The Macroeconomic Rebound Effect in China[1]

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Abstract

The rebound effect measures the fraction of an energy efficiency improvement that is offset by increased energy consumption. A rebound effect can arise at both the microeconomic level and the macroeconomic level. The macroeconomic rebound effect measures the effect of an increase in energy efficiency on overall energy demand after markets adjust and re-equilibrate. At the macroeconomic level, energy efficiency gains can increase energy consumption through two channels: the macroeconomic price effect and the macroeconomic growth effect. In this paper, we econometrically estimate the macroeconomic energy rebound effect in China. Our results show that there is a statistically significant macroeconomic price rebound effect for China, for each province, and for the short run, intermediate run, and the long run. We also find some evidence of a macroeconomic growth rebound in the short run and the intermediate run for some years either nation-wide or for some provinces in China; moreover, for some years and some provinces, we cannot reject backfire. The rebound effect is an important phenomenon that the government of China should not neglect when making energy policy, as it affects how improvements in energy efficiency translate into changes in energy consumption.

Keywords: rebound effect; macroeconomic price effect; macroeconomic growth effect; China; energy efficiency; two-level nested CES production function
***JEL* codes:** Q43, Q41

This draft: August 2017

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1. Introduction

Energy plays an important role in economic growth. However, the consumption of energy, particularly fossil fuel sources of energy, is associated with many problems including climate change and pollution. One possible way to reduce the greenhouse gas emissions and pollution caused by energy consumption without curbing economic growth is to increase the efficiency with which we use energy. At first blush it may seem intuitive that improving the efficiency of energy use will lead to a reduction in energy consumption. Evidence from history and empirical research shows, however, that the actual savings in energy consumption from an increase in energy efficiency can be less than the expected savings. A "rebound" effect arises when some of the gains from improving the efficiency of energy use is lost because of behavioral responses (Gillingham et al., 2013).

Energy-related issues are particularly acute in developing countries such as China, where energy consumption has been increasing rapidly, resulting in energy-related problems such as power shortages and environmental pollution (Si et al., 2017b). The International Energy Agency (2014) estimates that half of the world oil demand growth till 2035 is likely to come from China overtaking the U.S. as the world's biggest oil consumer (Si et al., 2017a). In 2011, China's CO_2 emissions constituted 29 percent of world CO_2 emissions (EDGAR, 2014; Si et al., 2017a). Policies that increase energy efficiency may seem to be one possible way to reduce the greenhouse gas emissions and pollution caused by energy consumption in China. However, owing to possible rebound effects, energy efficiency policies may be ineffective, or even have perverse consequences. Rebound effects in China therefore have important implications for policy.

A rebound effect can arise at both the microeconomic level and the macroeconomic level (Gillingham, Rapson and Wagner, 2016). The purpose of this paper is to estimate the size of China's macroeconomic rebound effect.

The rebound effect measures the fraction of an energy efficiency improvement that is offset by increased energy consumption. The macroeconomic rebound effect measures the effect of an increase in energy efficiency on overall energy demand after markets adjust and re-equilibrate (Gillingham, Rapson and Wagner, 2016). At the macroeconomic level, energy efficiency gains can increase energy consumption through two channels. The first channel for the macroeconomic rebound effect is the macroeconomic price effect: an energy efficiency improvement shifts the market demand curve for energy in, and consumers and producers will adjust until a new equilibrium is reached. The second channel for the macroeconomic rebound effect is the macroeconomic growth effect: an increase in energy efficiency can spur economic growth, either through a reallocation of growth through sectoral reallocation or overall growth through an increase in total factor productivity, and the economic growth requires additional energy consumption (Gillingham, Rapson and Wagner, 2016).

The macroeconomic rebound effect was first hypothesized by Jevons in his classic 1865 book <u>The Coal Question</u> (Jevons, 1865). In honor of Daniel Khazzoom and Leonard Brookes's seminal work on the rebound effect (Khazzoom, 1980; Khazzoom, 1987; Brookes, 1978), Saunders (1992) put forward the Khazzoom–Brookes postulate, which suggests that energy efficiency improvements might increase rather than decrease energy consumption, a phenomenon known as "backfire" that is represented by a rebound effect greater than 1 (Sorrell, 2007).

Much of the theoretical and empirical literature on the rebound effect has focused on the microeconomic rebound effect in the residential sector and the transportation sector (Gillingham, Rapson and Wagner, 2016 & references therein; Chan and Gillingham, 2015; Borenstein, 2015; Greening, Greene and Difiglio, 2000; De Borger, Mulalic and Rouwendal, 2016). According to Sorrell (2009), however, the macroeconomic rebound effect was Jevons' (1865) primary concern.

Few economists would deny that there exists a macroeconomic rebound effect in the real economy. But there is a debate over the magnitude of the rebound effect among energy economists. Dimitropoulos (2007) presents a comprehensive survey of the previous research in this area. Binswanger (2001) finds in his survey of empirical studies that the estimated size of the rebound effect varies with the method and data employed in the studies, and ranges from 5% to 50%.

The macroeconomic rebound effect is often estimated using computable general equilibrium (CGE) models (Barker, Ekins and Foxon, 2007a). The advantages of CGE models are that they are detailed, complex, and comprehensive. The drawbacks are that CGE models have may several limitations, including market and behavioral assumptions that may not be supported by empirical evidence, restrictive functional form assumptions, and sensitivity of the results to the base year chosen for the calibration and to assumed parameter values (Gillingham, Rapson and Wagner, 2016; Sorrell, 2007). Of the eight CGE modeling results surveyed by Sorrell (2007), all find a macroeconomic rebound effect greater than 37% and most studies showed macroeconomic rebound effects greater than 50%.

Turner (2009) uses a computable general equilibrium model to estimate the rebound effect in the UK, and finds evidence for a net negative economy-wide rebound effect as a result of the reduced intermediate energy input requirement of Scottish production sectors where efficiency increases in industrial energy use (Turner, 2013; Turner 2009). Using a computable general equilibrium model, Barker, Ekins and Foxon (2007b) find that the macroeconomic rebound effect arising from UK energy efficiency policies for the period 2000-2010 is around 11% by 2010, averaged across sectors of the economy. Barker, Dagoumas and Rubin (2009) use a sectoral dynamic macroeconomic computable general equilibrium model of the global economy to estimate the macroeconomic rebound effect. Grepperud and Rasmussen (2004) use a general equilibrium model to analyze the rebound effect in Norway.

In contrast to a computable general equilibrium model, a more parsimonious econometric model may have the advantages of being less sensitive to the many assumptions needed for a CGE model, and of estimating parameters econometrically from data. Adetutu, Glass and Weyman-Jones (2016) estimate economy-wide rebound effects using a combined stochastic frontier analysis and two-stage dynamic panel data approach, and find that in the short run, a 100% energy efficiency improvement is followed by a 90% rebound in energy consumption, but that in the long run it leads to a 136% decrease in energy consumption.

There have been some previous studies estimating the rebound effect in China. Zhou and Liu (2007) estimate the rebound effect of China's energy consumption from 1979 to 2004, and find that there are large differences in the magnitude of rebound effect from year to year. Guo, Guo and Ling (2010) estimate the rebound effect of energy consumption in industrial sectors in China. Liu and Liu (2008) find that the size of rebound effect in China is declining from 1985 to 2005. Li and Han (2012) calculate the energy rebound effect for three industries in China over the period 1997-2009. Zhang, Peng and Su (2017) estimate the energy rebound effect in the industrial sectors in China. Lu, Liu and Zhou (2017) use a CGE model to measure the rebound effect of different energy types in China.

In this paper, we build on the previous literature on the rebound effect and on the rebound effect in China by econometrically estimating the macroeconomic energy rebound effect in China. We contribute to the literature by estimating the macroeconomic energy rebound effect using an econometrical model rather than a computable general equilibrium model; by estimating the macroeconomic energy rebound effect in China at both the national and province levels; by estimating the macroeconomic energy rebound effect in China over multiple time horizons (short run, intermediate run, and long run); and by estimating not only the macroeconomic rebound effect but also its two constituent effects (the macroeconomic price effect and the macroeconomic growth effect).

Evidence for or against a rebound effect is obscured in energy/GDP ratios (Saunders, 2000a). One strength of our methodology and analysis is that we do not require either data on energy efficiency or the assumption that energy efficiency is given by the energy/GDP ratio. Instead, in order to estimate the macroeconomic rebound effect, price effect, and growth effect, we derive analytic expressions for the macroeconomic rebound effect, price effect, and growth effect from a production function. These analytic expressions for the macroeconomic rebound effect, price effect, and growth effect that we derive are functions of production function parameters, output, and energy consumption, and do not assume that energy efficiency is given by the energy/GDP ratio. We estimate the production function parameters econometrically using data on output, capital, labor, and energy consumption.

To further analyze the macroeconomic growth rebound effect, we derive an analytic expression for the macroeconomic growth rebound effect based on a definition of the growth rebound effect as a function of actual energy savings (AES) and potential energy savings (PES). This analytic expression for the macroeconomic growth effect is a function of total productivity (which we estimate econometrically using data on output, capital, labor, and energy consumption), output, and energy consumption, and captures the channel that an increase in energy efficiency can spur economic growth through an increase in total factor productivity, and the economic growth requires additional energy consumption.

Our methodology for estimating the macroeconomic rebound effect, price effect, and growth effect therefore only requires data on output, capital, labor, and energy consumption, and does not require either data on energy efficiency or the assumption that energy efficiency is given by the energy/GDP ratio.

Our results show that there is a statistically significant macroeconomic price rebound effect for China, for each province, and for the short run, intermediate run, and the long run. We also find some evidence of a macroeconomic growth rebound in the short run and the intermediate run for some years either nation-wide or for some provinces in China; moreover, for some years and some provinces, we cannot reject backfire. The rebound effect is an important phenomenon that the government of China should not neglect when making energy policy, as it affects how improvements in energy efficiency translate into changes in energy consumption.

The balance of our paper proceeds as follows. We discuss the macroeconomic rebound effect in Section 2. We describe our methods in Section 3 and our data in Section 4. We present our results in Section 5. Section 6 concludes.

2. Macroeconomic Rebound Effect

The macroeconomic rebound effect measures the effect of an increase in energy efficiency on overall energy demand after markets adjust and re-equilibrate (Gillingham, Rapson and Wagner, 2016). At the macroeconomic level, energy efficiency gains can increase energy consumption through two channels.

