-1}(n-h)\left(t_h^S\right)^{1-\sigma} = \frac{1}{n}\sum_{j\epsilon m}\sum_{i\epsilon m, i\neq j}\left(t_{ij}^S\right)^{1-\sigma}.$$

We also note that

$$\begin{aligned} & \frac{1}{n}\sum_{j\epsilon R, j\neq m}\sum_{i\epsilon m}\left(t_{ij}^S\right)^{1-\sigma} + \frac{1}{n}\sum_{j\epsilon m}\sum_{i\epsilon m, i\neq j}\left(t_{ij}^S\right)^{1-\sigma} \\ = & \sum_{j\epsilon R, j\neq i}\left(t_{ij}^S\right)^{1-\sigma} = \sum_{j\epsilon R, j\neq i}\left(t_{ji}^S\right)^{1-\sigma} \end{aligned}$$

so that ultimately, after dropping equal terms on both sides of the equation, we obtain

$$\frac{1}{\lambda^{1-\sigma}}R\left(t_{int}^S\right)^{1-\sigma} = R\left(t_{int}^S\right)^{1-\sigma}.$$

This implies $\lambda^{1-\sigma} = 1$. Through equation (37) we therefore arrive at the result that the price index is unaffected by aggregation, i.e., $P^L = P^S$.

B.3 The bias of omitting the interaction term

The trade cost function (20) includes an interaction term that combines the international border dummy with region-specific α_i and α_j variables. We can rewrite this trade cost function as

$$\ln\left(t_{ij}^{1-\sigma}\right) = \beta INT_{ij} + \ln\left(\delta_{ij}^{1-\sigma}\right) + \ln(\alpha_i\alpha_j)^{1-\sigma} - INT_{ij}\ln(\alpha_i\alpha_j)^{1-\sigma}.$$

Imagine a researcher imposes the traditional trade cost function without the interaction term. The β international border coefficient in the traditional function is then unbiased only in the special case of a zero covariance between the border dummy and the interaction term. Formally, we can state this condition as

$$\text{Cov}\left(INT_{ij}, INT_{ij}\ln\left(\alpha_i\alpha_j\right)^{1-\sigma}\right) = 0. \tag{40}$$

To simplify notation let

$$\begin{aligned} A_{ij} &= INT_{ij}, \\ B_{ij} &= INT_{ij}\ln\left(\alpha_i\alpha_j\right)^{1-\sigma}. \end{aligned}$$

so that condition (40) becomes

$$\begin{aligned}
&\operatorname{Cov}\left(A_{ij}, B_{ij}\right) = 0 \\
\Leftrightarrow &\sum_{ij}\left(A_{ij} - \overline{A}\right)\left(B_{ij} - \overline{B}\right) = 0,
\end{aligned}$$

where $\overline{A}$ and $\overline{B}$ denote the arithmetic averages of A_{ij} and B_{ij}.

Assume a sample with K national trade observations for which $INT_{ij} = 0$ and M international observations for which $INT_{ij} = 1$ such that we have $K+M$ total observations. We can rewrite the previous equation as

$$\begin{aligned}
K\left(-\overline{A}\right)\left(-\overline{B}\right) + \sum_{ij,INT_{ij}=1}\left(1-\overline{A}\right)\left(B_{ij} - \overline{B}\right) &= 0 \\
\Leftrightarrow K\overline{AB} + \left(1-\overline{A}\right)\sum_{ij,INT_{ij}=1}\left(B_{ij} - \overline{B}\right) &= 0
\end{aligned}$$

where the first term reflects the K national observations. We can rearrange the last equation as

$$\begin{aligned}
K\overline{AB} - \left(1-\overline{A}\right)M\overline{B} + \left(1-\overline{A}\right)\sum_{ij,INT_{ij}=1} B_{ij} &= 0 \\
\Leftrightarrow (K+M)\,\overline{AB} - M\overline{B} + \left(1-\overline{A}\right)\sum_{ij,INT_{ij}=1} B_{ij} &= 0.
\end{aligned}$$

Note that $\overline{A} = M/\left(K+M\right)$. The last equation thus simplifies to

$$\begin{aligned}
\left(1-\overline{A}\right)\sum_{ij,INT_{ij}=1} B_{ij} &= 0 \\
\Leftrightarrow \sum_{ij,INT_{ij}=1} \ln\left(\alpha_i\alpha_j\right)^{1-\sigma} &= 0 \\
\Leftrightarrow \sum_{ij,INT_{ij}=1} \left[\ln\left(\alpha_i\right) + \ln\left(\alpha_j\right)\right] &= 0.
\end{aligned}$$

There are two partner regions (one exporter i and one exporter j) for each of the M international observations. Let m_i denote the relative frequency with which region i appears as a partner in those observations (either as an exporter or as an importer). Then we can rewrite the last expression as

$$\begin{aligned}
\sum_{i=1}^{N} m_i \ln\left(\alpha_i\right) &= 0 \\
\Leftrightarrow \prod_{i=1}^{N} \alpha_i^{m_i} &= 1,
\end{aligned}$$

where N is the number of regions in the sample. That is, the geometric average of the region-specific α_i terms, weighted by the frequency in bilateral observations, is equal to 1. Given that $\alpha_i \geq 1$, it must be that $\alpha_i = 1$ holds for all i. This condition can only hold if region i is a micro region ($n_i = 1$) or if there are no spatial frictions ($\delta = 1$).

Appendix C: Data

This appendix describes our data sources in detail.

