Volume 94

Pages 1-1066 (January 2021)

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Previous vol/issue

Next vol/issue

Full text access

Editorial Board

Page ii

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Evidence on time-varying inflation synchronization

Karol Szafranek

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Business and institutional determinants of Effective Tax Rate in emerging economies

Elena Fernández-Rodríguez, Roberto García-Fernández, Antonio Martínez-Arias

Pages 692-702

Download PDF Article preview

Research article Full text access

Investor sentiment and stock price: Empirical evidence from Chinese SEOs

Yueqin Lan, Yong Huang, Chao Yan

Pages 703-714

Download PDF Article preview

Research article Full text access

Explain or conceal? Causal language intensity in annual report and stock price crash risk

Dongmin Kong, Lu Shi, Fan Zhang

Pages 715-725

Download PDF Article preview

Research article Full text access

Shadow prices of industrial air pollutant emissions in China

Yinyin Wu, Jie Yu, Malin Song, Jiandong Chen, Wenxuan Hou

Pages 726-736

Download PDF Article preview

Research article Full text access

Scale-adaptive estimation of mixed geographically weighted regression models

Feng Chen, Chang-Lin Mei

Pages 737-747

Download PDF Article preview

Research article Full text access

Winners and losers of central bank foreign exchange interventions

Research article Full text access

Are loans cheaper when tomorrow seems further?

Christophe Godlewski, Laurent Weill

Pages 1058-1065

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C t t t t D t

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1. Introduction

t 1978, C - t . H , t t t t t t . A t ’ - t tt , C t t t , t t , t , t fi t , , t fl , t t , t t . t t t , t t t . E , t t t t C t . D t t 11t 12t fi - P (2006–2010 2011–2015, t) t 13t F - P (2016–2020), t C t t t t t t t t t t t t t t t. A t t t , t t , (O$_2$) t (NO), t t t t t t t 8–10% fi - P . I t

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10 J 2019; 30 J 2020; A t 6 F 2020
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2. Literature review

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t t t . t -t t t
t t t t t t t t t t. -
t t , T, fi :

$$T = T_1 \cap T_2$$
$$= \{(x^n, x^p, y, y^a, b) \in R_+ : (x$$

T_F T_{MS} t :

$$\begin{aligned}&\max.\pi_y y_o - \pi_{x^n} x_o^n - \pi_{x^p} x_o^p - \omega_b b_o\\&s.t.\pi_y y_i - \pi_{x^n} x_i^n - \pi_{x^p} x_i^p - \omega_b b_i \le 0, i = 1,2,\cdots,n\\&\pi_y \ge \frac{1}{s}[1/y_o]\\&\omega_b \ge \frac{1}{s}[1/b_o]\end{aligned} \tag{8}$$

$$\begin{aligned}&\max.\pi_y y_o - \pi_{x^n} x_o^n - \pi_{x^p} x_o^p - \omega_b b_o + \omega_{x^p} x_o^p\\&s.t.\pi_y y_i - \pi_{x^n} x_i^n - \pi_{x^p} x_i^p \le 0, i = 1,2,\cdots,n\\&-\omega_b b_i + \omega_{x^p} x_i^p \le 0, i = 1,2,\cdots,n\\&\pi_y \ge \frac{1}{s}[1/y_o]\\&\omega_b \ge \frac{1}{s}[1/b_o]\end{aligned} \tag{9}$$

I t E . (6)–(9), y_o, x_o^n, x_o^p, b_o t t t t - t (D M)' t t, t, t t, t t, t . I t , m - t t t t , s t t t t , ω_{x^p} t t t t t T_2. I t t , t - t 1, 2, 3, 4, t .

3.3. Decomposing the shadow prices of pollutant emissions with LMDI

t t ' t t fi , , , t - , t , t (t ., 2013; D t ., 2015). t t t , t t t t t t fl t t t - t t .

It t - t t t - t E . (1) t t, t t t t t t t : t t t - - . t - t t t ($\frac{\partial y}{\partial x^p}$), t t t t t [2] (. ., t). tt t t t ($\frac{\partial b}{\partial x^p}$), t t t t t . C , t t t t t - - t t t . t t t t t t t t - t t t t t. O t t , t t t t , t t t t t t - t t t t t t - - t t. t t , t, - - t t E . (10).