The first channel for the macroeconomic rebound effect is the macroeconomic price effect: an energy efficiency improvement shifts the market demand curve for energy in, and consumers and producers will adjust until a new equilibrium is reached. The macroeconomic price effect is the economy-wide analog to the microeconomic direct rebound effect that works through prices (Gillingham et al., 2013; Gillingham, Rapson and Wagner, 2016). Unlike the microeconomic direct rebound effect, which can be calculated from the price elasticity of demand, the macroeconomic price effect depends on both the supply elasticity and the demand elasticity, whereby a more inelastic supply and a more elastic demand induce a higher rebound (Gillingham, Rapson and Wagner, 2016). Ghoddusi and Roy (2017) characterize the magnitude of the macroeconomic price rebound effect as a function of demand and supply elasticities.

The second channel for the macroeconomic rebound effect is the macroeconomic growth effect: an increase in energy efficiency can spur economic growth, either through a reallocation of growth through sectoral reallocation or overall growth through an increase in total factor productivity, and the economic growth requires additional energy consumption (Gillingham, Rapson, and Wagner, 2016). The more efficient production and use of energy at a macroeconomic scale encourages the substitution of energy inputs for other factors of production (e.g., labor) and drives economic productivity overall, which may change the composition of goods and services as well as the relative returns of investment in and growth of different sectors, and which results in economic growth and energy consumption (Jenkins, Nordhaus and Shellenberger, 2011; Gillingham, Rapson, and Wagner, 2016).

Following Saunders (2000a, 2000b, 2005), we derive the macroeconomic rebound effect as follows. Suppose the economy-wide production function is given by:

$$Y = f(K, L, E(\tau, F)), \tag{1}$$

where output Y is a function of capital K, labor L, and energy services E; and where energy services E is the following function of energy consumption F and energy efficiency τ (Howarth, 1997; Saunders, 2000a, 2000b, 2005, 2008):

$$E = \tau F . \tag{2}$$

The expression for the macroeconomic rebound effect is then given by:

$$R = 1 + \eta = 1 + \frac{\tau}{F}\frac{\partial F}{\partial \tau}, \tag{3}$$

where η denotes the elasticity of energy consumption F with respect to energy efficiency τ.

The macroeconomic rebound effect R can be decomposed into its two effects as follows:

$$R = 1 + \eta = 1 + \eta_p + \eta_g, \tag{4}$$

where the elasticity η of energy consumption F with respect to the energy efficiency τ can be decomposed to the macroeconomic price effect η_p and the macroeconomic growth effect η_g. The decomposition is derived from first expressing energy consumption F as:

$$F = \frac{F}{Y} Y \,, \tag{5}$$

and then decomposing the elasticity η of energy consumption F with respect to energy efficiency τ as follows:

$$\eta = \frac{\tau}{F}\frac{\partial F}{\partial \tau} = \frac{\tau}{(F/Y)}\frac{\partial (F/Y)}{\partial \tau} + \frac{\tau}{Y}\frac{\partial Y}{\partial \tau} \,. \tag{6}$$

Since $\frac{F}{Y}$ measures energy intensity, the first term in equation (6) denotes the macroeconomic price effect η_p, which measures the elasticity of energy intensity $\frac{F}{Y}$ with respect to energy efficiency τ:

$$\eta_p = \frac{\tau}{(F/Y)}\frac{\partial (F/Y)}{\partial \tau} \,, \tag{7}$$

and the second term denotes the macroeconomic growth effect η_g, which measures the elasticity of output Y with respect to energy efficiency τ, and which reflects possible increases in energy consumption resulting from the larger space of production possibilities (Saunders, 1992; Berkhout, Muskens and Velthuijsen, 2000; Sorrell and Dimitropoulos, 2008):

$$\eta_g = \frac{\tau}{Y}\frac{\partial Y}{\partial \tau} \,. \tag{8}$$

Suppose the production function is the following two-level nested CES production function (Sato, 1967):

$$Y = B[b(aK^{-\rho_1} + (1-a)L^{-\rho_1})^{\rho/\rho_1} + (1-b)(E)^{-\rho}]^{-1/\rho} \,, \tag{9}$$

where B is the total factor productivity (TFP) and where energy services E as a function of energy consumption F and energy efficiency τ is given by equation (2).

Substituting in our production function (9) into equations (3), (7), and (8) for the macroeconomic rebound effect R, the macroeconomic price effect η_p, and the macroeconomic growth effect η_g, respectively, we obtain the following expressions for the macroeconomic rebound effect and its two constituent effects in Proposition 1. The proof of Proposition 1 is provided in Appendix A.

Proposition 1: Given our production function (9), the macroeconomic rebound effect is given by:

$$R = 1 + \eta = \frac{1}{(1+\rho)\left(1-(1-b)\left(\frac{Y}{F}\right)^{\rho}\tau^{-\rho}\right)}. \tag{10}$$

We can decompose the elasticity η of energy consumption F with respect to the energy efficiency τ into the macroeconomic price effect η_p:

$$\eta_p = \frac{1}{1+\rho} - 1, \tag{11}$$

and the macroeconomic growth effect η_g:

$$\eta_g = \frac{(1-b)\left(\frac{Y}{F}\right)^{\rho}\tau^{-\rho}}{(1+\rho)\left(1-(1-b)\left(\frac{Y}{F}\right)^{\rho}\tau^{-\rho}\right)}. \tag{12}$$

3. Methods

3.1. Two-Level Nested CES Production Function

To estimate the macroeconomic rebound effect, we first estimate the production function.

Saunders (2008) provides a good summary of the current state of knowledge about the production function $Y = f(K, L, E(\tau, F))$. He examines and compares eight production or cost functions for exploring how energy efficiency gains affect energy consumption. Saunders (2000a, 2000b) uses a two-sector Cobb-Douglas production function. Wei (2007) analyzes the effect of energy efficiency gains on output and energy consumption with a Cobb-Douglas production function.

We use a two-level nested constant elasticity of substitution (CES) production function, for the following reasons. First, the CES production function is a general production function; the Cobb-Douglas, the Leontief, and the linear production functions are special cases of the CES production function (Intriligator, 1978). Second, the CES production function is well-suited for considering the effects of variation in the elasticity of substitution between factors of production. Typically, the greater the size of the elasticity of substitution between energy and other factors of production, the larger will be the rebound effect. The two-level CES production function allows for different elasticities of substitution between the different factors in the CES production function. Third, the elasticity of substitution between two factors may be considered as a fixed value in the short term.

The two-level nested CES production function equation that we estimate is:

$$\ln Y = \alpha_1 + \alpha_2 t + \alpha_3 t^2 - (1/\rho)\ln[b(aK^{-\rho_1} + (1-a)L^{-\rho_1})^{\rho/\rho_1} + (1-b)(\tau F)^{-\rho}] + u, \tag{13}$$

where Y, K, L, and F denote total output, capital stock, labor, and energy consumption, respectively, and where the total factor productivity (TFP) is given by:

$$TFP_t = B_t = \exp(\alpha_1 + \alpha_2 t + \alpha_3 t^2). \tag{14}$$

This nested CES production function is highly nonlinear, so we use nonlinear least squares

(NLLS) to obtain estimates of all parameters.[2] It should be noted that we expect the coefficients to satisfy the following constraints: $B > 0$, $\rho > -1$, $\rho_1 > -1$, $0 < a < 1$, and $0 < b < 1$.

3.2. *Macroeconomic Rebound Effect*

We estimate the macroeconomic rebound effect, price effect, and growth effect both at a national level and at a provincial level by plugging into equations (10), (11), and (12), respectively, our estimated parameters for the nested CES production function and the data. Standard errors are calculated using the Delta Method (DeGroot, 1986).

3.3. *Macroeconomic Growth Rebound Effect*

To further analyze the macroeconomic growth rebound effect, we estimate the macroeconomic growth rebound effect in the short run, the intermediate run, and the long run using a method based on the following definition of the growth rebound effect as a function of actual energy savings (AES) and potential energy savings (PES) (Guerra and Sancho, 2010; Azevedo, 2014):

$$R_g = 1 - (AES / PES). \tag{15}$$

The potential energy saving derived from technical progress is given by:

$$PES = Y_{t+1} * (EI_t - EI_{t+1}), \tag{16}$$

where Y_t total output and EI_t is energy intensity at year *t*. The intuition is as follows. Total

[2] We normalize the energy efficiency parameter τ, which merely changes the units of *F* and cannot be separately identified from the parameter *b*, to 1.

energy consumption is given by $E_t = Y_t * EI_t$. In year t+1, the potential energy consumption should be $E_{t+1} = Y_{t+1} * EI_t$ if there is no technical progress that changes the energy intensity. But in year t+1, energy intensity may decrease because of technical progress. The real energy consumption is thus $E_{t+1} = Y_{t+1} * EI_{t+1}$. Therefore, the potential energy savings derived from technical progress is $Y_{t+1} * (EI_t - EI_{t+1})$. The additional energy demand derived from economic growth because of technical progress, which represents the difference between potential energy savings and actual energy savings, is $\sigma_{t+1} * (Y_{t+1} - Y_t) * (EI_{t+1})$, where σ_{t+1} denotes contribution rate of technical progress to economic growth and where $\sigma_{t+1} * (Y_{t+1} - Y_t)$ is the size of economic growth derived from technical progress in year t+1.

The macroeconomic growth rebound effect can therefore be expressed as:

$$R_{g,t+1} = \frac{\sigma_{t+1} * (Y_{t+1} - Y_t) * (EI_{t+1})}{Y_{t+1} * (EI_t - EI_{t+1})}. \tag{17}$$

The macroeconomic growth effect captures the channel that an increase in energy efficiency can spur economic growth through an increase in total factor productivity, and the economic growth requires additional energy consumption.[3]

[3] An increase in energy efficiency can also spur economic growth through a reallocation of growth through sectoral reallocation, and this additional source of economic growth can also require additional energy consumption (Gillingham, Rapson and Wagner, 2016). The macroeconomic growth effect we estimate using equation (17), which is based on the definition of the growth rebound effect as a function of actual energy savings (AES) and potential energy savings (PES), does not capture the channel that an increase in energy efficiency can spur a reallocation of growth through sectoral reallocation that requires additional energy consumption. However, equation (17) does captures the channel that an increase in energy efficiency can spur overall economic growth through an increase in total factor productivity, and the economic growth requires additional energy consumption. Thus, the macroeconomic growth effect we estimate using equation (17) captures at least part of the macroeconomic growth effect. Moreover, the macroeconomic growth effect we estimate using equation (12) captures both channels through which an increase in energy efficiency can spur economic growth. In other words, the macroeconomic growth effect we estimate using equation (12) captures that an increase in energy efficiency can spur economic growth either through a reallocation of growth

Using the parameters and total factor productivity we estimate for a two-level nested CES production function, we calculate the contribution σ_{t+1} of growth in technological progress to output growth over time as:

$$\sigma_{t+1} = \frac{\dfrac{TFP_{t+1} - TFP_t}{TFP_t}}{\dfrac{Y_{t+1} - Y_t}{Y_t}}, \tag{18}$$

where *TFP* denotes total factor productivity and *Y* is aggregate output. Hence, an important step for this method is to estimate the value of total factor productivity.