C.1 Domestic exports: Commodity Flow Survey

For our measures of the shipments of goods within and across U.S. states, we use aggregate trade data from the Commodity Flow Survey, which is a joint effort of the Bureau of Transportation Statistics and the Census Bureau. We use survey results from 1993, 1997, 2002, and 2007. The survey covers the origin and destination of shipments of manufacturing, mining, wholesale trade, and selected retail establishments. The survey excludes shipments in the following sectors: services, crude petroleum and natural gas extraction, farm, forestry, fishery, construction, government, and most retail. Shipments from foreign establishments are also excluded; import shipments are excluded until they reach a domestic shipper. U.S. export (i.e., trans-border) shipments are also excluded.[38]

C.2 International exports from U.S. states: Origin of Movement

Our data on exports by U.S. states to foreign destinations are from the Origin of Movement series.[39] These data are compiled by the Foreign Trade Division of the U.S. Census Bureau. The data in this series identify the state from which an export begins its journey to a foreign country. However, we would like to know the state in which the export was produced. Below we provide details on the Origin of Movement series and its suitability as a measure of the origin of production.[40]

Beginning in 1987, the Origin of Movement series provides the current-year export sales, or free-alongside-ship (f.a.s.) costs if not sold, for 54 'states' to 242 foreign destinations. These export sales are for merchandise sales only and do not include services exports. The 54 'states' include the 50 U.S. states plus the District of Columbia, Puerto Rico, U.S. Virgin Islands, and unknown. Following Wolf (2000), we use the 48 contiguous U.S. states. Rather than all 242 destinations, we use the 50 leading export destinations for U.S. exports for 2005.[41] We use the annual data from 1993, 1997, 2002, and 2007 for total merchandise exports.[42]

[38] Erlbaum and Holguin-Veras (2006) note that sample size has been a major issue. The 1993 survey collected data from 200,000 establishments and the size was subsequently reduced to 100,000 in 1997 and 50,000 in 2002. In response to complaints from the freight data users community, the sample size was increased to 100,000 in 2007.

[39] Other studies that have used the Origin of Movement series include Smith (1999), Coughlin and Wall (2003) and Coughlin (2004).

[40] The highlighted details as well as much additional information can be found in Cassey (2009).

[41] In alphabetical order, these countries are Argentina, Australia, Austria, Belgium, Brazil, Canada, Chile, China, Colombia, Costa Rica, Denmark, Dominican Republic, Ecuador, Egypt, El Salvador, Finland, France, Germany, Guatemala, Honduras, Hong Kong, India, Indonesia, Ireland, Israel, Italy, Japan, Kuwait, Malaysia, Mexico, Netherlands, New Zealand, Norway, Panama, Peru, Philippines, Russia, Saudi Arabia, Singapore, South Africa, South Korea, Spain, Sweden, Switzerland, Taiwan, Thailand, Turkey, United Arab Emirates, United Kingdom, and Venezuela.

[42] We have also tried the data for manufacturing only (as opposed to total merchandise). The two series are very highly correlated (99 percent). The regression results are almost identical and we therefore do not report them.

Concerns about using the Origin of Movement series to identify the location of production are especially pertinent for agricultural and mining exports. We, however, focus on manufactured goods. Cassey (2009) has examined the issue of the coincidence of the state origin of movement and the state of production for manufactured goods.[43] The reason for restricting the focus to manufacturing is that the best source for location-based data on export production, "Exports from Manufacturing Establishments," covers only manufacturing.[44]

Cassey's key finding relevant to our analysis is that, overall, the Origin of Movement data is of sufficient quality to be used as the origin of the production of exports. Nonetheless, the data for specific states may not be of sufficient quality as the origin of production. These states are: Alaska, Arkansas, Delaware, Florida, Hawaii, New Mexico, South Dakota, Texas, Vermont, and Wyoming. He recommends the removal of Alaska and Hawaii in particular. As we use the 48 contiguous U.S. states, our data set is consistent with this recommendation.

C.3 Adjustments to the state trade data

Our simultaneous use of the intra-state and inter-state shipments data from the Commodity Flow Survey and the merchandise international trade data from the Origin of Movement series requires an adjustment to increase the comparability of these data sets. Such an adjustment arises because of three important differences between the data sources. First, the merchandise international trade data measures a shipment from the source to the port of exit just once, whereas the commodity flow data likely measures a good in a shipment more than once. For example, a good may be shipped from a plant to a warehouse and, later, to a retailer. Second, goods destined for foreign countries, when they are shipped to a port of exit, are included in domestic shipments. Third, the coverage of sectors differs between the data sources. The Commodity Flow Survey includes shipments of manufactured goods, but it excludes agriculture and part of mining. Meanwhile, the merchandise trade data includes all goods.

Identical to Anderson and van Wincoop (2003), we scale down the data in the Commodity Flow Survey by the ratio of total domestic merchandise trade to total domestic shipments from the Commodity Flow Survey. Total domestic merchandise trade is approximated by gross output in the goods-producing sectors (i.e., agriculture, mining, and manufacturing) minus international merchandise exports.[45] This calculation yields adjustment factors of 0.495 for 1993, 0.508 for 1997, 0.430 for 2002, and 0.405 for 2007.[46] Similar to Anderson and van Wincoop (2003) and as discussed by Balistreri and Hillberry (2007), our adjustment to the commodity flow data does not solve all the measurement problems, but it is the best feasible option.

[43] For the initial work on this issue, see Coughlin and Mandelbaum (1991) and Cronovich and Gazel (1999). As Cassey's (2009) analysis refers to manufactured goods, we note that we have also tried the Origin of Movement manufacturing data (as opposed to total merchandise) with virtually identical results.

[44] The data in the "Exports from Manufacturing Establishments" is available at http://www.census.gov/mcd/exports/ but does not contain destination information, so it cannot be used for the current research project.

[45] See Helliwell (1997, 1998) and Wei (1996).

[46] The difference between our adjustment factor for 1993 and that of Anderson and van Wincoop, 0.495 vs. 0.517, is due to data revision.

