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# The border effects and choices of competitive strategies of the provincial natural gas markets in China

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ABSTRACT

The provincial government competition is regarded as a key variable in China's market-oriented reform to explore whether natural gas market will be integrated from segmentation. A spatial price equilibrium model with two markets is advanced to theoretically explain the competitive policy tools of environmental regulation and pipelines investment will increase resource rent but decrease congestion rent, and lead to more segmentation and integration of gas market, respectively. However, it is difficult to quantify the price differences resulted from these two rents on gas trade network. Therefore, the price difference is selected as the dependent variable of the border effect model, and a model-based analytical framework is put forward to empirically study the mechanism of the border effects from provincial competition. Results indicate that: (i) Natural gas physical network builds a trade network for provincial competition, and government uses policy tools to redistribute these two rents to change the spatial allocation relationships of natural gas on the trade network. (ii) Market segmentation by these two rents generates the border effects which display heterogeneity on gas trade network after provincial competitions in different ways. (iii) Once the margins of the two rents are changed by a node in the node-centered niche gas market when gas trade network evolves from a small world to free-world, the government will self-adaptively migrate its competitive strategies to maximize its marginal revenue. Consequently, the migration helps the niche market and the whole market to be integrated from segmentation. Some suggestions are given for China's natural gas market integration.

## 1. Introduction

The recent two decades in China have illustrated the acceleration of the perfect competition of natural gas market from monopoly because of the market-oriented reforms. The reforms are expected to integrate the market by eliminating the invisible segmentations from monopolistic participants, pipeline congestion and pipeline ownership bundling, etc. (Paltsev and Zhang, 2015; Xu et al., 2017; Dong et al., 2018; Wang et al., 2022). Under the fiscal decentralization, the reforms and provincial government competition have fostered China's natural gas market, which is different from the liberalized markets in Europe and North America (Mohamed et al., 2020). In this system, the government tend to compete for more natural gas through the energy market segmentation to improve the energy utilization efficiency, better serving environmental performance (Que et al., 2018; Lin and Li, 2021; Zhang et al., 2022). However, lower energy allocation efficiency from segmentation has been criticized for less spatial integration (Shi and Shen, 2008; Lin and Du, 2013; Wei and Zheng, 2020). In fact, there is a potential contradiction between technological and allocation efficiencies from natural gas supply shortage in China. The contradiction would hinder a unified natural gas market to be built. Therefore, the positive and negative effects of provincial competitions should be considered to explore whether natural gas market will be integrated from segmentation. Unfortunately, academies and policymakers do not pay enough attention to these effects.

Under fiscal decentralization, administrative means are usually adopted to obtain more natural gas to reduce carbon emissions (Zhang et al., 2021; Liu et al., 2022). For instance, environmental regulation is

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employed to guide enterprises to consume natural gas rather than coal (Huang and Zou, 2020; Hu et al., 2022). Consequently, the regulation acts as a "curve shifter" to shift the demand curve to the right parallelly, just as the income increase, GDP growth and temperature drop (Wright, 1928; Burke and Yang, 2016; Yan et al., 2023). This shift would increase the gravity of the provincial market to attract natural gas, which produces the siphon effect of natural gas allocation (Wang et al., 2020). Provincial gas pipeline investment is another administrative tool. Governments intensively invest to build more provincial gas pipelines linked to the long-distance gas pipelines (Yu et al., 2011), to win the competitions of receiving more natural gas (Li et al., 2020; Xu and Klaiber, 2019). With these two tools, the government will change the demand function curve and make it possible for the government to have access to natural gas allocation, which will be illustrated in Section 3.1. Based on the demand function, these two tools build a bridge between allocation and technical efficiencies while also putting the stumbling blocks through the bridge. Therefore, this pursuit of political achievements drives the government to invisibly segment regional markets in natural gas network, thus forming the border of administrative monopoly (Wang et al., 2020).

However, it is a challenge to identify the border effect of the government from the variables of geography, technology, economy, and policy etc. In particular, natural gas pipeline network in China has stretched rapidly, reaching about $11 \times 10^4$ km (NEA, 2019), which has changed the structure of natural gas network (Xiao et al., 2012; Gao, 2020). What makes us more interested is how the provincial competitive strategies respond to the dynamically interconnected structure as it is more theoretically and practically valuable for policymakers to spatially integrate China's natural gas market under the fiscal decentralization.

## 2. Literature review

The literature review in this section begins with the border effect in gravity equation and the market segmentation in the law of one price. And then, we trace literatures about the border effect to be moderated by network structure change, and the motivation of individual's strategy choice in logit model. We find some indirect evidence that the border effect moderated by network could change the individual behavior strategies.

The border effect can indicate the extent or degree of regional market segmentation (Gorodnichenko and Tesar, 2009; Borraz et al., 2016). Two main lines of researches on measuring and identifying border effects might be summed up as the gravity equation pioneered by McCallum (1995) for international or across-regional free trade and the "law of one price" followed by Engel and Rogers (2001) for the integration between regional relative prices.

In gravity equation, a binary virtual variable was introduced to econometrically estimate the border effects among country-pairs or region-pairs of international or domestic trades (McCallum, 1995; Anderson and Van Wincoop, 2003; Coughlin and Novy, 2013; Wrona, 2018). For instances, with the gravity equation, Anderson and Van Wincoop (2003) find that borders reduced the trades between industrialized countries by 20%–50% by controlling geographical distance. However, the border effect of state-to-state trades in America was increasing (Coughlin and Novy, 2013). More surprisingly, the border effect between East- and West-Japan was 23.1%–51.3% lower than that within both regions (Wrona, 2018). These facts implied that there were unobserved variables in the binary variables which deserve further identification, since the gravity model is based on the regional preference for commodities, but not economic growth, populations and policies, etc., and they conceal the preference differences (Parsley and Wei, 2001). In addition, it is difficult to obtain the domestic trade data required by the gravity equation in many developing countries (Fan and Sun, 2009). Moreover, natural gas is supplied and allocated by gas producers or wholesalers rather than the governments. The governments can only change their own demands through policy tools while both supply and demand can be monopolized by the governments in the gravity model.

To overcome the above-mentioned drawbacks of the gravity equation, many scholars have turned to the law of one price in the spatial price equilibrium theory, to explore what segments the market (Parsley and Wei, 2001; Poncet, 2005; Brenton et al., 2014). Commonly, the relative price-pairs were used to substitute the pair-trade quantities in panel regression models to identify the border effect from the explanatory variables. With this relative price-pairs, Parsley and Wei (2001) found the border effect of trades between the U.S.A and Canada decreased significantly after the relative exchange rate was controlled. The same approach was also adopted by Poncet (2005) to investigate the provincial border effect in China and revealed that the border effect would decrease when the provincial competitions were decomposed from the virtual border variable. Following their researches, Avalos et al. (2016) developed a co-integration model and grasped the negative effects of gas pipeline constraints on market integration. Núñez et al. (2022) introduced the differentials of gas production and consumption between pairs of states in cross-section regression model to examine the effects of differentiated regional market on integration. The law of one price confirmed different equilibriums among regional markets, which was supported by the spatial equilibrium model (Samuelson, 1952). In essence, the price difference between any two markets is arisen by local supply and demand curves in these two markets. Meanwhile, the curves are usually shaped by the temperature, income, industry, pipeline and even pipeline capacity, etc. Therefore, this motivates us to study segmentation in China's natural gas market.

However, pairwise relative prices in geographical neighbors ignored the linkages across regions, and the border effect would be overestimated or below-estimated along physical network (e.g., natural gas, oil, and water networks). Cross-regional network should be introduced to construct the price-pairs. Ren et al. (2019) developed relative prices by introducing a binary matrix which describes the inter-linkages of gas pipeline network. The matrix was, however, fixed in time series analysis with the linkages, which does not consider moderating the border effect. Actually, the linkages always change in the long term (Xiao et al., 2012; Gao, 2020), which will attach the gas trade network to the physical network and will also drive it to evolve from random network to a small world or scale-free network (Geng et al., 2014; Chen et al., 2016). Donaldson (2018) noted these phenomena econometrically revealed the change of O-D's pairs of the network would significantly segment the market in panel regression. However, his study ignored the structure features, such as in-degree, out-degree, centrality, and average shortest path. Virtually, the aggregation and diffusion of gas trade were limited by the dynamic of these features (Zhang et al., 2016; Wang et al., 2016). Liu et al. (2022) and Gu and Xiao (2021) investigated the moderating effect of the closeness centrality in social network to moderate the behavior choices, and found the moderating effects had positive or negative effect. Moreover, Pillai et al. (2011), Ogbeibu et al. (2018) and Wu et al. (2022) revealed that the moderating effect would be shifted from the positive to the negative aspect, and vice versa, when the strength of these attributes increased or decreased.

The margin of the moderating effect is hardly observed except by Wei and Zheng (2020). They extracted the marginal effect of market segmentation by provincial competition on energy efficiency through the first-order derivative of relative price. If the effect is converted into the utilities of strategies in logit model, it could guide the strategies to be changed. There are few attempts to deal with this convert in social network. Fortunately, there are many studies about improving logit models in social network from two schemes. One scheme is that the features of network are inserted into the logit model as independent variables, e.g., the betweenness centrality was adopted by Calderoni and Superchi (2019) to investigate the criminal leader in network. Another is that the utility function is taken into account in the interacted-behavior in social network, e.g., altruism level of individuals was considered in utility function (Hsieh and Lin, 2021). In addition, the utility function could be developed with more researches to explore the motivation of behavior choices (Li et al., 2020; Lu et al., 2021; Cui et al., 2022).