$$\frac{\omega_b}{\pi_y} = \frac{\partial D}{\partial b} \Big/ \frac{\partial D}{\partial y} = \frac{\partial D/\partial x^p}{\partial D/\partial y} \Big/ \frac{\partial D/\partial x^p}{\partial D/\partial b} = \frac{\partial y}{\partial x^p} \Big/ \frac{\partial b}{\partial x^p} = \frac{\pi_{x^p}}{\pi_y} \Big/ \frac{\pi_{x^p}}{\omega_b} \tag{10}$$

It E . (10) t t t t t t, t t t t t t t t . I , t , fi , t t t

[2] I t , t t t t .

t t t t t t t . A t LMDI t t t t t (A , 2015), t t t t t - - t t . fi , t - t t :

$$\begin{aligned}&\Delta sp = \Delta e.s + \Delta e.c\\&\Delta e.s = \frac{sp_t - sp_{t-1}}{\ln(sp_t) - \ln(sp_{t-1})} \ln\left(\frac{e.s^t}{e.s^{t-1}}\right)\\&\Delta e.c = \frac{sp_t - sp_{t-1}}{\ln(sp_t) - \ln(sp_{t-1})} \ln\left(\frac{e.c^t}{e.c^{t-1}}\right)\end{aligned} \tag{11}$$

Δsp t t t t t , $\Delta e.s$ t t t t t t , $\Delta e.c$ t - - t t t t t . sp_t sp_{t-1} t t t t t ; $e.s^t$ $e.s^{t-1}$ t t t t ($\frac{\partial y}{\partial x^p}$) t $t-1$, t ; $e.c^t$ $e.c^{t-1}$ t t t t ($\frac{\partial b}{\partial x^p}$)[3] t $t-1$, t . t - - t t fl t t - t t t t t t t . t t t t , t - t t t t t t t t . A t t (Δsp, $\Delta e.s$, $\Delta e.c$) t t . P t Δsp t t t t , t t t t t . $\Delta e.s$ $\Delta e.c$ t , t t t t t - - t t t t t t , t t t t t . Ot , $\Delta e.s$ $\Delta e.c$ t , t t t t t - - t t t t t t t . I t , Δsp t t , t t t t t t t t, t t t t t t t . F t , Δsp t t , t t t t t t t t t t t t t t t t t t . It t t t t t, t , t . F , N t . (2010) t t - t t t t (GDP). t t . (2011) t t t t - t t t t t C t t . L t . (2017) t t N -t t C - t C . N t , t t fi t t t t t t t t t t t t t t t t t.

3.4. Regression model for testing the effectiveness of environmental regulation stringency

A t t t t t (F t ., 1993; A t H , 2016; H , 2019), t t t t t t - t , fi :

$$\ln emi_{i,t} = \alpha_0 + \alpha_1 \ln sp_{i,t-1} + \alpha_2 \ln^2 sp_{i,t-1} + \alpha_3 \ln ind_{i,t} + \alpha_4 \ln^2 ind_{i,t} + \varepsilon_{i,t} \tag{12}$$

t $emi_{i,t}$ t t t t i

[3] t t t t t, t t $\Delta e.c$ t t t - - t t t t t t t t .

t; $sp_{i,t-1}$ t t t t t-
t 1 i $t-1$, t t -
t , t t t -
(H , 2019); $ind_{i,t}$ t t
i t, t E t K t C (C
t ., 2018; L t ., 2019) t t t
t $ind_{i,t}$. t t ( ) t t t t

Table 2
B t t C ' t .

	C -	C t t t t	K t t
N t t	L , J , H	E t t	L
N t C t	B , , H ,	H -t t t	A
E t C t	, J ,	M t- t t t	A
t C t	F , G , H	E t- t t	G , F
M	, , H , I -M	C ; t t ; t t ,	
M t	H , H , J , A	tt t ; t t H , H t	
G t t t	, G , , C , G	C t t t t ; C t t t , C t t t	
G t N t t	G , , N , , t	E t t ; tt , t, , t t	G , N ,

Table 3
t t t C ' t - 2006, 2011, 2016 t t t (CN /t).