4. Data

We use national data on China's GDP, capital stock, labor, and aggregate energy consumption over the period 1981 to 2009 from the China Statistical Yearbook published by the China National Bureau of Statistics (CNBS). Table 1 presents summary statistics for the national data. Figure 1 plots China's GDP and energy consumption over time.

We use province-level data on GDP, capital stock, and labor force over the period 1986 to 2009 from the China Statistical Yearbook. We use data on energy consumption over the period 1995 to 2009 from the China Energy Statistical Yearbook. For the period 1986 to 1990, our data on China's energy consumption comes from the Thematic Database for Human-Earth System. The data over the period 1991 to 1994 come from the statistical yearbook of every province.

Chongqing was separated from Sichuan province in 1997. Thus, for the years 1997 to

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through sectoral reallocation or overall growth through an increase in total factor productivity, and the economic growth requires additional energy consumption.

2009, Chongqing's energy consumption was added to the energy consumption in Sichuan. Moreover, since data from Tibet and Hainan province are not available, our paper does not consider these two regions.

Table 2 presents summary statistics of the province-level variables used in this analysis.

5. Results

Table 3 presents the results from estimating the two-level nested CES production function in equation (12) using province-level data. The estimates of the parameters $\theta = (\alpha_1, \alpha_2, \alpha_3, b, \rho, \rho_1)$, when significant, are of the expected sign. Moreover, the estimates of α_1, α_2, and α_3 are all statistically significant at a 5% level, so that TFP has a significant quadratic time trend.

We estimate the macroeconomic rebound effect, price effect, and growth effect both at a national level and at a provincial level by plugging into equations (10), (11), and (12), respectively, our estimated parameters for the nested CES production function in Table 3 and the national and provincial data, respectively, presented in the previous section. Standard errors are calculated using the Delta Method (DeGroot, 1986).

The results are presented in Table 4. According to our results, the macroeconomic rebound effect is -0.1421 and consists entirely of a statistically significant macroeconomic price effect. The macroeconomic growth effect is a precisely estimated 0. The results are the same for the nation, for each province, and for the short run, intermediate run, and the long run. The reason the results do not vary by province or by time horizon is that since b is so close to 1, the values of Y and F do not matter much and the value of the rebound effect is driven primarily by the values of the parameters b and ρ instead.

To further analyze the macroeconomic growth effect, we use our estimates for TFP in Table 3 to calculate the short-run macroeconomic growth energy rebound effect for each year using the national data. Standard errors are calculated using the Delta Method (DeGroot, 1986). The results for each year are plotted in Figure B1 in Appendix B. We find that the macroeconomic growth rebound effect is higher in the earlier years of the time period analyzed, with values close to or greater than 1 four times before 1990, in the years 1982, 1983, 1986, and 1990. The macroeconomic growth rebound effect is smaller in the later years of the time period analyzed, with several negative but insignificant values from the years 2003 onwards. The macroeconomic growth rebound effect is extremely negative and significant in the year 1989.

We also use our estimates for TFP to calculate the short-run macroeconomic growth energy rebound effect for each province for each year. Standard errors are calculated using the Delta Method (DeGroot, 1986). Graphs of the short-run macroeconomic growth energy rebound effect for each province for each year are given in Figure C1 in Appendix C. Because Gansu, Jiangxi, and Shanghai have exceptionally high macroeconomic growth rebound effects and upper bounds of the confidence intervals for some years, Figures C2a, C2b, and C2c in Appendix C zoom in on the graphs for these respective provinces.

Table 5 summarizes the significance of the short-run macroeconomic growth energy rebound effect for each province for each year. Results show that the macroeconomic growth rebound effect is significant for all provinces for each year during the period 1987 to 1995. For some provinces and years during this period, the macroeconomic growth rebound effect is significant and negative; for other provinces and years, the macroeconomic growth rebound effect is significant and positive; and for the remaining provinces and years the macroeconomic growth rebound effect is significant and positive and its confidence interval includes a macroeconomic growth rebound effect of 1.

In contrast, the macroeconomic growth rebound effect is not significant at a 5% level for any province for any year over the period 1996 to 2009, though for some provinces in some years the confidence interval includes a rebound effect of 1.

Figure 2 presents the mean short-run macroeconomic growth rebound effect for each province, where the mean is taken over all the years over the period 1987-2009. For comparison, we also plot the mean national macroeconomic growth rebound effect both over the period of the national data set (1982-2009) and also over the subset of years covered in the province-level data set (1987-2009). Most provinces have a mean short-run macroeconomic growth energy rebound effect less than 1, with the exception of Guangxi and Jiangxi, which both have mean short-run macroeconomic growth rebound effects around 1, and Shanghai, which has a mean short-run macroeconomic growth energy rebound effect of 11.41.

Figure B2 in Appendix B presents the mean and standard deviation over all the years of the estimated province-level short-run macroeconomic growth energy rebound effect for each province. Results show that a province-level macroeconomic growth energy rebound effect of 0 is within one standard deviation of the mean province-level macroeconomic growth energy rebound effect for each province. A province-level macroeconomic growth energy rebound effect of 1 is also within one standard deviation of the mean province-level macroeconomic growth energy rebound effect for 22 out of 28 provinces. These 22 provinces are: Fujian, Gansu, Guangxi, Guizhou, Heilongjiang, Hubei, Hunan, Inner Mongolia, Jiangsu, Jiangxi, Jilin, Liaoning, Qinghai, Shaanxi, Shandong, Shanghai, Shanxi, Sichuan, Tianjin, Xinjiang, Yunnan, and Zhejiang.

Figure B3 in Appendix B presents the mean and standard deviation over all provinces of the estimated short-run macroeconomic growth energy rebound effect each year. We find that a province-level macroeconomic growth energy rebound effect of 0 is within one standard deviation of the mean province-level macroeconomic growth energy rebound effect in each year except the final four years of the data set (2006-2009), when one standard deviation above the mean is less than 0. A province-level macroeconomic growth energy rebound effect of 1 is within one standard deviation of the mean province-level growth energy rebound effect in all but one year (1992) in the first 9 years of the data set (i.e., the years 1987-1991 and 1993-1995) and also in the years 2002 and 2005.

Since 1989 was a year in which the national short-run macroeconomic growth energy rebound effect is extremely negative and also in which both the mean and the standard deviation of the province-level short-run macroeconomic growth energy rebound effect are very large, we examine the year 1989 in more detail by plotting the short-run macroeconomic growth energy rebound effect in 1989 both for the nation and for each province in Figure B4 in Appendix B.

In 1989, the short-run macroeconomic growth energy rebound effect is an extremely large and significant 216.66 for Shanghai. The lower bound of the 95% confidence interval for the macroeconomic growth rebound effect is also greater than 1 for Guangxi, Hubei, Jiangsu, Liaoning, Sichuan, Xinjiang, and Yunnan. The macroeconomic growth rebound effect is significant and positive and includes a rebound effect of 1 for Anhui, Beijing, Fujian, Gansu, Hebei, and Heilongjiang. However, the macroeconomic growth rebound effect is significant and negative for Guangdong, Guizhou, Inner Mongolia, Jilin, Ningxia, Qinghai, Shaanxi, Shandong, and Zhejiang.

To better understand the macroeconomic growth rebound effect in 1989, Table B1 in Appendix B presents the variables used to calculate the short-run growth macroeconomic growth rebound effect for both the nation level and for Shanghai in 1989. At the national level, the large negative value for the macroeconomic growth rebound effect in 1989 is driven by the small negative value for potential energy saving in 1989, which arises because energy intensity increases from 1988 to 1989. In Shanghai, the large positive value for the macroeconomic growth rebound effect in 1989 is driven by the small value for potential energy savings in 1989, which arises because energy intensity decreases very little from 1988 to 1989.

In addition to calculating the short-run macroeconomic growth energy rebound effect, we also calculate the intermediate-run macroeconomic growth rebound effect, which we define as the macroeconomic growth rebound effect over a 5-year interval. We calculate the intermediate-run macroeconomic growth rebound effect both nation-wide and for each province for each 5-year interval by using observations 5 years apart as t and t+1, respectively.

The national results for the intermediate-run macroeconomic growth rebound effect in each year are plotted in Figure B5 in Appendix B. We find that the intermediate-run macroeconomic growth rebound effect is higher and significant in the earlier years of the time period analyzed, with confidence intervals that include 1 in 1989, 1990, and 1991. The intermediate-run macroeconomic growth rebound effect is not significant in the later years of the time period analyzed, with several negative but insignificant values from the years 2005 onwards.

We also estimate the intermediate-run macroeconomic growth energy rebound effect for each province for each year. Graphs of the results are presented in Figure C3 in Appendix C; a summary of the significance of the results is presented in Table 6. We find that the intermediate-run macroeconomic growth rebound effect is significant for most province-years during the period 1991 to 1996. For some provinces and years during this period, the macroeconomic growth rebound effect is significant and negative; for other provinces and years, the macroeconomic growth rebound effect is significant and positive; and for the other provinces and years the macroeconomic growth rebound effect is significant and positive and its confidence interval includes a macroeconomic growth rebound effect of 1.

In contrast, the intermediate-run macroeconomic growth rebound effect is not significant at a 5% level for any province for any year over the period 1997 to 2009, though for some provinces in some years the confidence interval includes a macroeconomic growth rebound effect of 1.

Figure 3 presents the mean intermediate-run macroeconomic growth rebound effect for each province, where the mean is taken the intermediate-run macroeconomic growth rebound effect for that province for all years over the period 1991-2009. For comparison, we also plot the mean national macroeconomic growth rebound effect both over the period of the national data set (1986-2009) and also over the subset of years covered in the province-level data set (1991-2009). Most provinces have a mean intermediate-run macroeconomic growth energy rebound effect less than 1, with the exception of Qinghai, Tianjin, and Yunnan, which have mean intermediate-run macroeconomic growth rebound effects greater than 1.

Figure B6 in Appendix B presents the mean and standard deviation over all the years of the estimated province-level intermediate-run macroeconomic growth energy rebound effect for each province. We find that a province-level intermediate macroeconomic growth energy rebound effect of 0 is within one standard deviation of the mean province-level macroeconomic growth energy rebound effect for all provinces except Liaoning, where one standard deviation below the mean is greater than 0. A province-level intermediate-run macroeconomic growth energy rebound effect of 1 is also within one standard deviation of the mean province-level macroeconomic growth energy rebound effect for Anhui, Guizhou, Ningxia, Qinghai, Shanxi, Tianjin, and Yunnan.