To sum up, based on the law of one price, we establish a border effect model, a moderating effect model and a logit model to identify the border effect of provincial competition in gas trade network and explore the self-adaptive choice of the competitive strategies. The possible marginal contributions are as follows: (i) A spatial equilibrium model with two markets is established to reveal that by redistributing the resource and congestion rents, the provincial competition gives rise to natural gas market segmentation and then the border effect. It helps deepen the understanding of the border effect from the provincial competition. (ii) The pair-wise approach is applied to build the O-D's panel data of the provincial competitions for structurally decomposing their competitive strategies into the arcs on gas trade network, and provides econometric support for the border effect model to investigate the heterogeneity of the border effects on gas trade network; (iii) The logit model is extended to observe the migrating paths of provincial competitive strategies by using the marginal effect of competitive strategies on the price gap as the variable of the utility function It gives an insight into the self-adaptive response of competitive strategies to the structural change of gas trade network.

## 3. Methodology

### 3.1. Analytical framework

How does the government participate in natural gas allocation to compete for more natural gas? Samuelson (1952) argued that once the iceberg cost (transportation cost) was eliminated, two markets would be integrated at an equilibrium through two excess-supply curves. However, its implicit premise is that the market supply is sufficient. However, gas supply has always been in shortage in China (Wang et al., 2022). A two-stage model was introduced by Tietenberg and Lewis (2018) to illustrate the dynamic allocation of exhaustible resources in a market during two periods. They concluded that once marginal net benefits of the market are equal in two periods, the supplier would obtain the optimal profit. In essence, the discount rate shaped the different demand curves of this market in these two periods, thus forming two different markets. Inspired by Samuelson (1952) and Tietenberg and Lewis (2018), the two markets in time series are regarded as two spatial provincial markets, and a spatial price equilibrium model with two markets is advanced to illustrate the resource and congestion rents in the context of natural gas supply shortage, as shown in Fig. 1.

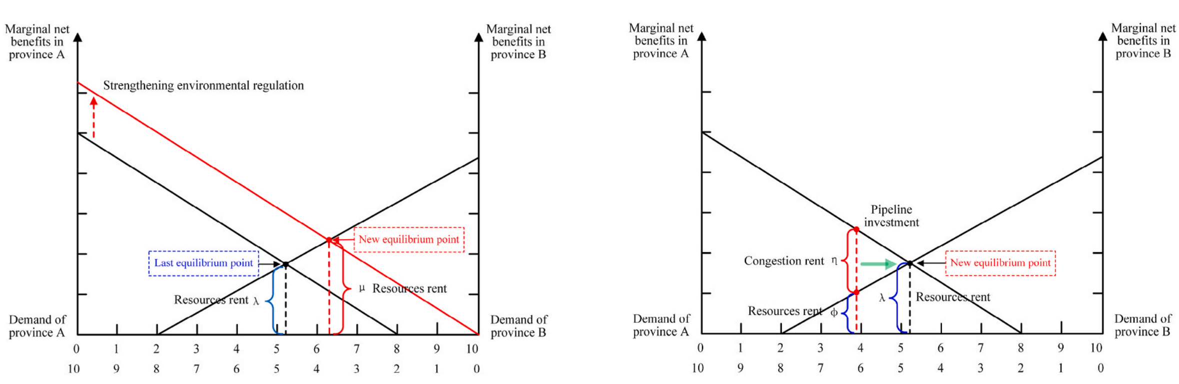
The curves of marginal net benefits in provincial markets A and B are illustrated in Fig. 1. The horizontal axis represents the total supply quantity for the two markets, assuming the total supply is 10 units. The vertical axis represents marginal net benefits (price minus marginal cost, seeing in Tietenberg and Lewis, 2018: p132, Fig.5.1). Once the marginal net benefits of A and B are equal where depicted by the cross point of line A and B in Fig. 1, the market equilibriums of the two markets will be achieved at this point. In Fig. 1(a), if the environmental regulation is intensified on market A, it will shift the inverse demand curve to the right, and then the equilibrium point will move from the last equilibrium point to a new one, as shown that the black line will move to the red line. The strengthened environmental regulation will increase the resource rent λ at the last equilibrium point. At this time, natural gas will flow from market B to A, and the price gap μ-λ will arise. Therefore, environmental regulation has intensified the scarcity of natural gas, resulting in more segmentation between market A and B. What's more, if there exists a bottleneck of pipeline capacity between markets A and B, the congestion rent η will prevent suppliers from arbitraging between the two markets as seen in Fig. 1(b). As a result, these two markets are segmented by resource rent φ and congestion rent η. The pipeline capacity between A and B will increase as the pipeline investment increases, because of which more natural gas will flow from market A to B. Although the two markets are still segmented, the gas pipeline investment has reduced the degree of market's segmentation.

It is difficult to accurately quantify the resource and congestion rents generated by provincial competition on natural gas network. If the price difference from these two rents is selected as the dependent variable of the border effect model, the model can help explain market segmentation by the resource and congestion rents. Therefore, an econometric framework is proposed in Fig. 2, to investigate the border effect and provincial competitions in China's natural gas network. The framework is described in three steps as follows:

**Step 1.** Constructing panel data of O-D's pairs. We extend the trade binary matrix from adjacent linkages proposed by Ren et al. (2019), to the cross-regional linkages considering the gas trades on physical gas network. The pair-wise approach is then applied to construct panel data of O-D's matrix with 0–1 variables, and it will hence prevent the border effects from overestimation.

**Step 2.** Identifying the border effects from provincial government competitions. There are two questions Q1 and Q2 to be answered, as shown in the green boxes in Fig. 2. To answer Q1, the two border effect models are performed respectively to examine whether the border effect is shifted from geography to gas trade network. Next, to answer Q2, four competitive strategies of provincial government, proposed by Zhang et al. (2010) as dummy variables, are attached to the O-D's matrix of gas trades in the border effect model to get insight into the heterogeneous border effects from the four strategies.

**Step 3.** Exploring the choices of provincial government competitive strategies. There are also another two questions to be answered. Firstly, the structural features of the trading network were extracted by SNA approach to act as moderating variables. Hence, the moderating effect of




(a) environmental regulation (b) pipeline investment

**Fig. 1.** The resource and congestion rents generated by the provincial competitions.

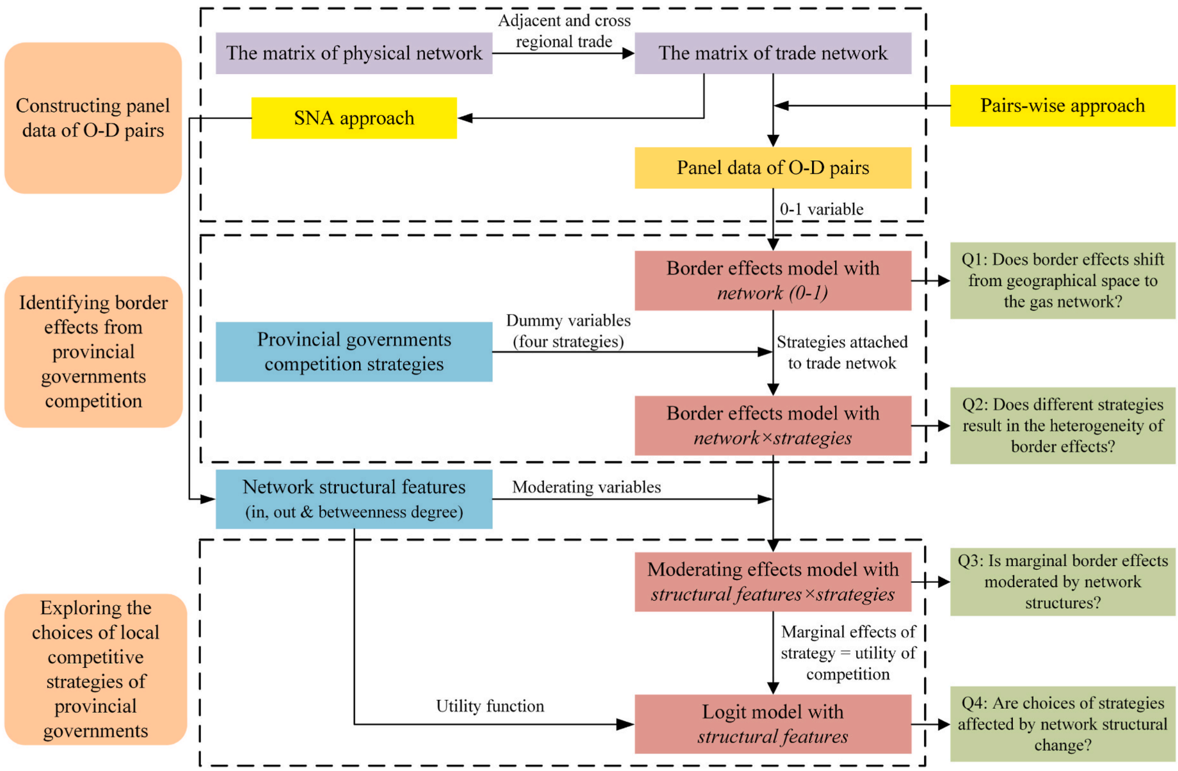



**Fig. 2.** Analytical framework for identifying the border effects and exploring the choices of competitive strategies.

these variables could identify which attribute plays a positive or negative role in the border effects of the strategies (Q3). Secondly, inspired by the marginal effect of strategies on market segmentation (Wei and Zheng, 2020), we treat the marginal effect as the utilities of strategies and then deploy them in the logit model to explore the response of the strategies to the structural change of gas trade network (Q4).