C.4 Other data

The rest of the data used in our empirical work can be characterized as well-known. We take export data between the 50 foreign countries in our sample from the IMF Direction of Trade Statistics. For individual U.S. states we use state gross domestic product data from the U.S. Bureau of Economic Analysis. For foreign countries, we use data on gross domestic product taken from the IMF World Economic Outlook Database (October 2007 edition).

We use the standard great circle distance formula to measure inter-state and international distances between capital cities in kilometers. As intra-state distance, we use the distance between the two largest cities in a state.

Table 1: Domestic and international border effects

Sample	U.S. only		U.S. and foreign countries	
Year	1993	1993, 1997, 2002, 2007	1993	1993, 1997, 2002, 2007
	(1)	(2)	(3)	(4)
$\ln(dist_{ij})$	-1.07***	-1.08***	-1.19***	-1.21***
	(0.03)	(0.03)	(0.02)	(0.02)
NAT_{ij} (national border dummy)	-1.47***	-1.48***		
	(0.20)	(0.19)		
INT_{ij} (international border dummy)			-1.25***	-1.21***
			(0.08)	(0.06)
Domestic trade (within U.S. states)	yes	yes	no	no
National trade (between U.S. states)	yes	yes	yes	yes
International trade (with foreign countries)	no	no	yes	yes
Observations	1,726	6,904	6,249	24,996
Clusters	--	1,726	--	6,249
Fixed effects	yes	yes	yes	yes
R-squared	0.90	0.90	0.81	0.82

Notes: The dependent variable is $\ln(x_{ij})$. OLS estimation. Robust standard errors are reported in parentheses, clustered around bilateral pairs ij in columns 2 and 4. Exporter and importer fixed effects in columns 1 and 2; state and country fixed effects in columns 3 and 4; those fixed effects are time-varying in columns 2 and 4. *** significant at 1% level.

Table 2: Border effects based on U.S. Census divisions

Sample	U.S. only		U.S. and foreign countries	
Year	1993	1993, 1997, 2002, 2007	1993	1993, 1997, 2002, 2007
	(1)	(2)	(3)	(4)
$\ln(dist_{ij})$	-1.07***	-1.04***	-1.17***	-1.21***
	(0.10)	(0.08)	(0.03)	(0.03)
NAT_{ij} (national border dummy)	-1.17***	-1.25***		
	(0.18)	(0.17)		
INT_{ij} (international border dummy)			-0.36***	-0.39***
			(0.11)	(0.10)
Domestic trade (within Census divisions)	yes	yes	no	no
National trade (between Census divisions)	yes	yes	yes	yes
International trade (with foreign countries)	no	no	yes	yes
Observations	81	324	2,746	10,984
Clusters	--	81	--	2,746
Fixed effects	yes	yes	yes	yes
R-squared	0.95	0.96	0.78	0.79

Notes: The dependent variable is $\ln(x_{ij})$. OLS estimation. Robust standard errors are reported in parentheses, clustered around bilateral pairs ij in columns 2 and 4. Exporter and importer fixed effects in columns 1 and 2; division and country fixed effects in columns 3 and 4; those fixed effects are time-varying in columns 2 and 4.
*** significant at 1% level.

Table 3: General equilibrium effects in response to removing the U.S. international border

	Panel 1: Common border effect								Panel 2: Heterogeneous border effects							
	Total effect		Direct effect		Indirect GE effects				Total effect		Direct effect		Indirect GE effects			
U.S. state	$\Delta \ln(x_{ij})$	=	$(1-\sigma)\ \Delta \ln(t_{ij})$	+	$(\sigma-1)\ \Delta \ln(P_iP_j)$	+	$\Delta \ln(y_iy_j/y^W)$		$\Delta \ln(x_{ij})$	=	$(1-\sigma)\ \Delta \ln(t_{ij})$	+	$(\sigma-1)\ \Delta \ln(P_iP_j)$	+	$\Delta \ln(y_iy_j/y^W)$	
	(1a)		(1b)		(1c)		(1d)		(2a)		(2b)		(2c)		(2d)	
Average	**0.23**	**=**	**0.31**	**+**	**-0.10**	**+**	**0.02**		**0.24**	**=**	**0.33**	**+**	**-0.11**	**+**	**0.02**	
AL	0.24	=	0.31	+	-0.08	+	0.01		0.11	=	0.18	+	-0.10	+	0.02	
AR	0.22	=	0.31	+	-0.10	+	0.02		0.45	=	0.60	+	-0.19	+	0.04	
AZ	0.21	=	0.31	+	-0.12	+	0.02		0.32	=	0.45	+	-0.17	+	0.03	
CA	0.24	=	0.31	+	-0.08	+	0.01		0.13	=	0.18	+	-0.06	+	0.01	
CO	0.23	=	0.31	+	-0.10	+	0.02		0.40	=	0.51	+	-0.14	+	0.03	
CT	0.25	=	0.31	+	-0.06	+	0.01		-0.07	=	-0.04	+	-0.03	+	0.00	
DE	0.25	=	0.31	+	-0.06	+	0.01		0.01	=	0.05	+	-0.05	+	0.01	
FL	0.21	=	0.31	+	-0.12	+	0.02		-0.13	=	-0.18	+	0.08	+	-0.02	
GA	0.23	=	0.31	+	-0.09	+	0.01		0.01	=	0.05	+	-0.05	+	0.01	
IA	0.22	=	0.31	+	-0.10	+	0.02		0.30	=	0.40	+	-0.13	+	0.03	
ID	0.23	=	0.31	+	-0.09	+	0.01		0.58	=	0.71	+	-0.16	+	0.03	
IL	0.25	=	0.31	+	-0.07	+	0.01		0.07	=	0.11	+	-0.04	+	0.01	
IN	0.24	=	0.31	+	-0.09	+	0.01		0.23	=	0.31	+	-0.10	+	0.02	
KS	0.22	=	0.31	+	-0.10	+	0.02		0.16	=	0.23	+	-0.09	+	0.02	
KY	0.24	=	0.31	+	-0.08	+	0.01		0.18	=	0.25	+	-0.09	+	0.02	
LA	0.22	=	0.31	+	-0.10	+	0.02		-0.27	=	-0.45	+	0.23	+	-0.05	
MA	0.23	=	0.31	+	-0.09	+	0.01		0.03	=	0.08	+	-0.06	+	0.01	
MD	0.25	=	0.31	+	-0.07	+	0.01		0.12	=	0.17	+	-0.06	+	0.01	
ME	0.20	=	0.31	+	-0.13	+	0.02		0.44	=	0.66	+	-0.28	+	0.05	
MI	0.22	=	0.31	+	-0.10	+	0.02		0.18	=	0.27	+	-0.12	+	0.02	
MN	0.25	=	0.31	+	-0.06	+	0.01		0.20	=	0.25	+	-0.06	+	0.01	
MO	0.23	=	0.31	+	-0.10	+	0.02		0.37	=	0.49	+	-0.15	+	0.03	
MS	0.22	=	0.31	+	-0.10	+	0.02		0.20	=	0.32	+	-0.15	+	0.03	