	2006	2011	2016
N t t	(0.0536; 0.0600; 0.1608; 0.1608)	(0.0936; 0.1382; 0.2153; 0.3881)	(0.1787; 0.2707; 0.4282; 0.7587)
N t C t	(0.1506; 0.1794; 0.3232; 0.4565)	(0.2450; 0.2982; 0.6532; 0.7884)	(1.2427; 1.8351; 3.5176; 4.1844)
E t C t	(0.2014; 0.1778; 0.3497; 0.4488)	(0.2872; 0.3531; 0.5392; 0.8681)	(0.6781; 0.9920; 1.9196; 3.0332)
t C t	(0.0727; 0.0915; 0.2610; 0.3723)	(0.1810; 0.2402; 0.3795; 0.7372)	(0.5141; 0.4937; 0.9994; 2.0119)
M	(0.0308; 0.0330; 0.0925; 0.0925)	(0.0599; 0.0990; 0.1281; 0.2694)	(0.2392; 0.2598; 0.7126; 0.8824)
M t	(0.0372; 0.0411; 0.1117; 0.1117)	(0.1108; 0.1753; 0.2253; 0.4501)	(0.2468; 0.4163; 0.6396; 1.3885)
G t t t	(0.0295; 0.0318; 0.0885; 0.0885)	(0.0862; 0.1129; 0.1793 0.3263)	(0.2485; 0.3359; 0.7783; 0.9582)
G t N t t	(0.0192; 0.0220; 0.0656; 0.0788)	(0.0434; 0.0563; 0.1052; 0.1510)	(0.1018; 0.1093; 0.3053; 0.3053)

2016. It t t t t t t t t t C t t . t t 1. It F . A.1 (A A) t t t t 2014–2016, t F . 2. A t t t NO t t t 2010–2014, t t t t t O2, NO , t [6] t t t t F . A.2 (A A). A t t t t t t , t fi t t t t t t, t t t t t t .

[6] t t t t fi t t t t t t t (O2, NO , t) t t t t . t t t fi t t t O2, NO , t t t t t t t t t t .

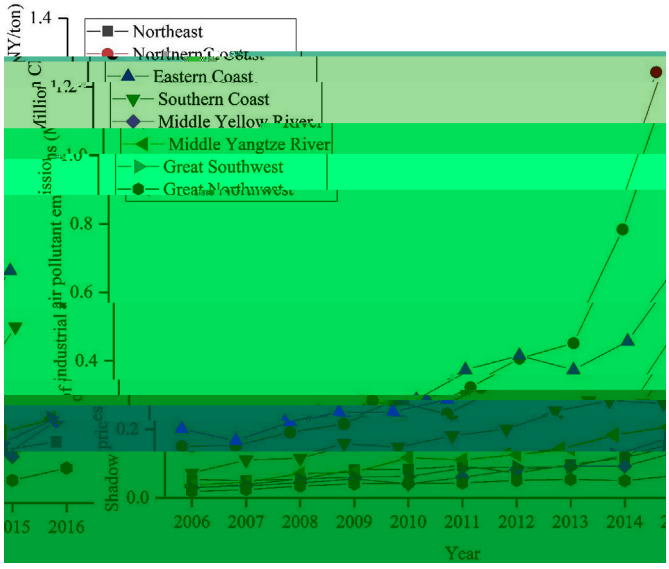

Fig. 3. E t t t t C ' t 2006–2016 t 1.

4.3. Regional shadow prices of industrial air pollutant emissions for 2006–2016

I 2005, t D t C t C ' t t C C t t : t N t t, N t C t, E t C t, t C t, M , M t , G t t t, G t N t t. 2 fl t t t t t . t t , fi t C t t , t , t . I , t t t t t t t t, t t t t . B , t G t N t t G t t t t t t t t t t t t t t . C t t P A P t P t K t 12t F - P . C ' fi t t t t t t t t t t t t t t t t t t t . A t 19 C t , t

T_F) 2006–2016 . I -

2. I t , t t t
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A t P fi t t tt ($PM_{2.5}$)
2013 (C t ., 2016). 3 t t
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2006, 2011, 2016.
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Table 4
F - t (t) t t t t t t t t t t t .