### 3.2. The O-D's matrixes of gas trade network

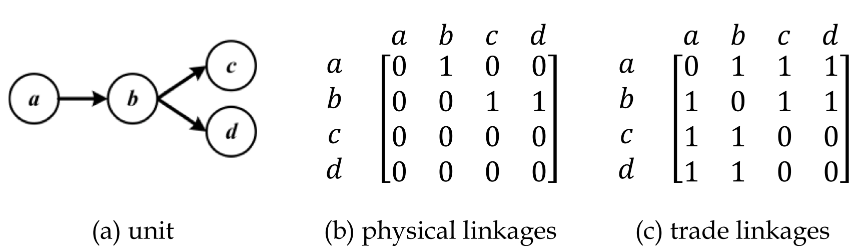
As depicted in Fig. 3(a), gas flows are directly transported in physical network from node *a* to node *b* and then to nodes *c* and *d*. Correspondingly, the linkages between nodes in physical network can be mathematically described as a 0–1 matrix as shown in Fig. 3(b). Therefore, the relationships of gas trades attached to the physical network can be constructed to express the neighboring and cross-regional trades as depicted in Fig. 3(c). It is worth noting that the trade linkage between any two nodes in gas trade matrix is generated through the distribution of natural gas in gas physical network. Therefore, the gas trade matrix indirectly represents the spatial relationship of natural gas allocation in nodes, which is different from those in gravity model and the law of one price.

In addition, the number of linkages in physical gas network is ever-increasing as shown in Appendix A (a) and (c). It will eventually boost gas trades in physical network, thus establishing gas trade network as shown in Appendix A (b) and (d). Physical network tends to evolve from random to small-world network, taking on ever-increasing of the average shortest path and ever-decreasing of agglomeration coefficient. In contrast, the evolution of trade network gradually emerges a double-scale characteristic of small-world and scale-free network, as shown in Appendix B.

### 3.3. Competitive strategies of provincial government

Two policy tools are usually adopted by the government to compete for more natural gas: the investment of provincial pipelines and the provincial environmental regulation. The per-capita investment of pipeline length is used to measure the investment intensity, and the pair-wise differentials of strength between two provinces interconnected by the linkage of trade network are represented as $InNetCom_{ijt}$. The total investment used for environmental governance, after deducting sewage charges, is adopted to weigh the environmental regulation. Similarly, the differentials of the pair-wise investments are expressed as $ERCom_{ijt}$. Therefore, these two kinds of pair-wise differentials are used to build panel data which is introduced into the first border effect model, as shown in Fig. 2.

However, it is difficult to trace the ratchet, scale and asymmetry




$$\begin{array}{c|cccc} & a & b & c & d \\ \hline a & 0 & 1 & 0 & 0 \\ b & 0 & 0 & 1 & 1 \\ c & 0 & 0 & 0 & 0 \\ d & 0 & 0 & 0 & 0 \end{array} \qquad \begin{array}{c|cccc} & a & b & c & d \\ \hline a & 0 & 1 & 1 & 1 \\ b & 1 & 0 & 1 & 1 \\ c & 1 & 1 & 0 & 0 \\ d & 1 & 1 & 0 & 0 \end{array}$$

**Fig. 3.** The unit of natural gas pipeline network and the linkage matrix.

effects from competitive strategies with two kinds of pair-wise differentials. Konisky (2007) and Zhang et al. (2010) studied the three effects based on strategic interaction model, and then proposed four kinds of strategies, including Race-to-Up (*RtU*), Race-to-Down (*RtD*), Strong-to-Weak (*StW*) and Weak-to-Strong (*WtS*). Following their work and inspired by Shen and Zhou (2020), we develop four kinds of strategies from the prior Bayesian decision theory as shown in Table 1. For example, $\Delta ER_{j,t-1} = ERCom_{j,t-1} - ERCom_{j,t-2}$ denotes the differential of environment regulation (*ER*) of *j* from *t-2* to *t-1* and $\Delta ER_{i,t} = ERCom_{i,t} - ERCom_{i,t-1}$, which is the differential of *ER* of *i* from *t-1* to *t*. If $\Delta ER_{j,t-1}$ and $\Delta ER_{i,t} < 0$, the government *i* tends to follow rival *j* and exercises the strategy *RtU*, by observing rival's historic decision-making. Panel data of strategies are introduced in the second border effect model, moderating model, and logit model, respectively.

### 3.4. Hypothesis and econometrics models

Four hypotheses are proposed in Fig. 2. In this section, the hypotheses will be explained in detail by the econometrics models as follows.

**H1**. *The natural gas pipeline network is changing from random network to scale-free network with small-world effect, which has shifted the border effect from geographical space to gas network.*

The first border effect model is developed as Eq. (1).

$$P_{ijt} = \alpha + \beta NetDis_{ijt} + \theta TradeNet_{ij,t-1} + \gamma Border_{ij} + \delta X_{ijt} + \lambda_i + \mu_t + \varepsilon_{ijt} \quad (1)$$

The explanatory variable $TradeNet_{ij,t-1}$ is a 0–1 variable used for representing the trade linkages between two provincial markets *i* and *j* in gas trade network as depicted in Fig. 3(c). In China, the long-distance pipelines are built year by year in sections. Generally speaking, there is a one-year lag in time for the government to build local pipelines which are linked to the long-distance pipelines. Therefore, the time lag of $TradeNet_{ij}$ is introduced in Eq. (1) and could overcome the endogeneity which is produced by reverse causality from $P_{ijt}$ (Ren et al., 2019). The transportation cost is denoted as $NetDis_{ijt}$ and can be calculated as $NetDis_{ijt} = ln(Dis_{ij})/ln(NetAccess_t)$. The $Dis_{ij}$ is the geographical distance between provinces *i* and *j*; $NetAccess_t$ is the shortest average path of gas network in the year *t* (Keeble et al., 1982; Bowen, 2000). Therefore, the cost implies the accessibility of gas trade network. Moreover, $Border_{ij}$ is a 0–1 variable which dominates the neighboring border in geographical space.

A series of controls $X_{ijt}$ are in Eq. (1), and they are composed of the differences of natural gas consumption $NGC_{ijt}$, per capita gross domestic product $PGDP_{ijt}$ and two competitive tools $ERCom_{ijt}$ and $InNetCom_{ijt}$ between two provincial markets *i* and *j* at time *t*. $\lambda_i$ denotes specific fixed effect and $\mu_t$ denotes time fixed effect. $\varepsilon_{ijt}$ is error term, and $\varepsilon_{ijt} \sim iid$. Additionally, these variables $NGC_t$, $PGDP_t$, $ERCom_t$ and $InNetCom_t$ are used as "shifters" to reshape the demand curves as seen in Fig. 1. The time in these control variables is not expressed by a time lag of one or two periods, but by the current period. This is because the supplier spatially allocates natural gas in any two markets based on the existing demand curves, as depicted in Fig. 1. Otherwise, the supplier dynamically allocates natural gas, and obtains the equilibrium prices at *t* and *t*+1, instead of the spatial equilibrium prices in two markets at time *t*. What's more, the robustness test on these control variables, as seen in Appendix E, confirms the above theoretical analysis in section 3.1.

**Table 1**
Environmental competitive strategies of the provincial government.

| learning and imitating | strategies |
|---|---|
| $\Delta ER_{j,t-1} > 0, \Delta ER_{i,t} > 0$ | Race-to-Up (*RtU*) |
| $\Delta ER_{j,t-1} < 0, \Delta ER_{i,t} < 0$ | Race-to-Down (*RtD*) |
| $\Delta ER_{j,t-1} < 0, \Delta ER_{i,t} > 0$ | Strong-to-Weak (*StW*) |
| $\Delta ER_{j,t-1} > 0, \Delta ER_{i,t} < 0$ | Weak-to-Strong (*WtS*) |

**H2**. *once provincial governments enter into gas trade network, their competitive strategies will be attached to the arcs of the network, resulting in the heterogeneity of the border effects on the arcs.*

The interaction items of $TradeNet_{ij,t-1} \times ERCom^k_{ijt}$ and $TradeNet_{ij,t-1} \times InNetCom^k_{ijt}$ are used to substitute $TradeNet_{ij,t-1}$ in Model 1. It means that the provincial government competitions are decomposed structurally into the arcs on gas trade network. And then, Model 2 is further developed to examine the border effects from the competitive strategies, as shown in Eq. (2). The continuous variables $ERCom^k_{ijt}$ and $InNetCom^k_{ijt}$ express the competitive intensity. It is easier to measure the response of competitive intensity to the dynamic linkages of the arcs with these two continuous variables rather than the dummy variables.

$$\begin{aligned} P_{ijt} &= \alpha + \beta NetDis_{ijt} + \theta^E_k \underbrace{\left(TradeNet_{ij,t-1} \times ERCom^k_{ijt}\right)}_{\text{environmental regulation competition}} \\ &+ \theta^E_k \underbrace{\left(TradeNet_{ij,t-1} \times InNetCom^k_{ijt}\right)}_{\textit{competition of network investment}} + \gamma Border_{ij} + \delta X_{ijt} + \lambda_i + \mu_t + \varepsilon_{ijt} \end{aligned} \quad (2)$$

**H3**. The marginal effects of market segmentation from government competition not only comes from the border effect of gas trade network, but also is dynamically moderated by the evolution of network structure.