MT	0.18	=	0.31	+	-0.15	+	0.03		1.08	=	1.37	+	-0.36	+	0.07
NC	0.22	=	0.31	+	-0.10	+	0.02		0.03	=	0.08	+	-0.06	+	0.01
ND	0.19	=	0.31	+	-0.15	+	0.03		0.77	=	1.03	+	-0.32	+	0.06
NE	0.23	=	0.31	+	-0.10	+	0.02		0.48	=	0.61	+	-0.16	+	0.03
NH	0.23	=	0.31	+	-0.09	+	0.01		0.28	=	0.42	+	-0.17	+	0.03
NJ	0.26	=	0.31	+	-0.05	+	0.01		0.03	=	0.06	+	-0.04	+	0.01
NM	0.20	=	0.31	+	-0.13	+	0.02		0.51	=	0.70	+	-0.24	+	0.05
NV	0.25	=	0.31	+	-0.06	+	0.01		0.83	=	0.91	+	-0.11	+	0.02
NY	0.18	=	0.31	+	-0.15	+	0.03		-0.05	=	-0.10	+	0.06	+	-0.01
OH	0.23	=	0.31	+	-0.09	+	0.01		0.14	=	0.21	+	-0.09	+	0.02
OK	0.22	=	0.31	+	-0.10	+	0.02		0.35	=	0.48	+	-0.17	+	0.03
OR	0.23	=	0.31	+	-0.09	+	0.01		0.27	=	0.37	+	-0.12	+	0.02
PA	0.22	=	0.31	+	-0.11	+	0.02		0.14	=	0.25	+	-0.13	+	0.02
RI	0.25	=	0.31	+	-0.07	+	0.01		0.19	=	0.28	+	-0.10	+	0.02
SC	0.23	=	0.31	+	-0.10	+	0.01		0.00	=	0.04	+	-0.04	+	0.01
SD	0.20	=	0.31	+	-0.14	+	0.02		0.86	=	1.11	+	-0.30	+	0.06
TN	0.23	=	0.31	+	-0.09	+	0.01		0.18	=	0.26	+	-0.11	+	0.02
TX	0.21	=	0.31	+	-0.11	+	0.02		-0.09	=	-0.10	+	0.02	+	0.00
UT	0.22	=	0.31	+	-0.10	+	0.02		0.42	=	0.54	+	-0.15	+	0.03
VA	0.25	=	0.31	+	-0.07	+	0.01		-0.03	=	-0.01	+	-0.03	+	0.00
VT	0.19	=	0.31	+	-0.14	+	0.02		0.21	=	0.42	+	-0.26	+	0.05
WA	0.20	=	0.31	+	-0.13	+	0.02		-0.09	=	-0.12	+	0.05	+	-0.01
WI	0.23	=	0.31	+	-0.10	+	0.01		0.11	=	0.17	+	-0.07	+	0.01
WV	0.23	=	0.31	+	-0.09	+	0.01		0.20	=	0.28	+	-0.10	+	0.02
WY	0.21	=	0.31	+	-0.11	+	0.02		0.61	=	0.78	+	-0.21	+	0.04

Notes: This table reports logarithmic differences of variables between an initial equilibrium with international border barriers and a counterfactual equilibrium where these border barriers are removed. Two scenarios are considered. The first scenario in panel 1 is based on a common international border barrier for all 48 U.S. states in the sample. The second scenario in panel 2 is based on heterogeneous international border barriers across U.S. states. The sample is balanced over the years 1993, 1997, 2002 and 2007 with 24,996 observations in total (6,249 for each year). Apart from the international border dummies the underlying regressions include log distance and time-varying state and country fixed effects. Columns 1a and 2a: average change in bilateral trade (total effect); columns 1b and 2b: change in bilateral trade costs scaled by the substitution elasticity due to the removal of the international border; columns 1c and 2c: average change in multilateral resistances scaled by the substitution elasticity; columns 1d and 2d: average change in incomes. The first row reports the simple average across all states. The reported numbers are rounded off to two decimal digits. For more information see the main text.