Figure B7 in Appendix B presents the mean and standard deviation over all provinces of the estimated intermediate-run macroeconomic growth energy rebound effect each year. We find that a province-level intermediate-run macroeconomic growth energy rebound effect of 0 is within one standard deviation of the mean province-level macroeconomic growth energy rebound effect in all years except 1994 and 2002, when one standard deviation below the mean is greater than 0. A province-level intermediate-run macroeconomic growth energy rebound effect of 1 is within one standard deviation of the mean province-level macroeconomic growth energy rebound effect in 1991, 1992, 1993, 1995, 1996, 1998, 1999, 2003, and 2008.

In addition to calculating the short-run and intermediate-run macroeconomic growth energy rebound effect both nation-wide and for each of the provinces for each year, we also calculate the long-run macroeconomic growth rebound effect, which we define as the macroeconomic growth rebound effect over the entire time period of our data set, and for which we use the first and last years of our data set as t and t+1, respectively. Figure 4 plots the long-run macroeconomic growth rebound effect for each province over the period 1986-2009. For comparison, we also plot the long-run national macroeconomic growth rebound effect both over the period of the national data set (1981-2009) and also over the subset of years covered in the province-level data set (1986-2009). Results show that the long-run macroeconomic growth rebound effect is not statistically significant either nation-wide or for any province. A long-run macroeconomic growth rebound effect of 1 is not within the 95% confidence interval for either the nation or for any province.

6. Conclusion

In this paper, we estimate China's macroeconomic rebound effect from energy consumption. Our methodology for estimating the macroeconomic rebound effect, price effect, and growth effect only requires data on output, capital, labor, and energy consumption, and does not require either data on energy efficiency or the assumption that energy efficiency is given by the energy/GDP ratio.

According to our results, China's total macroeconomic rebound effect is -0.1421 and consists entirely of a statistically significant macroeconomic price effect. The macroeconomic growth effect is a precisely estimated 0. The results are the same for the nation, for each province, and for the short run, intermediate run, and the long run.

To further analyze the macroeconomic growth effect, we estimate China's short-run, intermediate-run, and long-run macroeconomic growth rebound effect at both the national level and the province level. At the national level, the short-run macroeconomic growth rebound effect is higher in the earlier years of the time period analyzed, with values close to or greater than 1 four times before 1990, in the years 1982, 1983, 1986, and 1990. The short-run growth macroeconomic rebound effect is smaller in the later years of the time period analyzed, with several negative but insignificant values from the years 2003 onwards. The short-run growth macroeconomic rebound effect is extremely negative and significant in the year 1989.

At the province level, the short-run macroeconomic growth rebound effect is significant for all provinces for each year during the period 1987 to 1995. For some provinces and years during this period, the short-run macroeconomic growth rebound effect is significant and negative; for other provinces and years, the short-run macroeconomic growth rebound effect is significant and positive; and for the remaining provinces and years the short-run macroeconomic growth rebound effect is significant and positive and its confidence interval includes a macroeconomic growth rebound effect of 1. In contrast, the short-run macroeconomic growth rebound effect is not significant at a 5% level for any province for any year over the period 1996 to 2009, though for some provinces in some years the confidence interval includes a macroeconomic growth rebound effect of 1.

At the national level, the intermediate-run macroeconomic growth rebound effect is higher and significant in the earlier years of the time period analyzed, with confidence intervals that include 1 in 1989, 1990 and 1991. The intermediate-run macroeconomic growth rebound effect is not significant in the later years of the time period analyzed, with several negative but insignificant values from the years 2005 onwards.

At the province level, the intermediate-run macroeconomic growth rebound effect is significant for most province-years during the period 1991 to 1996. For some provinces and years during this period, the intermediate-run macroeconomic growth rebound effect is significant and negative; for other provinces and years, the intermediate-run macroeconomic growth rebound effect is significant and positive; and for the other provinces and years the intermediate-run macroeconomic growth rebound effect is significant and positive and its confidence interval includes a macroeconomic growth rebound effect of 1. In contrast, the intermediate-run macroeconomic growth rebound effect is not significant at a 5% level for any province for any year over the period 1997 to 2009, though for some provinces in some years the confidence interval includes a macroeconomic growth rebound effect of 1.

The long-run macroeconomic growth rebound effect is not statistically significant either nation-wide or for any province. A long-run macroeconomic growth rebound effect of 1 is not within the 95% confidence interval for either the nation or for any province.

Our results therefore suggest that there exists a macroeconomic price rebound effect in China. We find a statistically significant macroeconomic price rebound effect for China, for each province, and for the short run, intermediate run, and the long run.

We also find some evidence of a macroeconomic growth rebound in the short run and the intermediate run for some years either nation-wide or for some provinces in China, particularly in the earlier half of our data set; moreover, for some years and some provinces, we cannot reject backfire. However, for some years and some provinces, the short-run and/or the intermediate-run macroeconomic growth rebound effect is significant and negative. The short-run and intermediate-run macroeconomic growth rebound effects are less significant in the later half of our data set, and the long-run macroeconomic growth rebound effect is not statistically significant either nation-wide or for any province.

The rebound effect is an important phenomenon that the government of China should not neglect when making energy policy, as it affects how improvements in energy efficiency translate into changes in energy consumption, and therefore also whether policies that increase energy efficiency may be an effective way to reduce the greenhouse gas emissions and pollution caused by energy consumption in China. According to our results, owing to possible rebound effects, energy efficiency policies may be ineffective, or even have perverse consequences, in the short run or the intermediate run for some years either nation-wide or for some provinces in China, particularly in the earlier half of our data set.

References

Adetutu, M.O., Glass, A.J., and Weyman-Jones, T.G. (2016). Economy-wide estimates of rebound effects: Evidence from panel data. Energy Journal, 37 (3), 251-269.

Azevedo, I.M.L. (2014). Consumer end-use energy efficiency and rebound effects. Annual Review of Environment and Resources, 39, 393-418.

Barker, T., Dagoumas, A., and Rubin, J. (2009). The macroeconomic rebound effect and the world economy. Energy Efficiency, 2, 411-427.

Barker, T., Ekins, P., and Foxon, T. (2007a). Macroeconomic effects of efficiency policies for energy-intensive industries: The case of the UK Climate Change Agreements, 2000–2010. Energy Economics, 29 (4), 760–778.

Barker, T., Ekins, P., and Foxon, T. (2007b). The macro-economic rebound effect and the UK economy. Energy Policy, 35, 4935–4946.

Berkhout, P.H.G., Muskens, J.C., and Velthuijsen, J.W. (2000). Defining the rebound effect. Energy Policy, 28 (6–7), 425–432.

Binswanger, M. (2001). Technological progress and sustainable development: what about the rebound effect? Ecological Economics, 36(1), 119–32.

Borenstein, S. (2015). A microeconomic framework for evaluating energy efficiency rebound and some implications. Energy Journal, 36 (1), 1-21.

Brookes, L. (1978). Energy policy, the energy price fallacy and the role of nuclear energy in the UK. Energy Policy, 6(1), 94–106.

Chan, N.W., and Gillingham, K. (2015). The microeconomic theory of the rebound effect and its welfare implications. Journal of the Association of Environmental and Resource Economists, 2(1), 133-159.

De Borger, B., Mulalic, I., and Rouwendal, J. (2016). Measuring the rebound effect with micro data: A first difference approach. Journal of Environmental Economics and Management, 79, 1-17.

DeGroot, M.H. (1986). Probability and Statistics. Boston, MA: Addison-Wesley Publishing Company.

Dimitropoulos, J. (2007). Energy productivity improvements and the rebound effect: an overview of the state of knowledge. Energy Policy, 35, 6354–6363.

Emission Database for Global Atmospheric Research [EDGAR]. (2014). CO2 time series 1990-2011 per region/country. URL: http://edgar.jrc.ec.europa.eu/overview.php?v=CO2ts1990-2011

Gillingham, K., Rapson, D., and Wagner, G. (2016). The rebound effect and energy efficiency policy. Review of Environmental Economics and Policy, 10 (1), 68-88.

Gillingham, K., Kotchen, M., Rapson, D., and Wagner, G. (2013). The rebound effect is over-played. Nature, 493, 475-476.

Ghoddusi, H., and Roy, M. (2017). Supply elasticity matters for the rebound effect and its impact on policy comparisons. Energy Economics. doi: 10.1016/j.eneco.2017.07.017

Guerra, A.-I., and Sancho, R. (2010). Rethinking economy-wide rebound measures: An unbiased proposal. Energy Policy, 38 (11), 6684-6694.

Guo, C., Guo, J., and Ling, Y. (2010). Estimating the rebound effect of energy consumption of industrial sectors in China based on the perspective of technological advancement. Resources Science, 32 (10), 1389-1395.

Greening, L.A, Greene, D.L, and Difiglio, C. (2000). Energy efficiency and consumption—the rebound effect—a survey. Energy Policy, 28 (6–7), 389–401.

Grepperud, S., and Rasmussen, I. (2004). A general equilibrium assessment of rebound effects. Energy Economics, 26 (2), 261–282.

Howarth, R.B. (1997). Energy efficiency and economic growth. Contemporary Economic Policy, 15(4), 1–9.

International Energy Agency [IEA]. (2014). World Energy Outlook 2014.

Intriligator, M.D. (1978). Econometric Models, Techniques and Applications. Englewood Cliffs, NJ: Prentice Hall.

Jenkins, J., Nordhaus, T., and Shellenberger, M. (2011). Energy emergence: Rebound and backfire as emergent phenomena. Oakland, CA: Breakthrough Institute.

Jevons, W.S. (1865). The coal question: an inquiry concerning the progress of the nation, and the probable exhaustion of our coal-mines. London: Macmillan and Co.

Khazzoom, J.D. (1980). Economic implications of mandated efficiency in standards for household appliances. Energy Journal, 1(4), 21–40.

Khazzoom, J.D. (1987). Energy savings from the adoption of more efficient appliances. Energy Journal, 8(4), 85-89.

Li, L., and Han, Y. (2012). The energy efficiency rebound effect in China from three industries perspective. Energy Procedia, 14, 1105-1110.

Liu, F.-C., and Liu, Y.-Y. (2008). Rebound effect of energy consumption due to technological progress: Empirical analysis based on provincial panel data in China. Resources Science, 30 (9), 1300-1306.

Lu, Y., Liu, Y., and Zhou, M. (2017). Rebound effect of improved energy efficiency for different energy types: A general equilibrium analysis for China. Energy Economics, 62, 248-256.

Sato, K. (1967). A two-level constant-elasticity-of-substitution production function. Review of Economic Studies, 43, 201-218.

Saunders, H.D. (1992). The Khazzoom–Brookes postulate and neoclassical growth. Energy Journal, 13(4), 131–48.

Saunders, H.D. (2000a). A view from the macro side: rebound, backfire and Khazzoom–Brookes. Energy Policy, 28(6–7), 439–49.