The moderating effect model is advanced in Eq. (3), with the three network's attributes out-degree ($OutDegree_{it}$), in-degree ($InDegree_{it}$) and betweenness degree ($BetDegree_{it}$) taken into account. Moreover, they are interacted with $ERCom^k_{ijt}$ and $om^k_{ijt}$ , respectively. These three attributes could be employed to measure the aggregation, diffusion and integration of resources allocation in a niche market which is composed of the nodes centered on a node in gas trade network. The attributes moderate the marginal effect of market segmentation from the competitive strategies. Therefore, Model 4 is developed, as shown in Eq. (4), to investigate whether this marginal effect will spread along the directed arcs in gas trade network or not.

$$\begin{aligned} P_{ijt} &= \alpha + \beta NetDis_{ijt} + \theta^E_k \left(TradeNet_{ij,t-1} \times ERCom^k_{ijt}\right) \\ &+ \theta^I_k \left(TradeNet_{ij,t-1} \times InNetCom^k_{ijt}\right) + \rho^E_k \left(OutDegree_{it} \times ERCom^k_{ijt}\right) \\ &+ \sigma^E_k \left(InDegree_{it} \times ERCom^k_{ijt}\right) + \varphi^E_k \left(BetDegree_{it} \times ERCom^k_{ijt}\right) \\ &+ \rho^I_k \left(OutDegree_{it} \times InNetCom^k_{ijt}\right) + \sigma^I_k \left(InDegree_{it} \times InNetCom^k_{ijt}\right) \\ &+ \varphi^I_k \left(BetDegree_{it} \times InNetCom^k_{ijt}\right) + \gamma Border_{ij} + \delta X_{ijt} + \lambda_i + \mu_t + \varepsilon_{ijt} \end{aligned} \quad (3)$$

$$\begin{aligned} \frac{\partial P_{ijt}}{\partial ERCom^k_{ijt}} &= \underbrace{\theta^E_k TradeNet_{ij,t-1}}_{\textit{Moderating effects of arcs}} \\ &+ \underbrace{\rho^E_k OutDegree_{it} + \sigma^E_k InDegree_{it} + \varphi^E_k BetDegree_{it}}_{\textit{Moderating effects of nodes}} \end{aligned} \quad (4)$$

**H4**. *The choice of competitive government strategies follows the principle of maximizing marginal utility of market segmentation to adapt to the dynamic changes of network structure.*

Essentially, the marginal value $\frac{\partial P_{ijt}}{\partial ERCom^k_{ijt}}$ in Model 4 is the marginal rent from the provincial competition, and can be viewed as the utility of the competitive strategy. Therefore, if it is inserted into the utility function of the logit model, the model could be used to gain insight into the adaptive choice of the competitive strategies in gas trade network, as shown in Model 5 and Model 6 formulated in Eq. (5) and 6, respectively. The government *i* chooses an environmental strategy *k*, yielding the utility $U^E_{ik}$ which could be decomposed into the observable utility $V^E_{ik}$

with the unobservable random utility $\varepsilon_{ik}^E$, namely $U_{ik}^E = V_{ik}^E + \varepsilon_{ik}^E$. Here, the observable utility $V_{ik}^E$ is equal to the marginal value $\frac{\partial P_{ijt}}{\partial \chi_{ijt}^k}$ in Model 4, and the $U_{ik}^E$ could be expressed as Eq. (5):

$$U_{ik}^E = \theta_k^E Trade + \rho_k^E OutDegree_{it} + \sigma_k^E InDegree_{it} + \varphi_k^E BetDegree_{it} + \varepsilon_{ik}^E \tag{5}$$

Taking the two strategies choice as an example, the government $i$ will choose the environmental strategy 1 if and only if $U_{i,1}^E > U_{i,2}^E$. And then the probability can be estimated by Model 6, as shown in Eq. (6).

$$\begin{aligned} prob\left(U_{i,k=1}^E > U_{i,k=2}^E\right) &= prob\left(V_{i,k=1}^E - V_{i,k=1}^E > \varepsilon_{i,k=2}^E - \varepsilon_{i,k=1}^E\right) \\ &= prob\Big[\left(\theta_1^E - \theta_2^E\right) TradeNet_{ij,t-1} + \left(\rho_1^E - \rho_2^E\right) OutDegree_{it} \\ &\quad + \left(\sigma_1^E - \sigma_2^E\right) InDegree_{it} + \left(\varphi_1^E - \varphi_2^E\right) BetDegree_{it} \\ &\quad > \varepsilon_{i,k=2}^E - \varepsilon_{i,k=1}^E\Big] \end{aligned} \tag{6}$$

The multinomial logit Model (MNL) assumes that the strategies should satisfy IIA (McFadden, 1987), referring to $(\varepsilon_{i,k=2}^E - \varepsilon_{i,k=1}^E) \sim Logistic(0, \sigma^2)$. And then, the probability of the government chooses strategy 1 could be estimated by Model 7, as shown in Eq. (7). In addition, the logit model assumes that the error term is logit distribution but not the normal distribution. The maximum likelihood estimation (MLE) will be adopted in the logit Model.

$$prob_{i,k=1}^E = \frac{exp\left(V_{i,k=1}^E\right)}{\left[exp\left(V_{i,k=1}^E\right) + exp\left(V_{i,k=2}^E\right)\right]} \tag{7}$$

### 3.5. Data description

The gas price data is from CEIC database. To avoid the effect from inflation on the analysis results, the price data is reduced by the 2000 price index. Data on natural gas consumption, GDP, environmental investment, and length of provincial pipelines derives from China's provincial statistical yearbooks and National Bureau of Statistics from 2004 to 2018. The data of natural gas pipeline network comes from the statistical yearbooks of CNPC, SINOPEC and CNOOC.

The kernel density curves of the variables $P_{ij}$, $ERCom_{ij}$, $InNetCom_{ij}$, $NGC_{ij}$ and $PGDP_{ij}$ are shown in Appendix C. The mean of $P_{ij}$ increases from 2008 to 2013, and gradually decreases after 2013, which is similar to the $ERCom_{ij}$. The curves of all these variables follow the single-peak distributions. Therefore, the results of mean estimation in above-proposed models are approximately unbiased. On the contrary, the curves of $InNetCom_{ij}$, $NGC_{ij}$ and $PGDP_{ij}$ move to the right, which indicate their differences are being widened. This means that the layout of natural gas allocation in China will be gradually changed by these differences. However, the curves of $P_{ij}$ and $ERCom_{ij}$ move slightly to the left. That is, as the differences of $InNetCom_{ij}$, $NGC_{ij}$ and $PGDP_{ij}$ increase, the market tends to move from segmentation to integration. Meanwhile, the competition of provincial environmental regulation is also weakening.

## 4. Empirical analyses

### 4.1. Identification of border effects on gas trade network

In this section, the panel data from 2003 to 2017 is divided into two panels before 2010 and after 2010. And the Model 1 is used to economically examine the border effects when gas trade network evolves from random to small world or scale-free networks. The results are listed in Table 2.

The coefficients of $Border_{ij}$ are significantly negative while their absolute values decrease after 2010. These phenomena show that the gas markets between geographical neighboring provinces are integrated. However, the decrease means that the larger-scale gas trade is gradually shifted from geography to gas physical network, which could be observed from the positive coefficient of $TradeNet_{ij,t\text{-}1}$ in columns (3) and (4) as shown in Table 2. Moreover, the coefficient of $TradeNet_{ij,t\text{-}1}$ indicates the congestion rents on the arcs in gas trade network have produced the price gaps which segment the gas market, as shown in Fig. 1 (b). Meanwhile, the coefficient of $ERCom_{ijt}$ is significantly positive after 2010, indicating that the governments intervene the gas trade network to compete for more natural gas through environmental regulation.