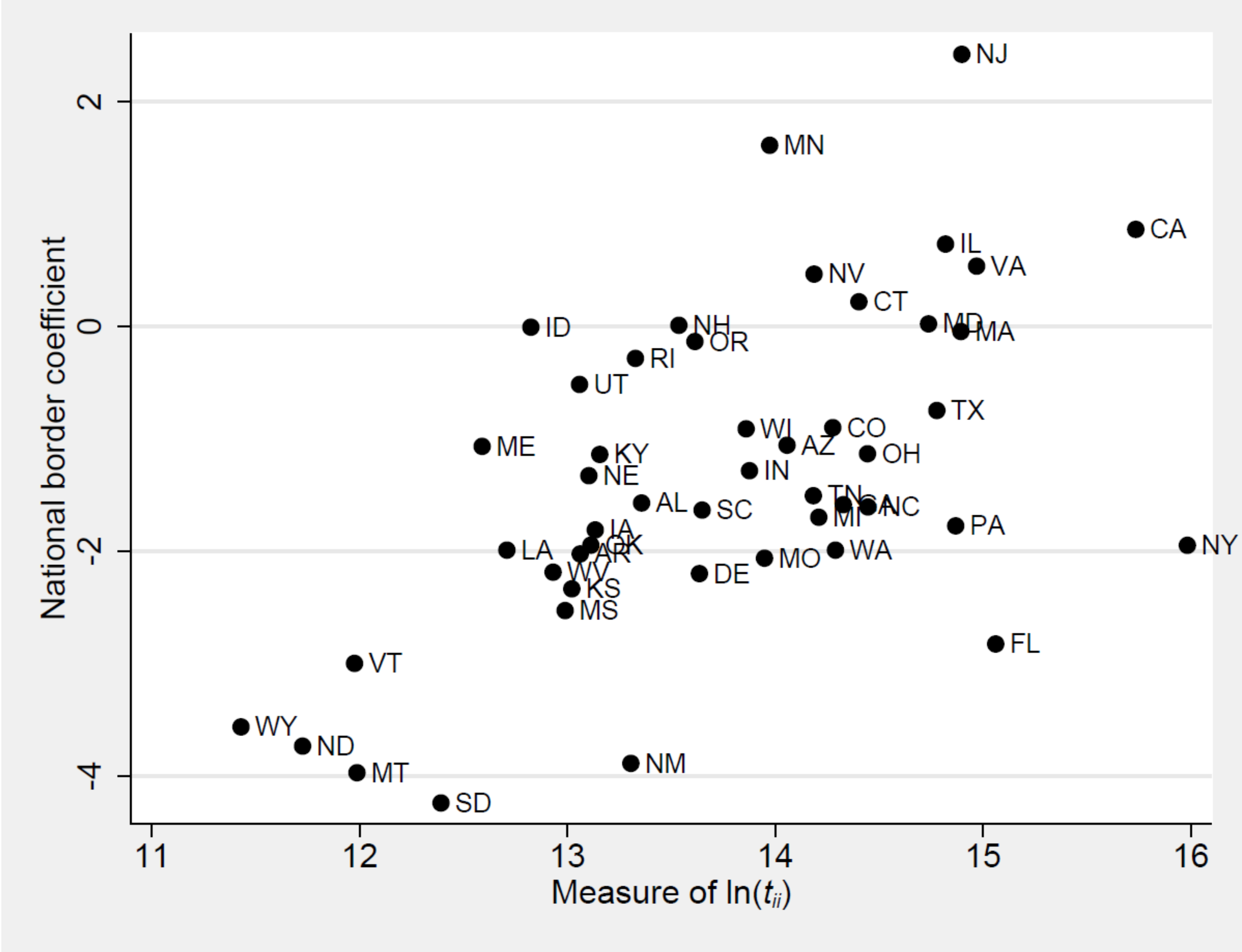

Figure 1: Plot of national border dummy coefficients for the 48 contiguous U.S. states against the logarithm of a model-consistent proxy for internal trade costs t_{ii}. The mean of the coefficients is -1.32. The average standard error is 0.13 (not plotted). More details are provided in the main text.