Saunders, H.D. (2000b). Does predicted rebound depend on distinguishing between energy and energy services? Energy Policy, 28, 497–500.

Saunders, H.D. (2005). A calculator for energy consumption changes arising from new technologies. B.E. Journal of Economic Analysis and Policy: Topics, 5 (1), Article 15.

Saunders, H.D. (2008). Fuel conserving (and using) production functions. Energy Economics, 30, 2184-2235.

Si, S., Chalfant, J.A., Lin Lawell, C.-Y.C., and Yi, F. (2017a). The effects of China's biofuel policies on agricultural and ethanol markets. Working paper, Cornell University.

Si, S., Lyu, M., Lin Lawell, C.-Y.C., and Chen, S. (2017b). The effects of energy-related policies on energy consumption in China. Working paper, Cornell University.

Sorrell, S. (2007). The rebound effect: an assessment of the evidence for economy-wide energy savings from improved energy efficiency. UK Energy Research Centre, November.

Sorrell, S. (2009). Jevons' Paradox revisited: The evidence for backfire from improved energy efficiency. Energy Policy, 37(4), 1456-1469.

Sorrell, S., and Dimitropoulos, J. (2008). The rebound effect: Micro-economic definitions, limitations and extensions. Ecological Economics, 65, 636-649.

Turner, K. (2009). Negative rebound and disinvestment effects in response to an improvement in energy efficiency in the UK economy. Energy Economics, 31, 648-666.

Turner, K. (2013). "Rebound" effects from increased energy efficiency: A time to pause and reflect. Energy Journal, 34(4), 25-42.

Wei, T. (2007). Impact of energy efficiency gains on output and energy use with Cobb–Douglas production function. Energy Policy, 35(4), 2023–2030.

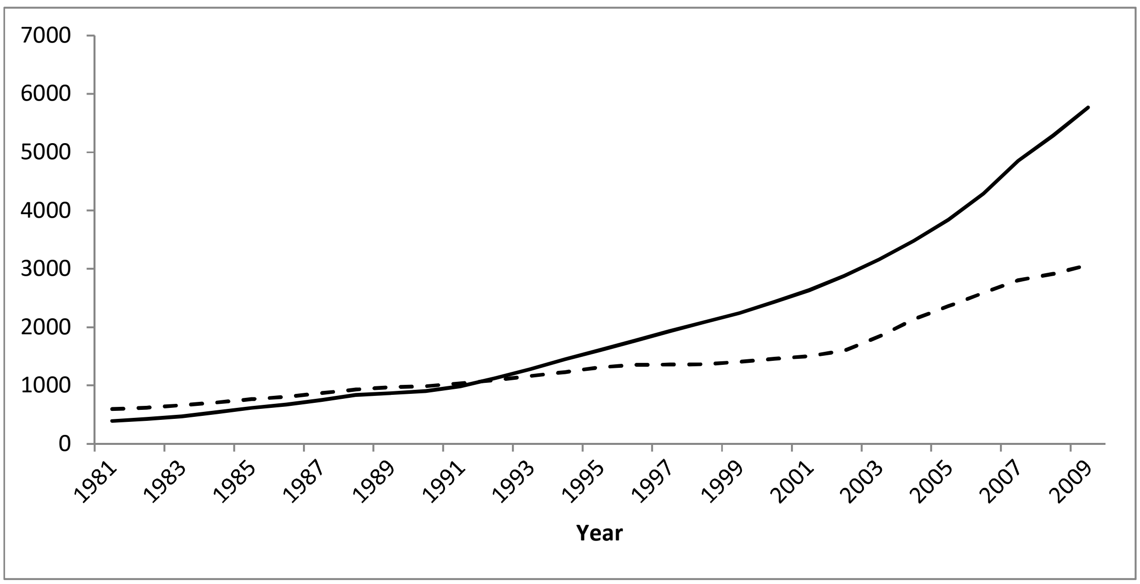
Zhang, Y.-J., Peng, H.-R., and Su, B. (2017). Energy rebound effect in China's Industry: An aggregate and disaggregate analysis. Energy Economics, 61, 199-208.

Zhou, Y., and Liu, Y.-Y. (2007). The effect of technological progress on the energy consumption rebound effect. [In Chinese]. Economist, 2, 45-52.

Table 1. Summary statistics for national data, 1981-2009

Variable	Obs	Mean	Std. Dev.	Min	Max
GDP (10^8 Yuan)	29	20542.12	15590.16	3907.73	57662.31
Capital (10^8 Yuan)	29	50286.99	52075.1	5765.35	196655.9
Labor (100 million people)	29	648.2576	111.3533	437.25	779.95
Energy consumption (10^4 tce)	29	1430.297	715.9276	594.47	3066.47

Figure 1. National GDP and energy consumption



Notes: The solid line indicates GDP in billion Yuan and the dotted line indicates energy consumption in 10^4 tce.

Table 2. Mean values of province-level data, 1986-2009

Region	GDP (10^8 Yuan)	Capital stock (10^8 Yuan)	Labor (10^4 people)	Energy consumption (10^4 tce)
Anhui	490.0354	642.28	3199.73	4731.5
Beijing	1040.622	5073.55	754.5896	4067.167
Fujian	830.35	1119.38	1627.324	3510.792
Gansu	386.4113	1207.081	1324.586	3129.543
Guangdong	1940.039	4338.44	3887.53	10175.79
Guangxi	476.5779	1030.352	2418.419	2950.75
Guizhou	211.8833	593.145	1903.745	4037.583
Hebei	1532.76	3079.611	3258.447	11876.54
Heilongjiang	644.3371	1243.59	1556.91	6425.333
Henan	1081.003	3198.558	4890.994	9111.542
Hubei	813.8025	1321.805	2572.458	6752.292
Hunan	701.515	1377.952	3424.138	6106.625
Inner Mongolia	521.0229	1571.795	1004.246	5226.875
Jiangsu	2444.23	5633.941	3712.08	10306.63
Jiangxi	428.6592	932.6496	1975.486	2781.542
Jilin	525.4667	1098.615	1144.278	4433.792
Liaoning	1819.255	1500.868	1939.135	10646.08
Ningxia	111.1392	217.7633	255.2933	1373.333
Qinghai	67.49208	210.0696	239.2575	993.2083
Shaanxi	564.16	1468.926	1745.876	3676.25
Shandong	2394.171	6210.815	4656.64	13343.58
Shanghai	2468.591	4150.398	810.8496	5527.25
Shanxi	498.4046	1859.814	1419.598	8285.75
Sichuan	1016.47	3588.689	6118.118	11114.04
Tianjin	635.8104	1601.858	464.94	3014.542
Xinjiang	420.8358	994.1033	687.9888	3596.5
Yunnan	389.9738	307.6621	2213.198	3663.542
Zhejiang	1617.049	3432.298	2833.211	6651.458

Table 3. Two-level nested CES production function for China

	Dependent variable is log GDP
α_1	-1.1609***
	(0.0584)
α_2	0.0383***
	(0.0078)
α_3	-0.0011***
	(0.0003)
ρ	-8.0380
	(23.5009)
b	0.9999***
	(0.0000)
a	0.8294***
	(0.0197)
ρ_1	-0.4550**
	(0.1699)
Observations	672
R-squared	0.9187

Notes: Robust standard errors are in parentheses. Significance codes: *** p<0.001, ** p<0.01, * p<0.05.

Table 4. Macroeconomic rebound effect

Rebound effect *R*	**Price effect** η_p	**Growth effect** η_g
-0.1421	-1.1421 *	0.0000 ***
(0.4744)	(0.4744)	(0.0000)

Notes: Standard errors are in parentheses. Significance codes: *** p<0.001, ** p<0.01, * p<0.05.

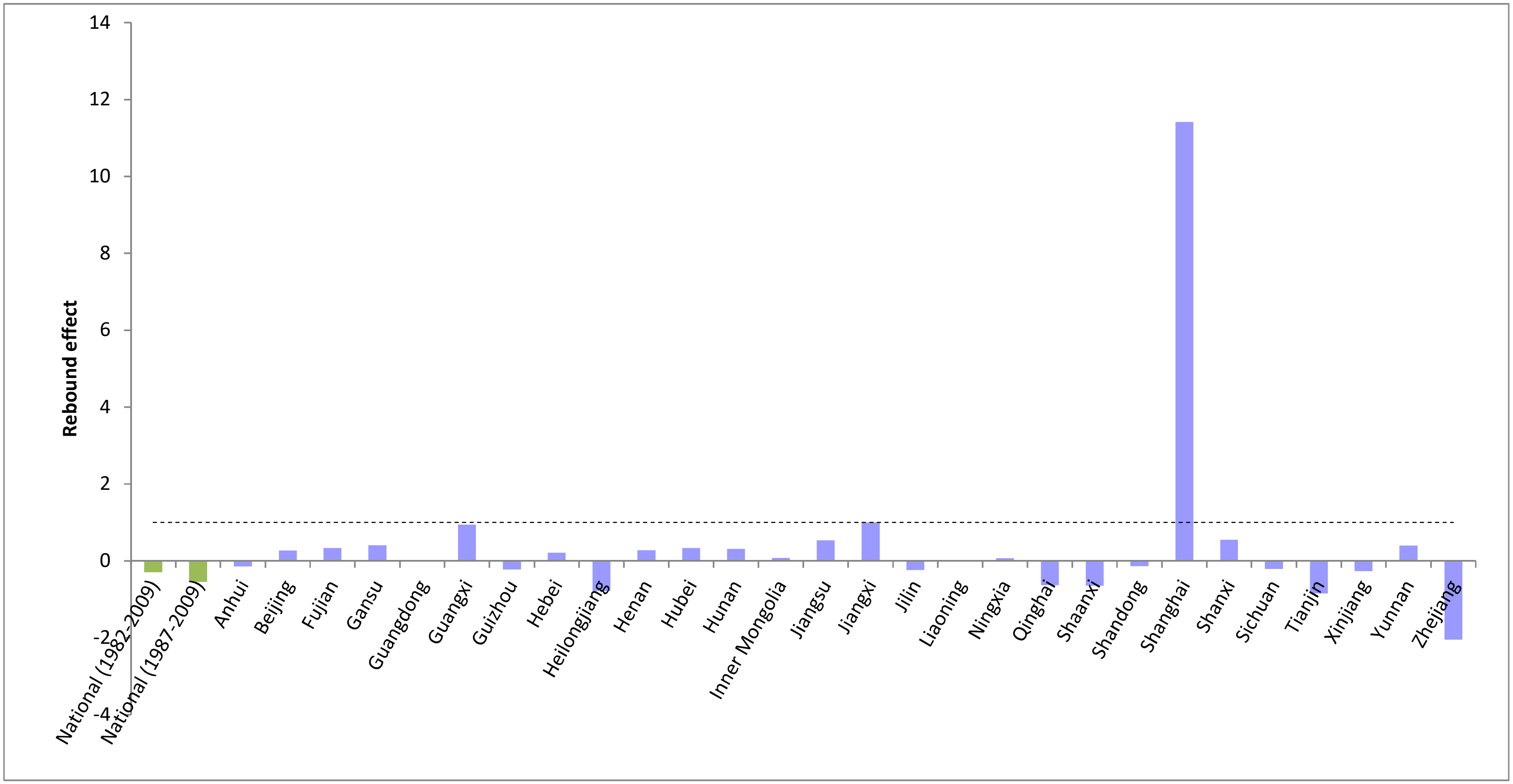
Table 5. Significance of province-level short-run macroeconomic growth rebound effect by province and year