**Table 2**
The estimation of the border effects on gas trade networks.

| | 2003–2010 | | 2011–2017 | |
|---|---|---|---|---|
| | (1) | (2) | (3) | (4) |
| $NetDis_{ijt}$ | 0.0739*** | 0.0607*** | 1.4717*** | 1.4276*** |
| | (0.0192) | (0.0172) | (0.2496) | (0.2503) |
| $TradeNet_{ij,t\text{-}1}$ | 0.0172 | 0.0121 | 0.4493** | 0.4391** |
| | (0.0401) | (0.0394) | (0.1542) | (0.1543) |
| $Border_{ij}$ | −0.0761*** | −0.0765*** | −0.1627*** | −0.1612*** |
| | (0.0127) | (0.0125) | (0.0305) | (0.0303) |
| $ERCom_{ijt}$ | −0.0055 | −0.0050 | 0.0432*** | 0.0433*** |
| | (0.0048) | (0.0046) | (0.0080) | (0.0080) |
| $InNetCom_{ijt}$ | 0.0039 | 0.0050 | −0.0006 | −0.0004 |
| | (0.0049) | (0.0049) | (0.0078) | (0.0078) |
| $NGC_{ijt}$ | | 0.0147*** | | 0.0383*** |
| | | (0.0041) | | (0.0081) |
| $PGDP_{ijt}$ | | −0.7478*** | | 0.1105 |
| | | (0.1291) | | (0.1499) |
| Constant | 0.5329*** | 3.0932*** | −2.4917** | −3.6378* |
| | (0.1121) | (1.3184) | (0.8188) | (1.7897) |
| Trend | ✓ | ✓ | ✓ | ✓ |
| Time-fixed | ✓ | ✓ | ✓ | ✓ |
| Individual-fixed | ✓ | ✓ | ✓ | ✓ |
| N | 6960 | 6960 | 6090 | 6090 |
| adj-$R^2$ | 0.3281 | 0.3420 | 0.2528 | 0.2556 |

Notes: This table reported the estimated border effects of network. Heteroscedasticity-Robust Standard Errors are reported in parentheses. ***. $p < 0.001$. **. $p < 0.01$. *. $p < 0.1$.

It is worth noting that $NGC_{ijt}$ does segment natural gas market in the perspective of geography and network, because there is a shortage of natural gas supply in China, and the greater the coefficient of $NGC_{ijt}$, the greater the scarce rent of gas resources. The resource rents are the main source of market segmentation, and will increase because of environmental regulation which could be explained in Fig. 1(a). Therefore, the border effect model could be used to identify the resource and the congestion rents along the arcs in gas trade network.

In addition, permutation test is carried out to examine the robustness of the border effect model (as shown in Appendix D). The results of Model 1 are robust with the statistically significant difference between 0 and 0.157. We test the lag effect of all variables in Model 1 (seeing Appendix E) and find that there is a lag effect of long-distance pipeline network structure, while lag effects of other variables are insignificant.

### 4.2. Heterogenous border effects of provincial competitions

The Model 2 is used to estimate the border effects of the $ERCom_{ijt}$ and $InNetCom_{ijt}$ to observe whether the government segments gas trade network after 2010 or not, and then to explore the heterogenous border effects of the four strategies along the arcs on the network. The results are shown in Fig. 4.

If we compare the coefficients of $ERCom_{ijt}$ and $InNetCom_{ijt}$ in Model 1 and Model 2, respectively, as shown in Tables 1 and 2, we find that the coefficient of $ERCom_{ijt}$ is larger in Model 2 while the coefficient of $InNetCom_{ijt}$ changes from insignificant to negative significant. These two phenomena can be observed from the two interactions ($TradeNet_{ij,t-1} \times ERCom_{ijt}$ and $TradeNet_{ij,t-1} \times InNetCom_{ijt}$) in Model 2. Thus, the average border effects of $ERCom_{ijt}$ and $InNetCom_{ijt}$ are decomposed by the $TradeNet_{ij,t-1}$ into the arcs. Furthermore, the positive border effect of $TradeNet_{ij,t-1} \times ERCom_{ijt}$ indicates that gas trade market will be segmented by environmental regulation along the arcs, which

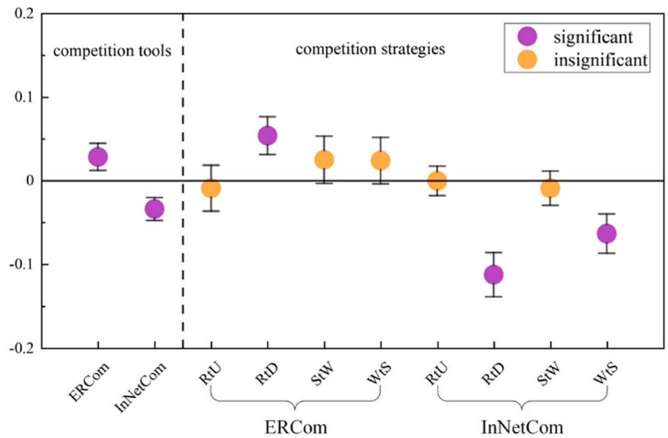



**Fig. 4.** The border effects of the competitive tools and strategies (Notes: the circles in this Figure indicate the interactive coefficients between competitive tools and strategies, and *TradeNet* is omitted in this Figure).

can be attributed to the fact that higher resource rent ($\lambda$) is generated by the strengthening environmental regulation as illustrated in Fig. 1 (a). In contrast, the negative effect of $TradeNet_{ij,t-1} \times InNetCom_{ijt}$ shows the pipeline investments reduce the congestion rents ($\eta$) on the arcs a, as illustrated in Fig. 1 (b).

Additionally, it could be observed that the coefficients of the four competitive strategies exhibit the heterogeneity of the border effects. The coefficient of the strategy *RtD* in the $ERCom_{ijt}$ is significantly positive while those of other three strategies are insignificant. This means that the border effect of $ERCom_{ijt}$ is dominated by the strategy *RtD*. Once the *RtD* strategy is adopted, the two curves in Fig. 1(a) shift downward, and the two governments linked by an arc have the incentive to reduce resource rents ($\lambda$) by decreasing the intensities of their environmental regulations, so as to obtain premium natural gas. Although this strategy can reduce the natural gas market segmentation, it is not beneficial for the natural gas consumption.

On the contrary, it is not the coefficients of other two strategies but the investment strategies *RtD* and *WtS* in the $InNetCom_{ijt}$ that are significantly negative, showing that the border effects of $InNetCom_{ijt}$ is in charge of the strategies *RtD* and *WtS*. It is because the construction of long-distance pipeline accelerated the evolution of gas trade network from the small-word to the scale-free network from 2011 to 2017. The preferential linkage of scale-free network encouraged the governments to intervene the small-world network at lower local pipeline investment. These two strategies adopted by the government indicate that the government is willing to take the "free-riding" with less pipeline investment to obtain more natural gas.

Undoubtedly, the border effect is the externality of the resource and congestion rents generated by the provincial competitions. Governments' competitions, as nodal attribute data, in gas trade network change the spatial distribution relationships of natural gas resources in gas trade network. Meanwhile, the four competitive strategies change resource rents and congestion rents on the arcs in different ways, which contributes to the heterogenous border effects. Moreover, the heterogenous border effects suggest that the structural change of gas trade network should be considered because there is more than one node linked to a node. What's more, two control variables $NGC_{ijt}$ and $PGDP_{ijt}$ were also added to Model 2, to test the robustness of the estimated results. There was no significant difference between re-estimated results and the above, proving the robustness of the above results.

### 4.3. Moderating effects of gas trade network's structure

To gain insight into the insignificant border effects of the strategies as shown in Fig. 4, we separate three attributes of nodes (*BetDegree*, *OutDegree* and *InDegree*) from the linkages $TradeNet_{ij,t-1}$. Therefore, Models 3 and 4 are used to investigate whether the border effects of the competitions are moderated by the structure of gas trade network in the perspective of the arcs and nodes. The coefficient $\theta$ is the moderating effect of the arcs $TradeNet_{ij,t-1}$ on the four strategies which are given in the bottom of Fig. 5. The coefficients φ、ρ and σ which are denoted as the green or blues circles are also the moderating effects of a node with the three attributes on the four competitive strategies.

The moderating effect coefficients of the three strategies $RtU(\theta_{RtU})$, $RtD(\theta_{RtD})$ and $StW(\theta_{StW})$ on the acres are significant positive, as seen in Fig. 5(a). It indicates that once a new arc is produced, the existing border effects of these three strategies of environmental regulation will display positive marginal increase, which could be explained by the evolution of gas trade network structure. When the gas network evolves from small-word to scale-free network, more and more linkages $TradeNet_{ij,t-1}$ will change from 0 to 1, that is, there will be more new linkages between two nodes in gas trade network. The newly-increased linkages will trigger new provincial competitions, and increase the resource rents. This phenomenon will finally be spread to the whole gas trade network. Eventually, the spread of border effects redistributes the resource rents and congestion rents on the network, restructuring the relationships of natural gas allocation on the trade network.