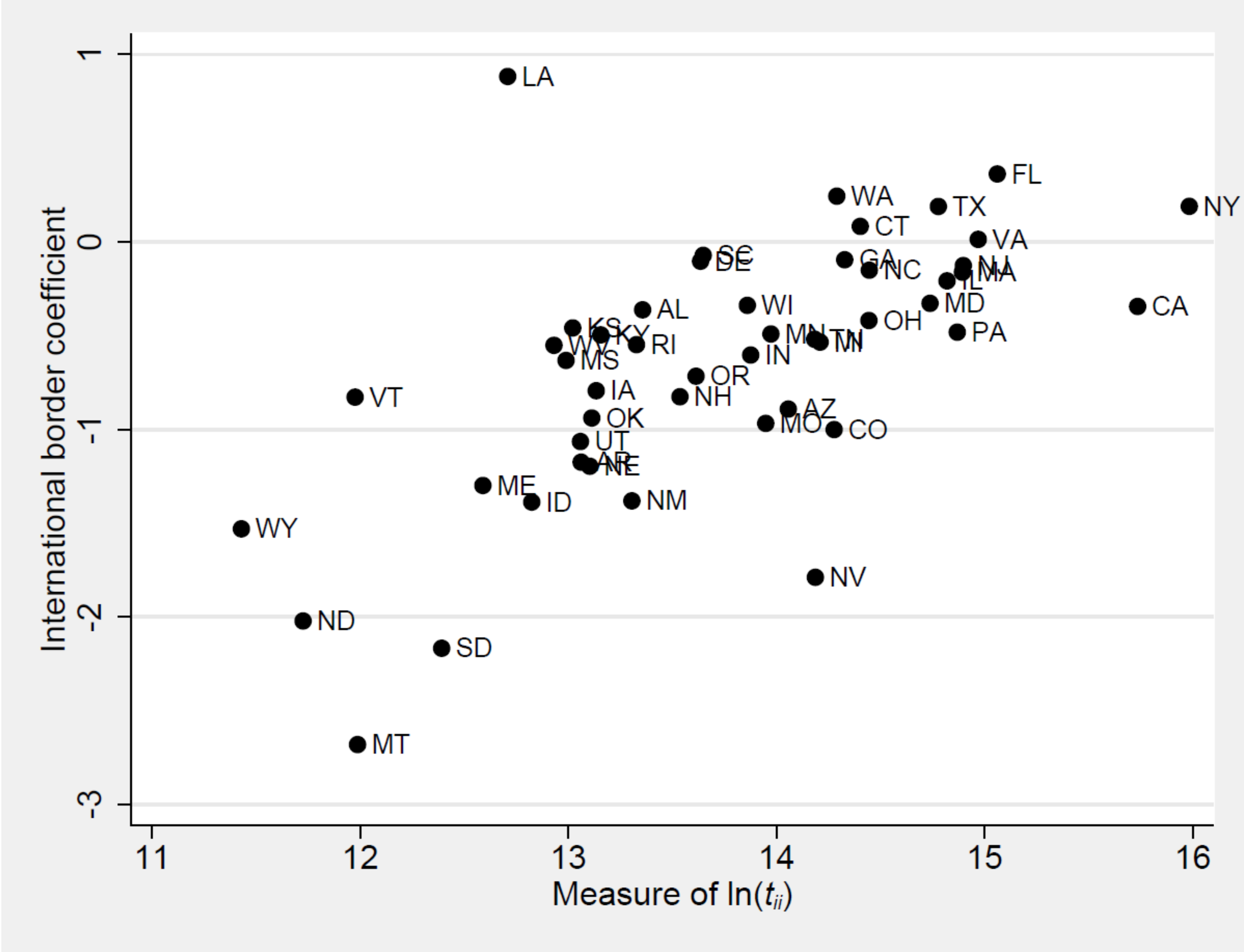

Figure 2: Plot of international border dummy coefficients for the 48 contiguous U.S. states against the logarithm of a model-consistent proxy for internal trade costs t_{ii}. The mean of the coefficients is -0.64. The average standard error is 0.13 (not plotted). More details are provided in the main text.

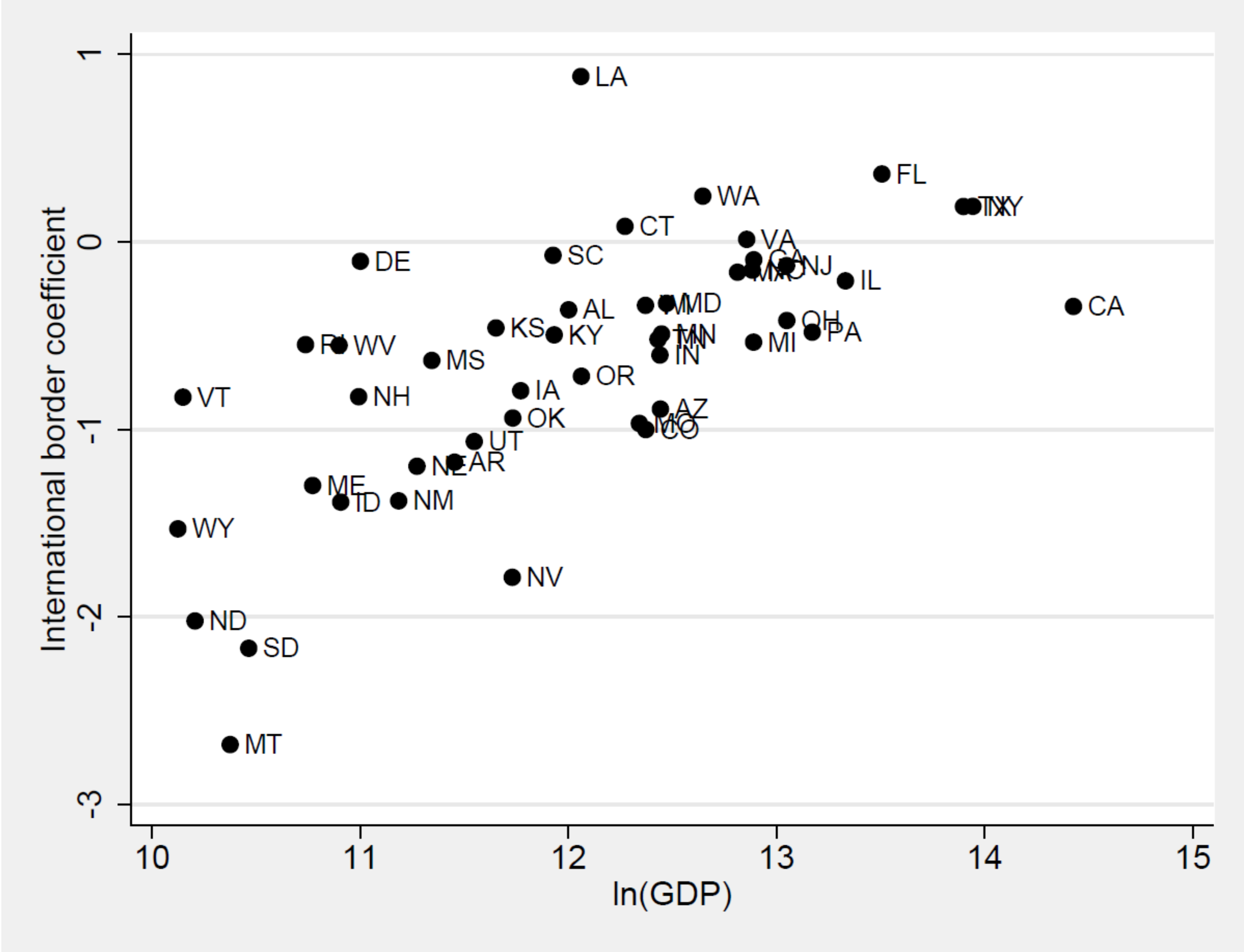

Figure 3: Plot of international border dummy coefficients for the 48 contiguous U.S. states against the logarithm of state GDP. The mean of the coefficients is -0.64. The average standard error is 0.13 (not plotted). More details are provided in the main text.