	1987	1988	1989	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009
National	***	***	†	***	***	*	*	*	*										**	**			
Anhui	†	†	***	†	†	*	*	*	***									**					
Beijing	*	*	***	***	***	*	***	*	*									**					
Fujian	***	***	***	***	*	*	*	*	***				**			**		**	**				
Gansu	***	*	***	***	***	*	*	***	*				**					**	**				
Guangdong	*	*	†	*	*	*	*	*	†					**	**	**	**	**					
Guangxi	†	***	***	†	*	*	***	***	†		**			**		**			**				
Guizhou	†	†	†	***	***	†	*	†	†		**	**		**				**		**			
Hebei	***	*	***	*	***	*	*	*	*							**		**	**				
Heilongjiang	***	*	***	***	†	*	*	†	*								**	**					
Henan	*	***	*	***	***	*	*	*	*			**		**					**				
Hubei	***	†	***	*	***	*	*	*	†							**			**				
Hunan	***	***	*	***	***	***	*	***	***							**							
Inner Mongolia	***	*	†	†	***	*	*	*	*							**							
Jiangsu	***	*	***	*	***	*	*	*	*								**						
Jiangxi	***	***	*	*	*	*	*	***	†				**			**		**	**				
Jilin	*	*	†	†	*	*	*	*	***														
Liaoning	*	*	***	†	*	*	†	*	***														
Ningxia	†	***	†	†	*	*	*	*	*						**	**				**			
Qinghai	†	†	†	*	*	***	†	†	†							**	**			**			
Shaanxi	***	*	†	†	***	*	*	***	†								**	**					
Shandong	***	*	†	***	†	*	*	*	*							**							
Shanghai	***	*	***	***	*	*	*	*	***								**						
Shanxi	***	†	*	*	***	*	***	***	†								**		**	**			
Sichuan	***	†	***	*	***	*	*	*	†			**			**	**			**				

Tianjin	†	†	*	†	†	*	*	*	*					**				**					
Xinjiang	*	†	***	***	*	***	†	*	***											**			
Yunnan	***	*	***	†	*	*	*	***	†					**						**			
Zhejiang	†	†	†	†	*	*	*	†	†							**		**					

Significance codes: † significant and negative at 5% level; * significant and positive at 5% level; ** confidence interval includes a rebound effect of 1; *** significant and positive at 5% level and confidence interval includes a rebound effect of 1.

Figure 2. Mean province-level short-run macroeconomic growth rebound effect by province



Note: For each province, the mean is taken over all years over the period 1987-2009. A rebound effect of 1 is indicated by the horizontal dashed line.

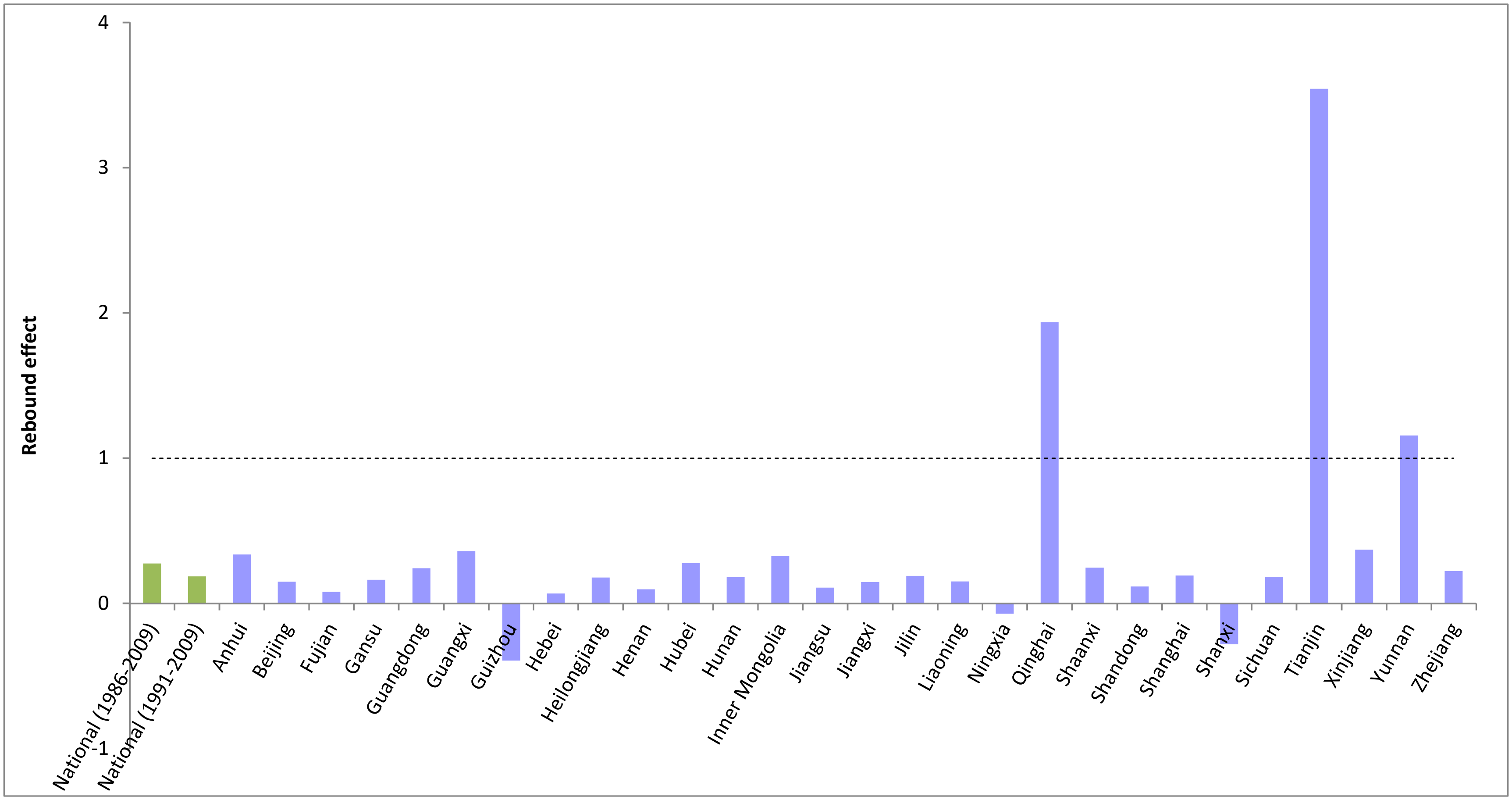
Table 6. Province-level intermediate-run macroeconomic growth rebound effect by province and year

	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009
National	***	*	*	*	*	*								**	**	**	**	**	
Anhui	†	***	***	*	*	*													
Beijing	*	*	*	*	*	*													
Fujian	*	*	*	*	*	*									**				
Gansu	*	*	*	*	*	*										**	**		
Guangdong	*	*	*	*	*	*		**	**				**	**	**	**			
Guangxi	***	***	***	*	*	*	**						**					**	
Guizhou	†	†	***	***	***	†			**					**					
Hebei	*	*	*	*	*	*							**		**				
Heilongjiang	***	*	*	*	*	*													
Henan	*	*	*	*	*	*							**					**	
Hubei	***	***	*	*	*	*								**	**	**	**		
Hunan	***	*	*	*	*	*												**	**
Inner Mongolia	***	***	***	*	*	*					**							**	
Jiangsu	*	*	*	*	*	*								**				**	
Jiangxi	*	*	*	*	*	*									**		**		
Jilin	***		***											**					
Liaoning	*	*	*	*	*	*													
Ningxia	†	***	***	*	*	*				**									
Qinghai	***	***	***	*	***	***	**		**				**		**				**
Shaanxi	*	*	*	*	***	***										**			
Shandong	***	*	*	*	*	*												**	
Shanghai	***	*	*	*	*	*													
Shanxi	***	*	*	*	†	*						**	**	**		**			
Sichuan	***	*	*	*	*	*										**	**		

Tianjin	***	***	***	*	*	*													
Xinjiang	*	*	*	*	*	***	**							**					
Yunnan	***	*	*	*	*	*		**	**				**	**				**	
Zhejiang	*	*	*	*	*	***	**	**					**		**	**	**		

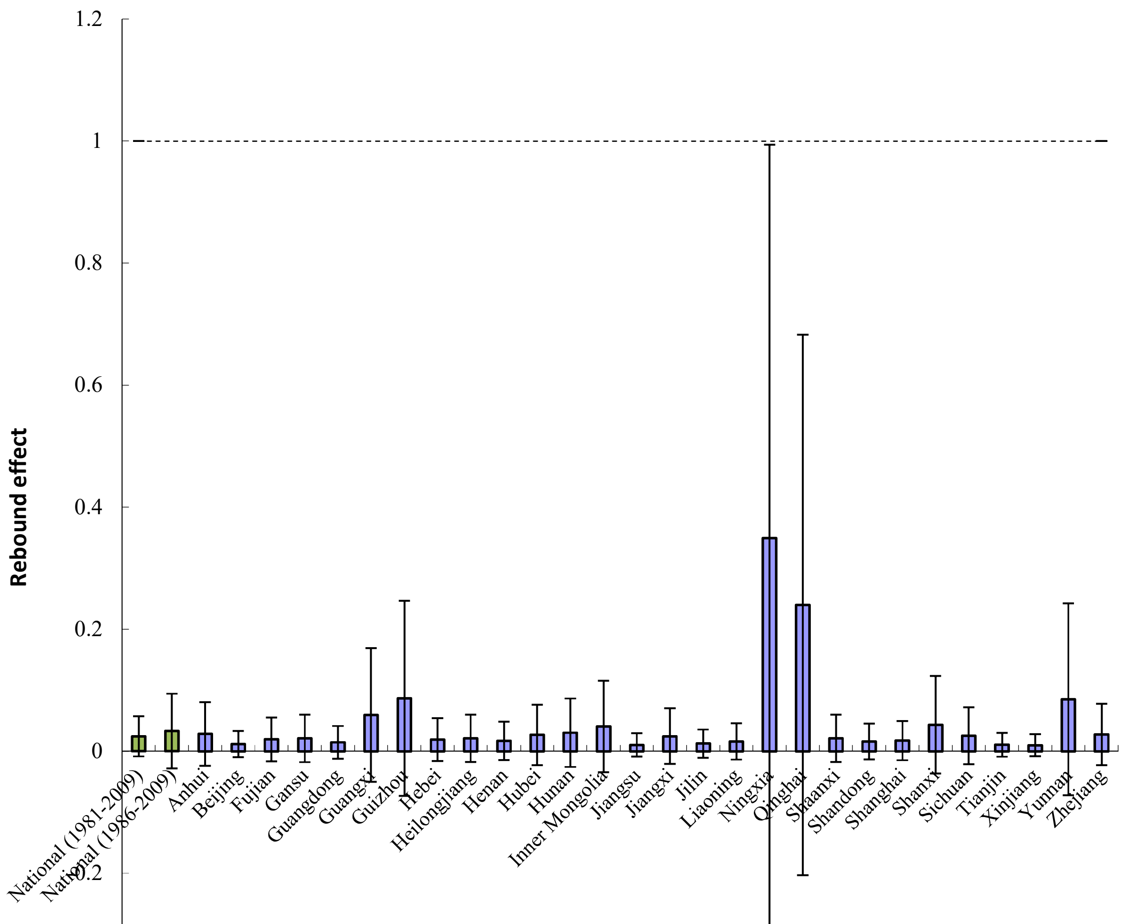
Significance codes: † significant and negative at 5% level; * significant and positive at 5% level; ** confidence interval includes a rebound effect of 1; *** significant and positive at 5% level and confidence interval includes a rebound effect of 1.