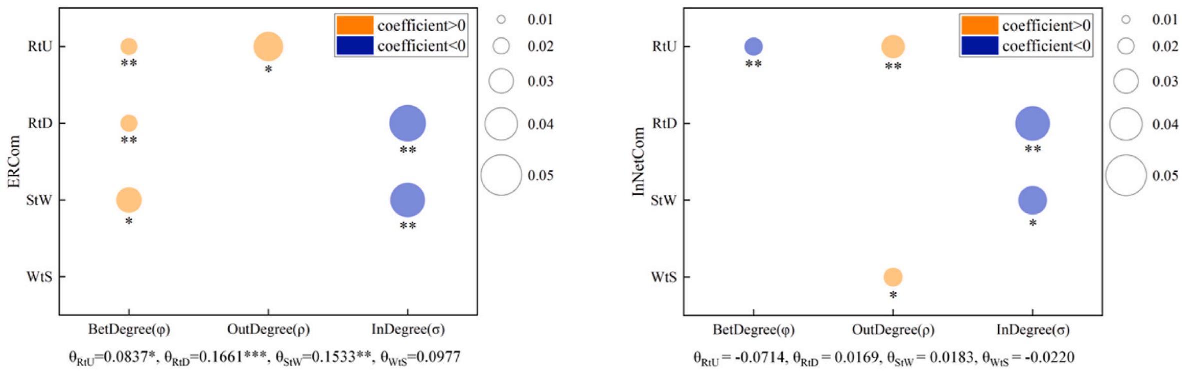
However, we are surprised to find that the moderating effects of the arcs on the four competitive strategies from pipeline investment are insignificant while those of the nodes are significant, but smaller than those of the arcs. These two phenomena suggest that the spread of the border effects along the arcs might be adjusted locally by nodes. Furthermore, we investigate the moderating effects of three attributes of a node in the niche market on the border effects of the competitive provincial strategies.

The *BetDegree* plays a positive role in moderating the border effects of the strategies of environmental regulation: *RtU*, *RtD*and *StW*, as shown in Fig. 5(a). In fact, the border effects generated by the three strategies will be transferred to other nodes in local trade network by a node with higher *BetDegree*, incurring the overlay of the border effects on the arcs. As a result, the overlay will adjust natural gas distribution in this niche market. Similarly, the border effect of the strategy of pipeline investment *RtU* is negatively moderated by the *BetDegree* since the congestion rent could be reduced by the investment competition, as shown in Fig. 1 (b).

Moreover, the *OutDegree* plays an active role in moderating the border effects of the competitive environmental regulation strategy *RtU* and the two competitive strategies of pipeline investment (*RtU* and *WtS*). It is more likely for a node with higher *OutDegree* to obtain more natural gas when the natural gas flows to downstream nodes in the niche market. The government located at this node usually employs the above three competitive strategies to increase the resource or congestion rent to retain more natural gas. It should be noted that the moderating effects of the two pipeline investment strategies (*RtU* and *WtS*) are positive, which means the congestion rent will increase slightly.

As shown in Fig. 5, contrary to the moderating effects of *OutDegree*, the effect of *InDegree* on the two strategies (*RtD* and *StW*) is negative because a node with higher *InDegree* will diversify gas supply from more upstream nodes. The diversity provides the node with more gas supply channels, which is likely to unblock pipeline transportation, and then decreases the congestion rents. Meanwhile, the diversity not only avoids constraint from gas supply of a single upstream node, but also decreases the barriers of the resource rents from the environmental regulation. Therefore, the resource and congestion rents in the niche market will decrease slightly because of the moderating effects of *InDegree*, providing a small boost to the gas market integration.

It can be seen from above results in this section that the moderating effects of the structure of gas trade network deviate the competitive strategy adopted by the governments from their expectations. Although the resource rents increase as the number of linkages rises, the resource




(a) Environmental regulation competition

(b) Pipeline investment competition

**Fig. 5.** The moderating effects produced by gas network structure and node.

rents, when crossing nodes, or hedged by the marginal reduction of congestion rent, will be redistributed optimally by nodes in the niche market. Therefore, the integration of the niche market will contribute to the integration of the whole gas market from segmentation.

### 4.4. Self-adaptive choices of the competitive strategies

As mentioned in Section 4.3, the moderating effects of network structure is the marginal value of the border effect of competitive strategy, which may affect the choice of the existing competitive strategies. Therefore, Models 6 and 7 are used to investigate the response of provincial competitive strategies to the change of network structure. For this reason, we mainly focus on the influence of the *BetDegree*, *OutDegree* and *InDegree* of the node attribute on the changing of competitive strategies because when making decisions on competitive strategies, the governments have to consider the games between their strategies and the strategies located at other nodes.

It is necessary to check whether independent IIA assumption is satisfied before the logit model is applied to the choices of competitive strategy. One of the four strategies *RtU*, *RtD*, *StW* and *WtS* was selected as the baseline group to test whether it is independent from other three strategies, and the results are shown in Table 3. The $Chi^2$ of the strategy *RtU* and other three strategies are greater than 0 while there are coefficients less than 0 in IIA Test of strategies *RtD*, *StW* and *WtS*. Hence, *RtU* is selected as the baseline strategy for environmental regulation strategies. Similarly, *RtD* is also selected as the baseline strategy for pipeline investment strategies. And then, the migration paths of the four competitive strategies of the environmental regulation and pipeline investment are illustrated in Fig. 6.

If we examine the migration paths of environmental regulation competitive strategies, the migrations of strategies are centered on the strategy *RtU,* as shown in Fig. 6. An increase in the *BetDegree* would produce three mitigation paths: *RtU*→*RtD*, *RtU*→*StW*, and *WtS*→*RtU* with the odds of 1.02, 1.03 and 1.05, respectively. Obviously, the governments are willing to migrate from strategy *RtU* to *RtD* and *StW*, because the odds of migrating from these two migrations are higher than those from *WtS* to *RtU* when the moderating effect of the *BetDegree* takes place. Actually, the governments should also realize that relaxing environmental regulation will reduce the resource rents, which will lower the market price and eventually make it easier for them to obtain more natural gas. Similarly, this migration mechanism can also explain the role of *OutDegree* and *InDegree* in the strategy migration from *RtU* to *RtD* and *StW*. Therefore, as these three attributes increase, the governments will have to migrate the competition of environmental regulation because the resource rent generated by environmental regulation competition will raise the market price, conversely reducing the gas supply by the suppliers, as seen in Fig. 1(a).

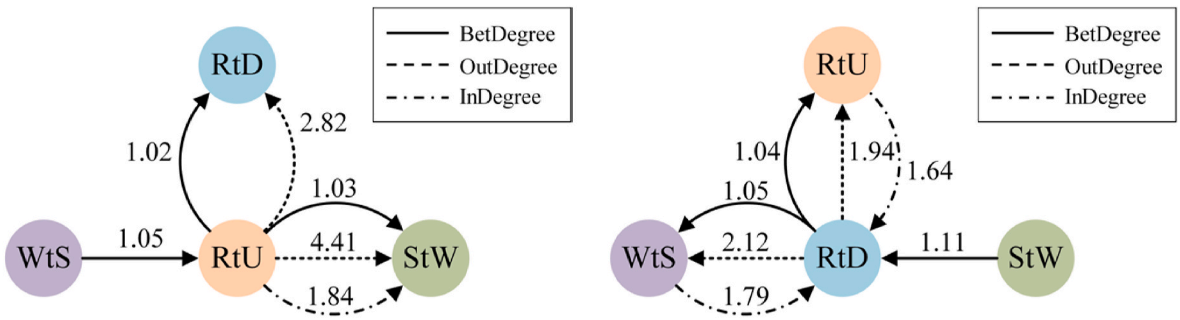
The pipeline investment competition has migrated from strategy *RtD* to *RtU* and *WtS* for the *BetDgree* and *OutDegree.* The governments realize that it is better to increase pipeline investment rather than change the competitive strategy when *BetDgree* and *OutDegree* increase as shown in Fig. 6(b) because they employ these two attributes of nodes to dominate natural gas allocation in niche market. Therefore, the increase of pipeline investment will reduce the congestion rents produced by pipeline bottleneck, so that the governments have access to more natural gas. However, the migration paths from strategies from *RtU*, *WtS* and *StW* to *RtD* are moderated by the *InDgree*. As mentioned in section 4.2, the greater the *InDgree* of a node, the more natural gas it can obtain from more upstream nodes in the niche market. Therefore, the government shows more willingness to reduce its own pipeline investment, and then gets free or lower congestion rent from the pipeline investment from upstream nodes.

It can be concluded that once the nodes change the marginal rents of the resource and congestion rents from the competitive strategies, the variations of the marginal rents will drive the suppliers to redistribute gas flows, which will update the spatial relationships of gas allocation in the niche market. Therefore, the marginal rents provide market signals for the governments to adapt their competitive strategies to the structural change of gas trade network. Moreover, the self-adaptive choice of the competitive strategies suggests the competitions will boost the

**Table 3**
IIA test results.

| Benchmark strategies | Environment regulation competition | | | | Pipeline network investment competition | | | |
|---|---|---|---|---|---|---|---|---|
| Selected Strategies | RtU | RtD | StW | WtS | RtU | RtD | StW | WtS |
| *RtU* | – | −0.31 | 3.51 | 4.36 | – | 5.17 | −3.65 | 7.03 |
| *RtD* | 5.15 | – | 5.21 | 9.21 | 8.34 | – | 5.84 | 4.12 |
| *StW* | 9.63 | 1.36 | – | −3.55 | 6.98 | 1.27 | – | −2.98 |
| *WtS* | 2.34 | 5.33 | −1.87 | – | −4.01 | 9.23 | 6.12 | – |

Notes: H0: the baseline strategy is related to other strategies. If $Chi^2$ of the Hausman test is greater than 0, H0 will be rejected, meaning that two strategies satisfy the IIA hypothesis; otherwise, H0 will be accepted, meaning that two strategies don't satisfy the IIA hypothesis.