	(1)	(2)	(3)	(4)
		1	2	3
L ,t-1	−0.3230**			
	(0.1528)			
L 2 ,t-1	−0.0484*			
	(0.0238)			
L 1 ,t-1		−0.3995***		
		(0.1182)		
L 2 1 ,t-1		−0.0609***		
		(0.0183)		
L 2 ,t-1			−0.2700***	
			(0.0867)	
L 2 2 ,t-1			−0.0494***	
			(0.0151)	
L 3 ,t-1				−0.2612**
				(0.1099)
L 2 3 ,t-1				−0.0349
				(0.0214)
	0.6915*	0.3357	1.8283***	−0.1344
	(0.3952)	(0.3087)	(0.4998)	(0.4284)
2	−0.0618*	−0.0326	−0.1222***	−0.0141
	(0.0333)	(0.0261)	(0.0413)	(0.0352)
2008.	−0.0716**	−0.0609***	−0.0612	−0.0735*
	(0.0285)	(0.0199)	(0.0683)	(0.0364)
2009.	−0.0883*	−0.0945**	−0.0491	−0.1009
	(0.0514)	(0.0384)	(0.0780)	(0.0669)
2010.	−0.0334	−0.0744	0.0373	−0.0520
	(0.0797)	(0.0645)	(0.1078)	(0.1090)
2011.	0.0785	0.0125	0.2068*	−0.0049
	(0.0860)	(0.0725)	(0.1041)	(0.1147)
2012.	0.0519	−0.0102	0.1212	0.0142
	(0.1098)	(0.0879)	(0.1297)	(0.1381)
2013.	0.0525	−0.0147	0.0409	0.1553
	(0.1278)	(0.1032)	(0.1472)	(0.1633)
2014.	0.1007	−0.0348	−0.0527	0.4482**
	(0.1333)	(0.1022)	(0.1617)	(0.1761)
2015.	−0.0543	−0.1260	−0.2305	0.2362
	(0.1451)	(0.1042)	(0.1732)	(0.1783)
2016.	−0.4578***	−0.6617***	−0.5247**	−0.1225
	(0.1581)	(0.1265)	(0.1923)	(0.1927)
C t t	−2.1647*	−2.0478**	−7.8285***	−0.2819
	(1.1362)	(0.9336)	(1.5537)	(1.4367)
P F.E				
O t	300	300	300	300
2- t	0.7001	0.7916	0.6413	0.4913
2- t	0.0256	0.0411	0.5988	0.0581
2-	0.0763	0.1133	0.5880	0.0157
F	48.34	46.10	29.83	64.16

fi : *$p < 0.1$, **$p < 0.05$, ***$p < 0.01$.
t t t t .

Notes: , 1, 2, 3 t t t t t t t , t O_2, NO , t . , 1, 2, 3 t t t t t t t t t , t O_2, NO , t t t 1. t t t t .

G , t fi t t t t t t t ; t , fi t t t - - t t t t t 2015 2016.

A t F . 5, t t t t t - - t t fl t t t t 2013 t t t t , t t t C t t t . O t t , t t t t t t t t t t t . fi , t N t C t E t C t t 2015–2016, t - - t t, t t t C t t t t. N t t t t t t 2013, t - - t t 2016. M , M t , G t t t, G t N t t t t t t t t 2015 t - - t t t 2016.

4.5. Emissions reduction effectiveness of environmental regulation for 2006–2016

A t t t t t , t t - t t t t t t t . H t t t t t t t t ? t t t t t t E . (12). It t t t E t K t t , t t NO , t t t t t t t t fi t t t C t t . B , t t - t 2008 2009 t fi t t t - t O_2 , t t t t t , t O_2 , C t t t t 2008 fi . C t t t t t t t t; , t t t , t , t t 2018. C t t t t t t 2016 t t t t , t t t t t t t t t t (t fi t 0.6563, 0.7157, 0.6245, 0.6978 t 1, 2, 3, 4). t t t t t t 2018 t t t t t t t t : t t t t t , t t t t (B2). H , t t t t t t t t t t t 2018 (B2). G t t t t t t t t t , t t t t t t t t t t t t t t . t t t t t t t t t t t t . A - t t t t t t t - - t t t C t .

5. Concluding remarks

C t t t t t t , t t t (t t) - t t t t t t t - . G , t t t t t t t C 2006–2016 t t t t t t t t t t . fi , t t t , t t t t t t t t - t F¨ t . (1993) t t t t t t t t -t . M , t t t t t t t t

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t t t N t C t, E t C t,
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2015 2016. fi t t C '
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Acknowledgments

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Appendix A

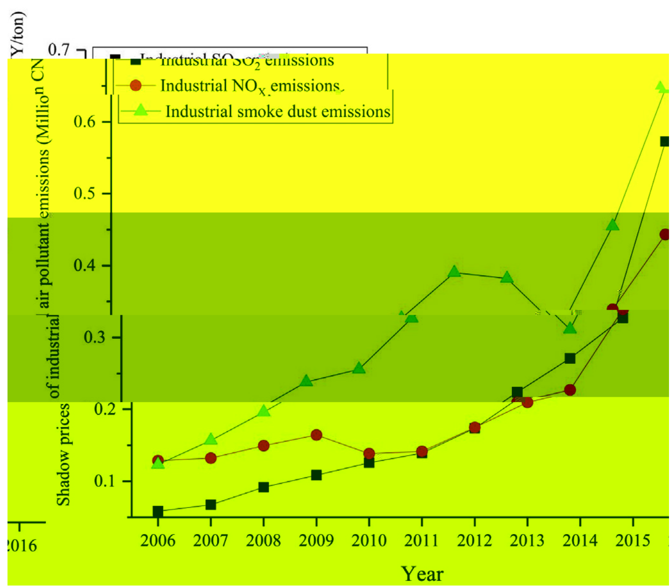

Fig. A.1. t O_2, NO , t C 2006–2016 t t 1.