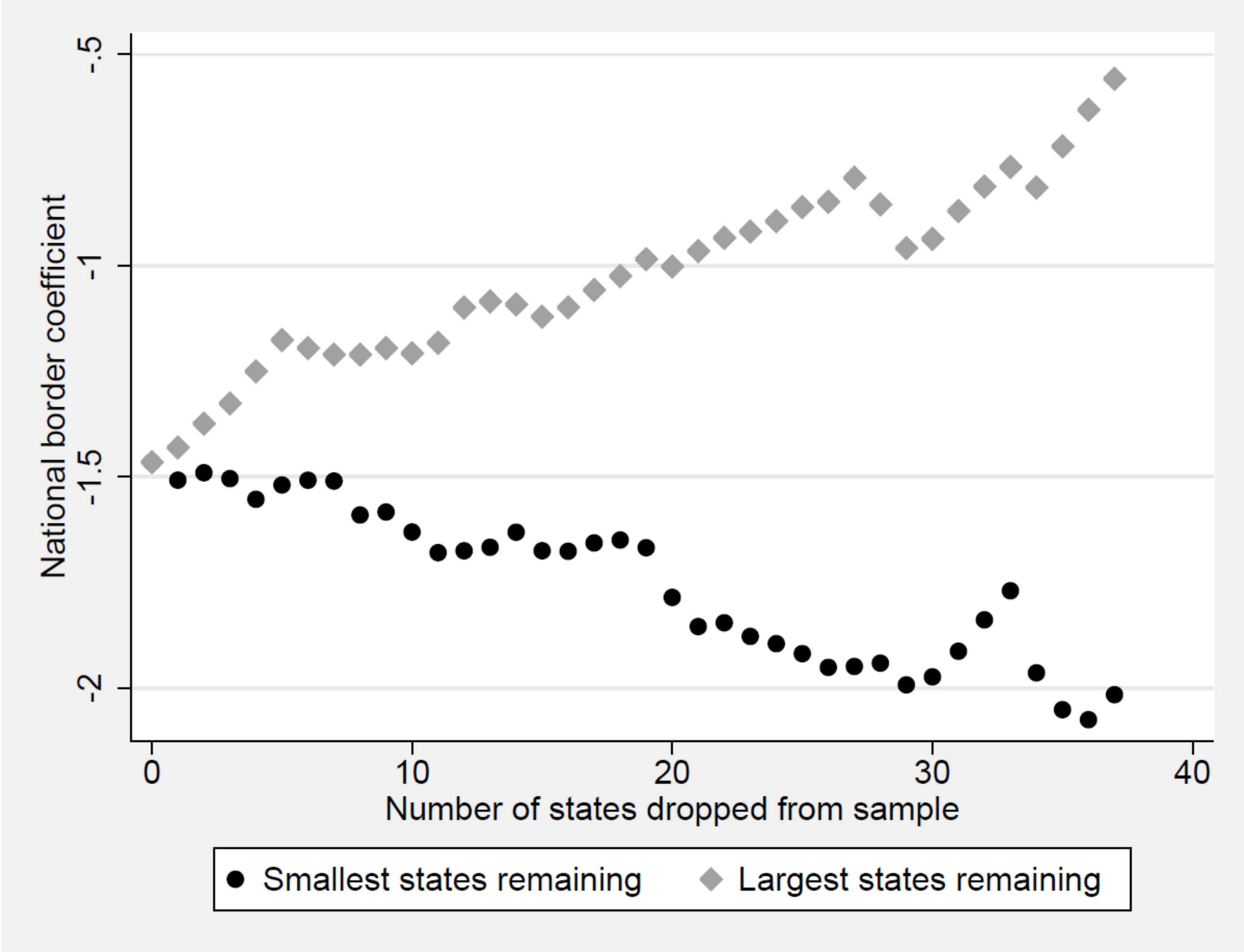

Figure 4: Plot of common national border dummy coefficients estimated for different samples of U.S. states. When zero states are dropped, the coefficient is -1.47 as in column 1 of Table 1. Black dots plot the coefficients obtained by successively dropping the largest remaining state from the sample such that the smallest states are remaining. The grey diamonds plot the coefficients obtained by successively dropping the smallest remaining state such that the largest states are remaining. More details are provided in the main text.