Figure 3. Mean province-level intermediate-run macroeconomic growth rebound effect by province



Note: For each province, the mean is taken over the intermediate-run rebound effect for that province for all years over the period 1991-2009. A rebound effect of 1 is indicated by the horizontal dashed line.

Figure 4. Long-run macroeconomic growth rebound effect



Note: The long-run rebound effect for each province spans the period 1986-2009. Error bars indicate the 95% confidence interval. A rebound effect of 1 is indicated by the horizontal dashed line.

Appendix

Appendix A

Proof of Proposition 1:

The partial derivative of output *Y* with respect to energy consumption *F* is given by:

$$
\begin{aligned}
\frac{\partial Y}{\partial F} &= -\frac{1}{\rho} B[b(aK^{-\rho_1} + (1-a)L^{-\rho_1})^{\rho/\rho_1} + (1-b)(\tau F)^{-\rho}]^{-\frac{1}{\rho}-1}(-\rho)(1-b)(\tau F)^{-\rho-1}\tau \\
&= BY^{1+\rho}(1-b)\tau^{-\rho}F^{-\rho-1} \\
&= (1-b)B\left(\frac{Y}{F}\right)^{1+\rho}\tau^{-\rho}.
\end{aligned}
\tag{A1}
$$

The elasticity S_F of output *Y* with respect to the energy consumption *F* is given by:

$$
S_F = \frac{\partial Y}{\partial F}\frac{F}{Y} = P_F\frac{F}{Y} = (1-b)\left(\frac{Y}{F}\right)^{\rho}\tau^{-\rho}, \tag{A2}
$$

where $P_F = \frac{\partial Y}{\partial F}$ equals the marginal productivity of energy consumption *F*, and can be thought of as representing the real energy price.

Following Saunders (2008), we use the implicit function theorem to deduce the expression of rebound effect. The solution vector is:

$$
\begin{bmatrix} \frac{\partial Y}{\partial \tau} \\ \frac{\partial F}{\partial \tau} \end{bmatrix} = -J^{-1}\begin{bmatrix} \frac{\partial \psi_1}{\partial \tau} \\ \frac{\partial \psi_2}{\partial \tau} \end{bmatrix} = \frac{S_F}{P_F(1-S_F)}\begin{bmatrix} -\frac{P_F}{S_F} & P_F \\ -1 & 1 \end{bmatrix}\begin{bmatrix} -\frac{S_F Y}{\tau} \\ -\frac{\rho}{1+\rho}\frac{F}{\tau}\frac{P_F}{S_F} \end{bmatrix}, \tag{A3}
$$

where:

$$
J = \begin{bmatrix} 1 & -P_F \\ 1 & -\frac{P_F}{S_F} \end{bmatrix}. \tag{A4}
$$

Thus, the elasticity η of energy consumption *F* with respect to the energy efficiency τ is given by:

$$
\eta = \frac{\tau}{F}\frac{\partial F}{\partial \tau} = \frac{1}{(1+\rho)(1-S_F)} - 1 , \tag{A5}
$$

We can decompose this elasticity into the price effect η_p:

$$\eta_p = \frac{\tau}{(F/Y)}\frac{\partial(F/Y)}{\partial\tau} = \frac{\tau}{F}\frac{\partial F}{\partial\tau} - \frac{\tau}{Y}\frac{\partial Y}{\partial\tau} = \frac{1}{(1+\rho)(1-S_F)} - 1 - \frac{S_F}{(1+\rho)(1-S_F)} = \frac{1}{1+\rho} - 1, \quad \text{(A6)}$$

and the growth effect η_g:

$$\eta_g = \frac{\tau}{Y}\frac{\partial Y}{\partial\tau} = \frac{1}{1+\rho}\frac{S_F}{1-S_F}. \quad \text{(A7)}$$

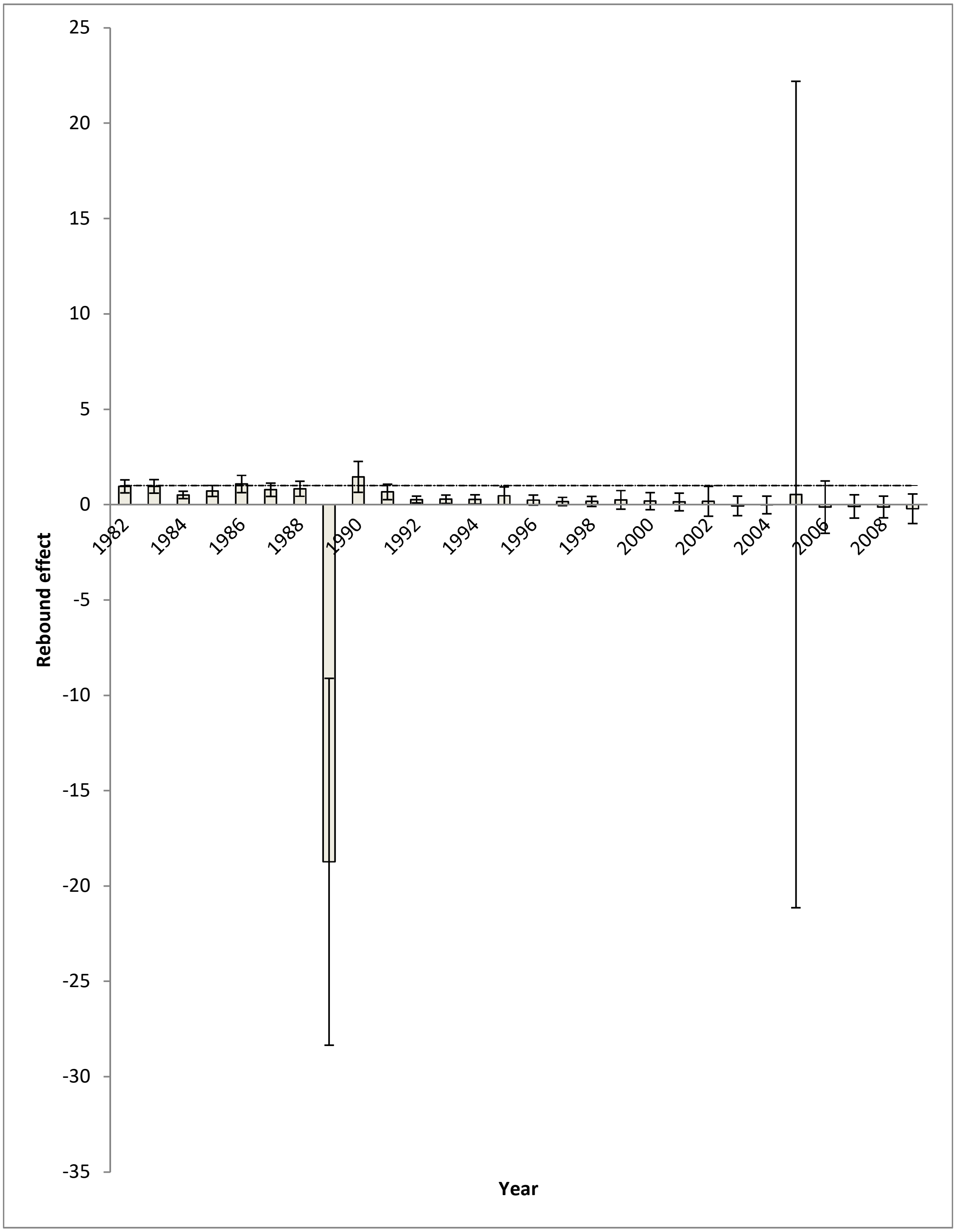
The rebound effect R is therefore given by:

$$R = 1+\eta = \frac{1}{(1+\rho)(1-S_F)} = \frac{1}{(1+\rho)\left(1-(1-b)\left(\frac{Y}{F}\right)^{\rho}\tau^{-\rho}\right)}. \quad \text{(A8)}$$