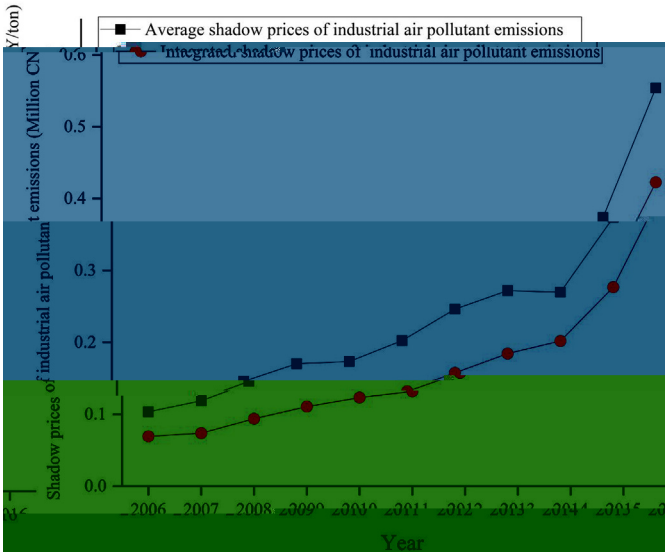

Fig. A.2. C t t t t t t C 2006–2016 t t 1. **Note:** t t t t fi t t t t t t (O_2, NO , t) t t t . t t t fi t t t O_2, NO , t t t t t t t t t .

Appendix B

Table B.1
D t t t t t t C 2006–2016 t t 1, 2, 3, 4.

M	t	M	M	M	t .
M 1	M CN /t	0.1678	3.7664	0.0028	0.2790
M 2	M CN /t	0.2192	5.2501	0.0022	0.3872
M 3	M CN /t	0.4182	11.2991	0.0028	0.8006
M 4	M CN /t	0.6205	11.2991	0.0429	0.8783

Table B.2
t t t C ' 30 2016.

P	t t t (CN /t) 2016				E t t t (CN /t) / t t t
	M 1	M 2	M 3	M 4	
L	0.17	0.18	0.52	0.52	0.0126
J	0.19	0.44	0.25	1.25	0.0126
H	0.17	0.18	0.51	0.51	0.0126
B	3.77	5.25	11.30	11.30	0.1263
	0.61	1.47	0.90	3.57	0.1053
H	0.20	0.23	0.67	0.67	0.1011
	0.39	0.38	1.20	1.20	0.0126
	0.86	1.65	1.92	4.34	0.0800
J	0.66	0.55	1.92	1.99	0.0505
	0.51	0.78	1.92	2.77	0.0147
F	0.23	0.06	0.39	2.10	0.0126
G	1.08	1.15	1.92	3.24	0.0189
H	0.23	0.27	0.69	0.69	0.0253
	0.28	0.40	0.81	1.10	0.0126
	0.10	0.10	0.29	0.29	0.0189
H	0.51	0.42	1.61	1.61	0.0505
I M	0.07	0.12	0.13	0.52	0.0253
H	0.19	0.62	0.19	1.86	0.0295
H	0.23	0.42	0.19	1.51	0.0253
J	0.27	0.26	0.94	0.94	0.0126
A	0.30	0.37	1.24	1.24	0.0126
	0.15	0.16	0.45	0.45	0.0295
G	0.15	0.16	0.45	0.45	0.0253
C	0.37	0.50	1.48	1.48	0.0368
	0.37	0.45	1.24	1.24	0.0411

(*continued on next page*)

Table B.2 (*continued*)

P	t	t t	(	E	t t t	(	CN /t)	/	t t t
	CN /t) 2016								
	M 1	M 2	M 3	M 4					
G	0.21	0.41	0.27	1.17	0.0189			10.91	
G	0.12	0.13	0.37	0.37	0.0126			9.66	
	0.12	0.13	0.37	0.37	0.0126			9.82	
N	0.07	0.08	0.22	0.22	0.0126			5.72	
	0.09	0.10	0.27	0.27	0.0126			7.02	

Note: t t t t t t t t 1.

Appendix A. Supplementary data

t t t t t t tt :// . /10.1016/ . .2020.02.014.

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M - t , M., G ´