(a). Environmental regulation competitive strategy (b). Pipeline investment competitive strategy

**Fig. 6.** The mitigation paths of the four competitive strategies driven by the three attributes of nodes: the *BetDegree*, *OutDegree* and *InDegree*.. (Notes: the numbers located on the arcs are multiples of the increase in odds, and the arrows refer to the migrated direction of the strategies.)

integration of the niche market. An incentive-compatible mechanism should be established in the niche market to improve the allocation efficiency of natural gas.

## 5. Conclusions and implications

We regard the provincial competition as a key variable in China's natural gas market, and theoretically explain the resource and congestion rents. The rents derive from provincial competitions which also lead to gas market segmentation. Furthermore, we also choose the price difference resulted from the rents as dependent variable of the border effect model, and then propose an econometric framework to empirically analyze the mechanism of the border effect from provincial competition on gas trade network. The main conclusions are as follows:

(1)Provincial competitions change the relationships of natural gas resource allocation by redistributing resource and congestion rents through policy tools: environmental regulation and pipeline investment competitions. The former increases resource rents which encourages suppliers to supply more natural gas to the markets with higher marginal revenue. However, the latter reduces the congestion rents which guide suppliers to make an arbitrary between markets with low marginal revenue and markets with higher marginal revenue until all markets have equal marginal revenue. Therefore, the competitions can't really achieve local protectionism because they could not control natural gas supply.
(2)The border effect is the externality of the resource and congestion rents which are generated by the competition, and then the heterogeneity of the effects is attributed to the allocation relationships changed by competitive strategies in different ways on gas trade network. As node attribute data, the competition spatially redistributes the existing resource and congestion rents on gas trade network. When the border effect is decomposed into each arc of gas trade network, we can observe that the allocation relationship between any two markets is adjusted by the competitive strategies through the border effect. Therefore, this adjustment creates the heterogeneity of the border effects and reconstructs the spatial allocation relationships on gas trade network.
(3)The governments actively adjust their competitive strategies to adapt to the dynamic of gas trade network structure for maximizing their marginal revenue or odds. Most of the competitive strategies will be self-adaptively migrated to the strategies which reduce the resource and congestion rents in the niche market. Therefore, in a node-centered niche market, provincial competition, whether it is environmental regulation or pipeline investment competition, will reduce the resource and congestion rents in local networks and improve the integration degree of the niche market. Consequently, the competition endogenously drives the integration of natural gas market from segmentation in China.

Some implications are as follows:

(1)The market-oriented reform of China's natural gas market should take natural gas consumption into account in policymaking. Although environmental regulations have segmented natural gas market, they have promoted the large-scale growth of natural gas consumption. The pipeline investment not only optimizes the structure of gas pipeline network, but also expands the scope of natural gas market. Therefore, policymakers should evaluate the short-term and long-term effects of the provincial competition on market-oriented natural gas reform and deregulate natural gas market step by step, to avoid excessive competition to promote the sustainable development of natural gas market.
(2)China's natural gas market should increase natural gas supply and speed up the infrastructure construction to gradually resolve the contradiction between efficiency and environmental performance. Objectively speaking, natural gas supply shortage and insufficient infrastructure urge the government to strengthen environmental regulation and pipeline investment to compete for more natural gas and improve environmental performance. Therefore, China should continue to increase natural gas supply to reduce resource rent and prevent the government from adopting environmental regulations for more natural gas. In addition, the government should be encouraged to invest in local gas pipeline construction through the signal of congestion rents to reduce market entry barriers.
(3)More regional trading centers should be established to integrate regional gas market. China's natural gas trade network will evolve from small-world to scale-free network with the extension of physical pipeline network, and more nodes with high centrality will gradually appear. That is to say, several niche markets centered on the higher-centrality nodes will gradually emerge in the trade network. Therefore, Chinese central government should speed up the construction of regional natural gas trading centers to help the governments capture the price signals of nodes in time and make the optimal competitive strategy. Although the Chinese central government has established three natural gas and oil trading centers in Shanghai, Chongqing, and Xinjiang, respectively, more sub-centers should be established for the niche markets, so as to better capture the regional price signal for high-efficient allocation of natural gas.

## CRediT authorship contribution statement

**Xiaolin Wang:** Conceptualization, Formal analysis, Funding acquisition, Methodology, Writing – original draft, Writing – review & editing. **Xiangyi Lu:** Data curation, Formal analysis, Methodology,

Software, Validation, Visualization, Writing – original draft, Writing – review & editing. **Jun Chen:** Conceptualization, Formal analysis, Writing – original draft. **Xiangping Hu:** Supervision, Writing – review & editing.

## Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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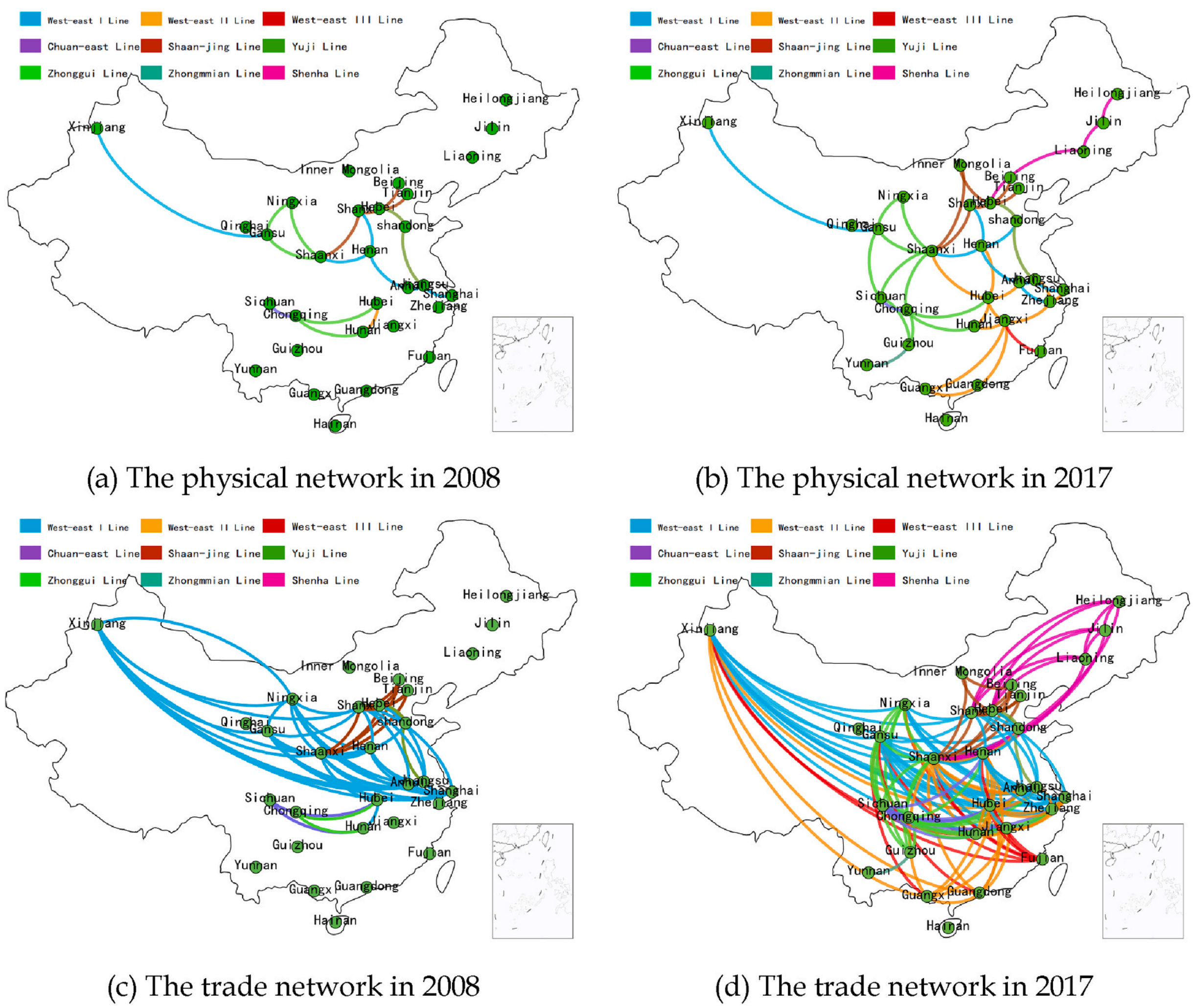
## Appendix A. The physical network and trade network of China's natural gas market