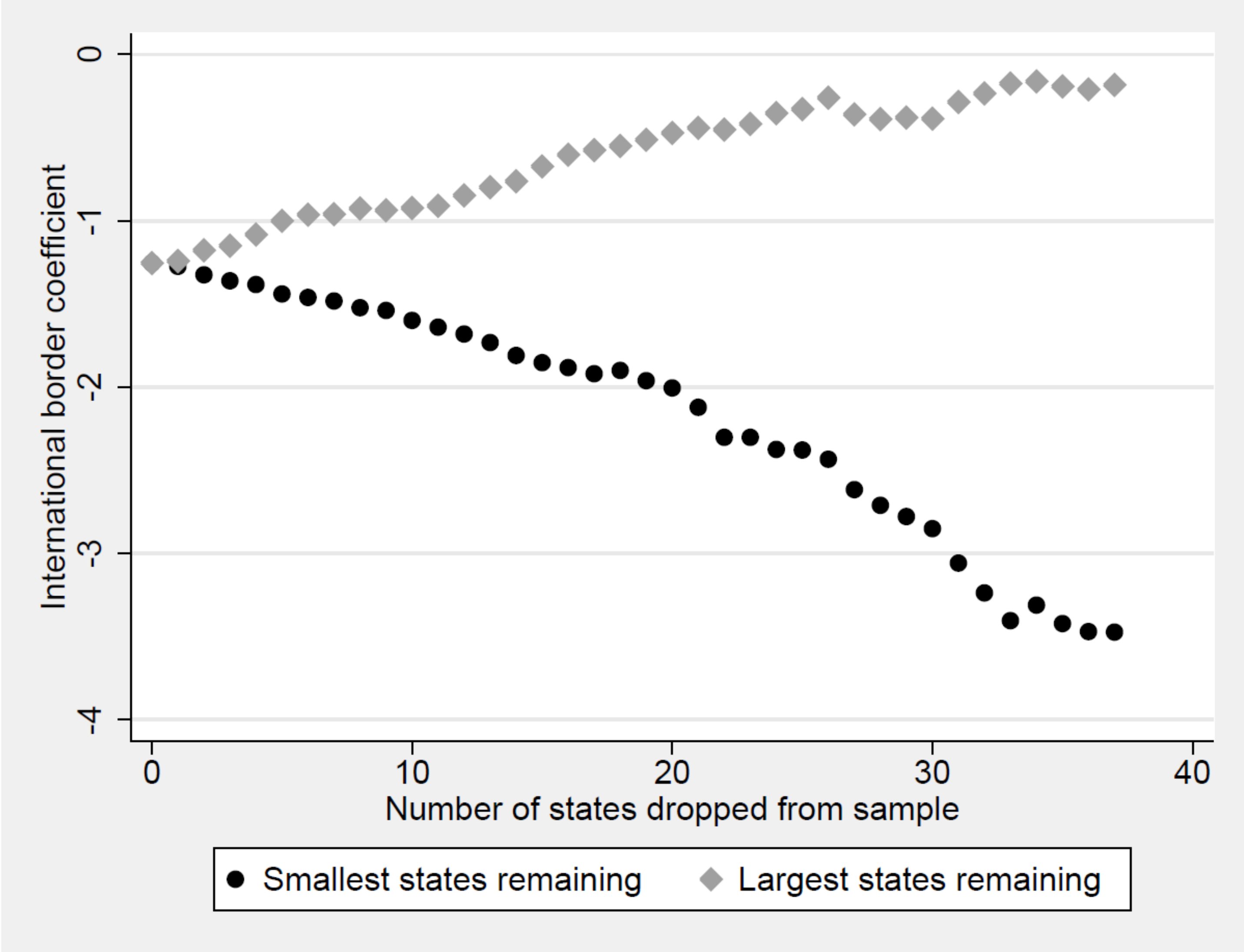

Figure 5: Plot of common international border dummy coefficients estimated for different samples of U.S. states. When zero states are dropped, the coefficient is -1.25 as in column 3 of Table 1. Black dots plot the coefficients obtained by successively dropping the largest remaining state from the sample such that the smallest states are remaining. The grey diamonds plot the coefficients obtained by successively dropping the smallest remaining state such that the largest states are remaining. More details are provided in the main text.

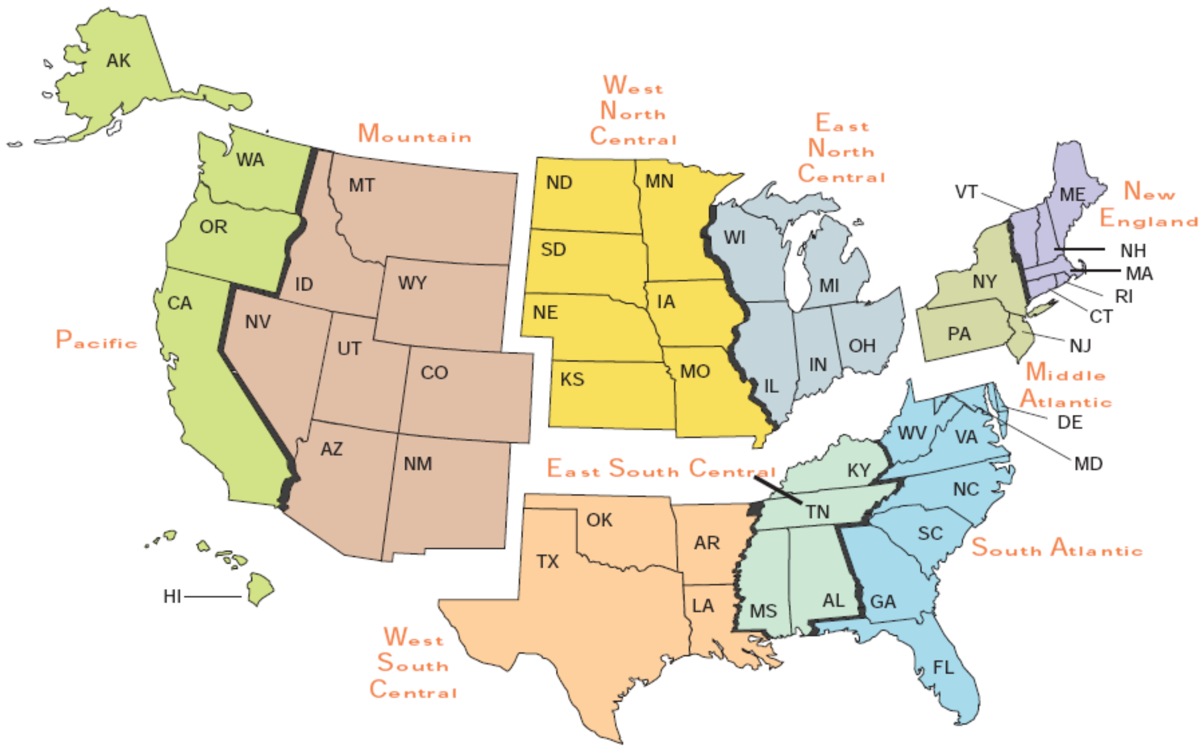

Figure 6: A map of the nine U.S. Census divisions (source: U.S. Department of Energy).