(a) The physical network in 2008

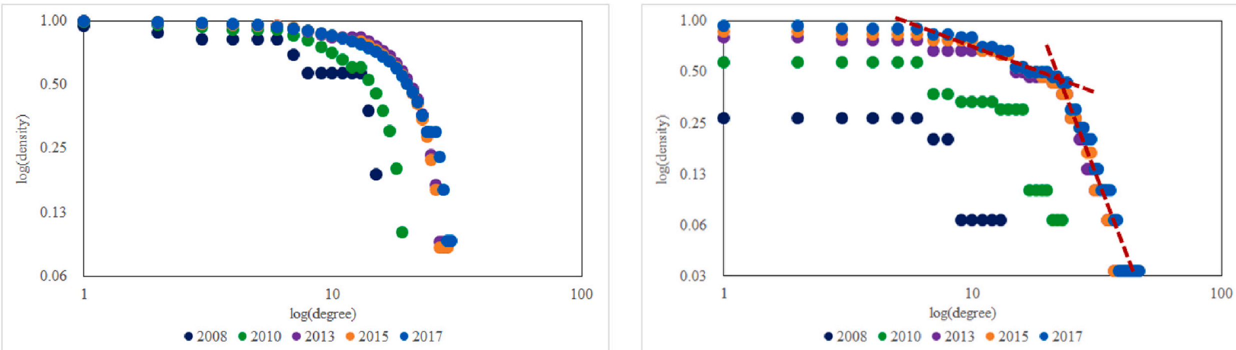
(b) The physical network in 2017

(c) The trade network in 2008

(d) The trade network in 2017

**Fig. A.** The network linkages of physical network and trade network.

## Appendix B. Structural features of physical network and trade network




(a) physical network (b) trade network

**Fig. B.** The degree distributions of physical network and trade network.

**Tab.B**
The average shortest paths and clustering coefficient of networks

| | physical network | | | | | trade network | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | 2008 | 2010 | 2013 | 2015 | 2017 | 2008 | 2010 | 2013 | 2015 | 2017 |
| average shortest path | 2.643 | 2.961 | 3.062 | 3.369 | 3.36 | 1.345 | 1.641 | 1.616 | 1.652 | 1.677 |
| clustering coefficient | 0.389 | 0.443 | 0.431 | 0.390 | 0.366 | 0.952 | 0.814 | 0.786 | 0.797 | 0.789 |

## Appendix C. The kernel density curves of the variables

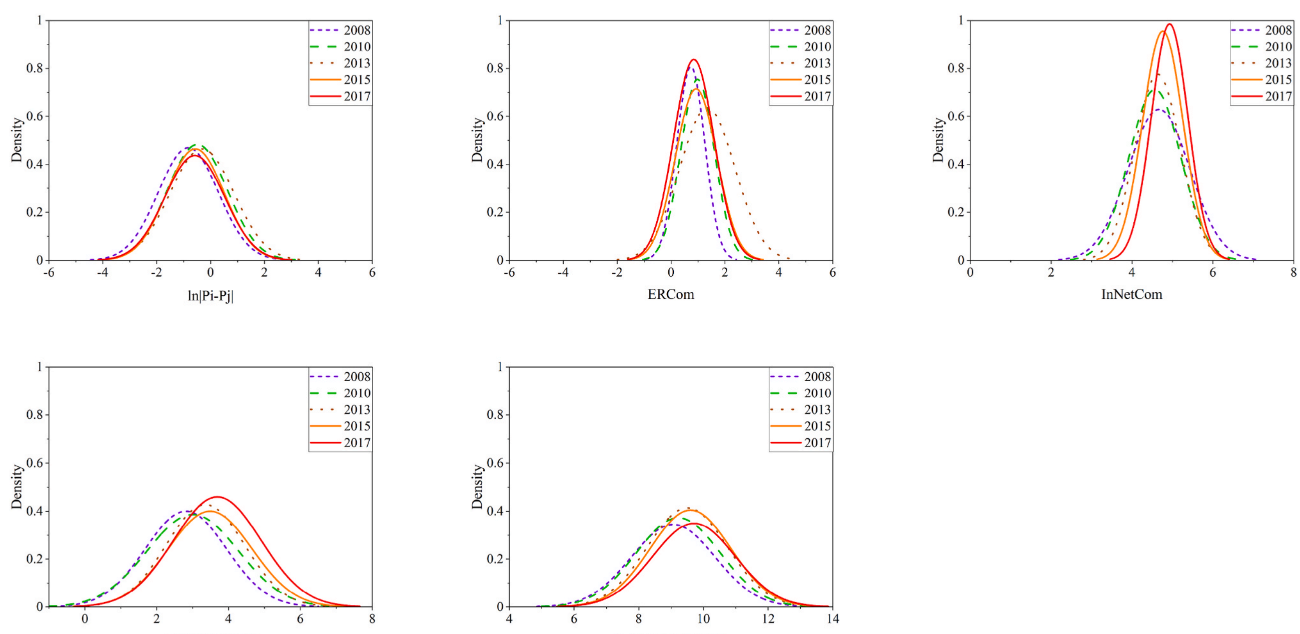



**Fig. C.** The kernel density curves of the variables.

## Appendix D. Robust test of results from Model 1

The permutation test proposed by Anderson and Robinson (2001) is adopted to test the robustness of results. 2140 samples are randomly selected from the full samples of trading network (N = 13050) to construct a random network marked as simulative treatment while the remaining samples were used as the simulative control. After 1000 times of repeated sampling, the distribution of $P_{ijt}$ gap between the simulative treatment and the simulative control was observed (shown in Fig. D-1). Results showed that the mean of $P_{ijt}$ gap between the simulative treatment and the simulative control was close to 0, but the gap between the actual treatment and the actual control treatment group was 0.157. The results of Model 1 were robust with the statistically significant difference between 0 and 0.157.

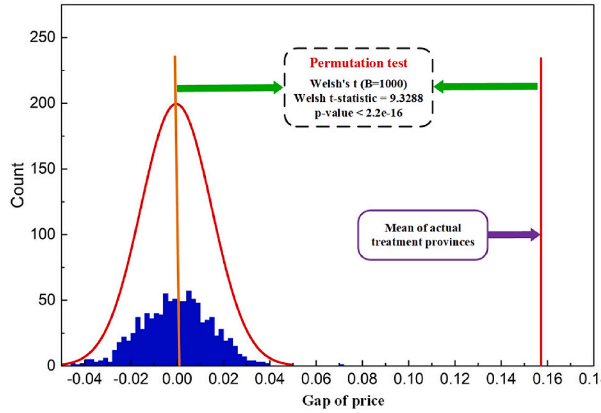



**Fig. D.** Robust test of results from Model 1.

## Appendix E. Test of lag effects

In addition to the theoretical discussion on the network border effect model for the natural gas market in Part III, we have adopted some classical algorithms to identify the lag period of the independent variables in border effect model. The lag period of Eq. (1) is the basis of other models, so the tests take Eq. (1) as the object. The Schwert's rule of thumb 1 provides a definition for the lag period of short panel data (Schwert, 2002). In this study, the statistic $l_4 = int\{4(T/100)^{1/4}\} = 1, when\ T = 16$. Therefore, only first-order lag is employed in tests.

Based on the selection of the lag period of the variables, we construct three models for tests, named Test 1, Test 2, and Test 3. Test 1: all variables are not lagged except the first-order lag of the pipeline network. Test 2: all variables are not lagged. Test 3: first order lag for all variables. ACF and BIC are employed to choose the best setting of lag period. Firstly, based on the ACF test, the time-series autocorrelation of the residuals of the three models is compared to observe which model minimizes the time-series autocorrelation of the residuals. Thus, it is concluded that the model has explained all the lagged effects. Meanwhile, the fitting effects under the three lag period settings are compared based on the BIC criterion. The AIC criterion is not adopted here because it is more suitable for assessing the predictive effect of the model while the BIC is applied to assess the fitting effect of the model (Han et al., 2017). As we place more emphasis on the explanation of how governmental behavior shapes the market equilibrium, the BIC criterion is more applicable. The results of ACF and BIC are as follows.

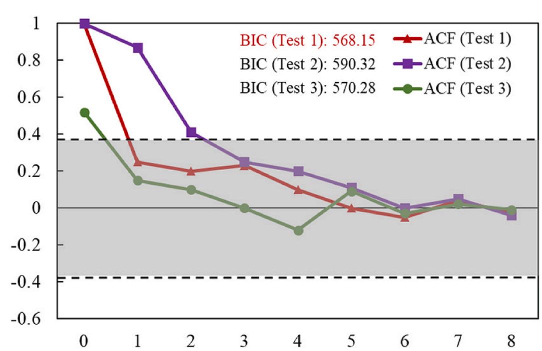



**Fig. F.** ACF and BIC of Model F-1, F-2 and F-3.

Fig.F. presents both the ACF and BIC test results of Test 1–3. It could be seen from the ACF test results that the first-order lag coefficients of Test 1 and Test 3 are insignificant, indicating that the time lag effect is insignificant under these two model settings. This implies that variable lag period choices (one-period lag only for the pipe network pioneered lag for all variables) could explain the time lag effect in the boundary effect model. Furthermore, BIC of Test 1 is smaller from the comparison of the BIC values of Test 1 and Test 3, which indicates that the model with a one-period lag of only the pipe network is better fitted. It can also be explained by the simplicity of the model design that the model setup is simpler for the one-period lag of only the pipe network and there is no information loss. In addition, our theories have implied that environmental regulation competition, pipeline network investment competition, and even economic development competition only affect the current market equilibrium from the perspective of resource allocation in the two regions in the same period. Therefore, the boundary effect model in this paper can explain the time lag effect and eliminate the coefficient estimation bias caused by the lagged variables.

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