□

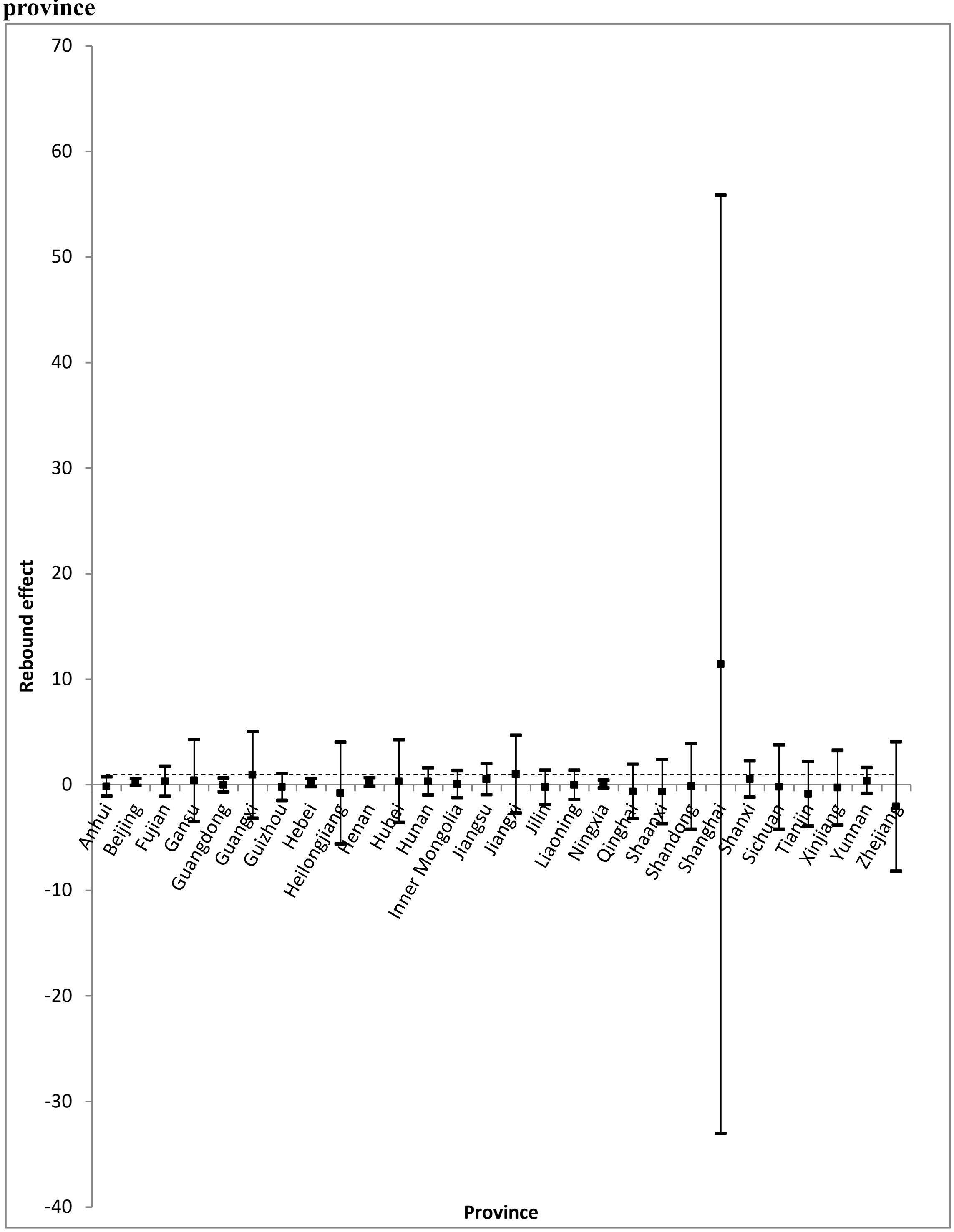
Appendix B

Figure B1. Short-run macroeconomic growth rebound effect by year



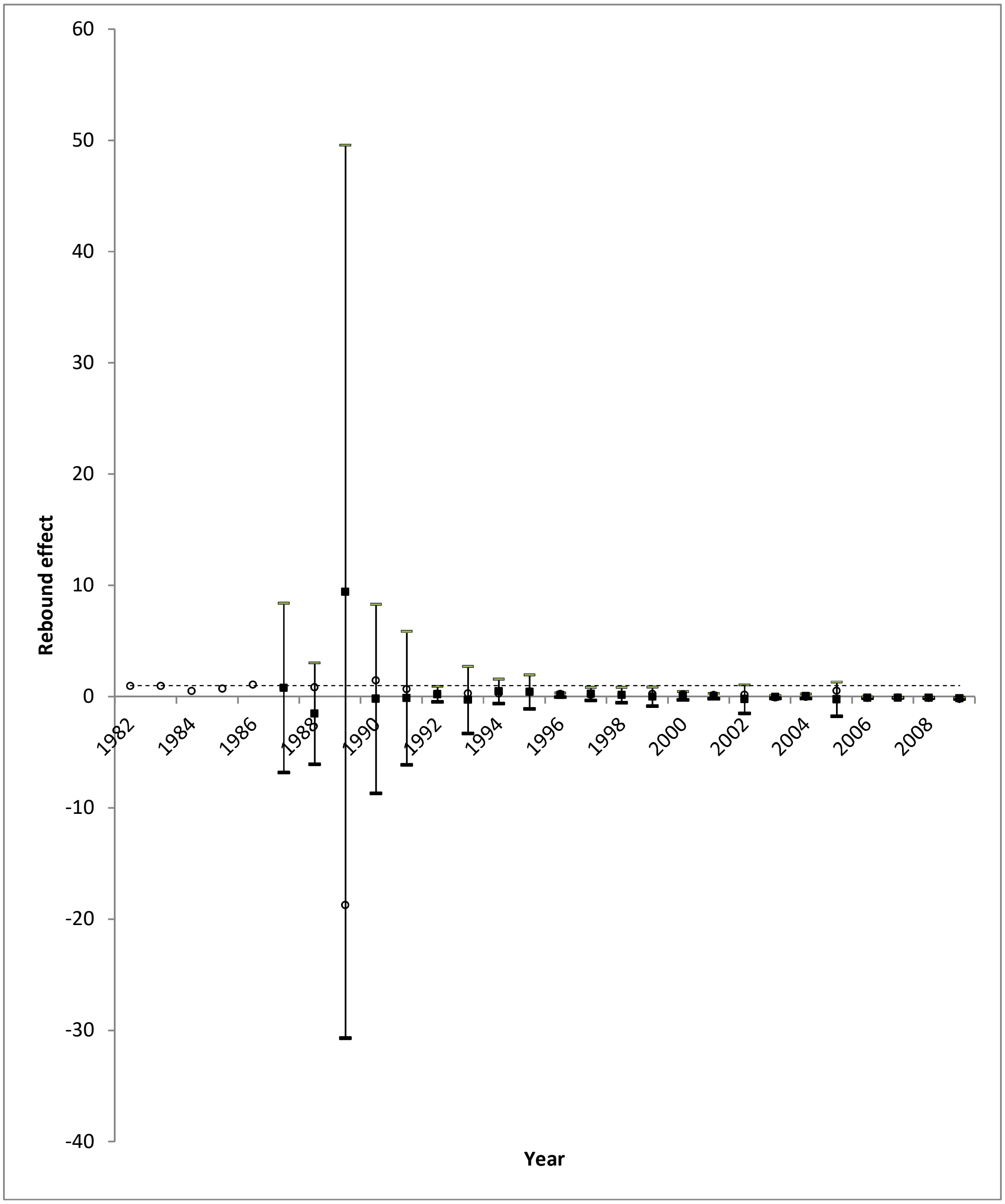
Note: Error bars indicate the 95% confidence interval. A rebound effect of 1 is indicated by the horizontal dashed line.

Figure B2. Mean province-level short-run macroeconomic growth rebound effect by province



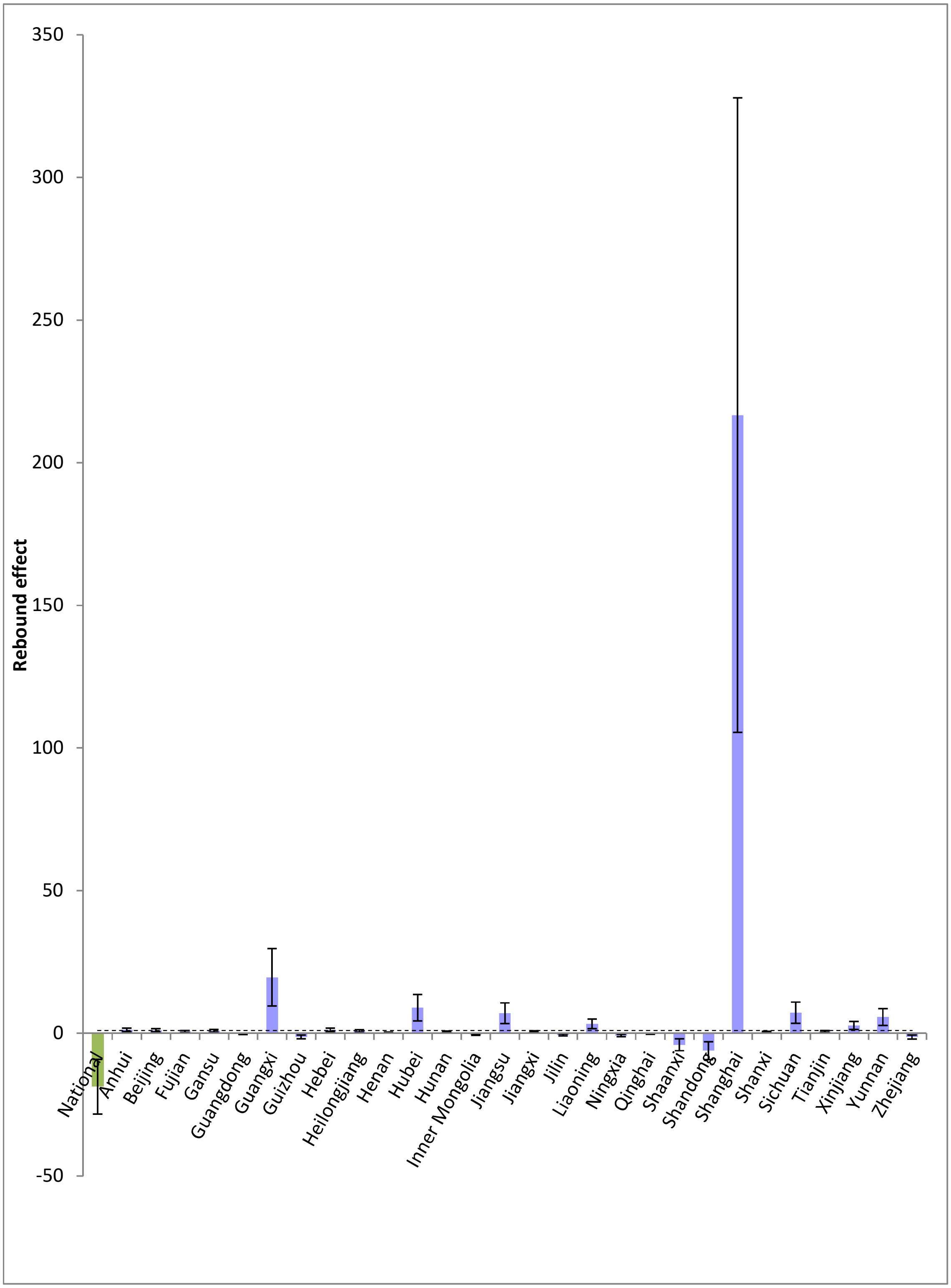
Notes: For each province, the mean is taken over all years over the period 1987-2009. Error bars indicate one standard deviation above and below the mean. A rebound effect of 1 is indicated by the horizontal dashed line.

Figure B3. Mean province-level short-run macroeonomic growth rebound effect by year



Notes: For each year, the mean is taken over all provinces. Filled squares indicate the mean over all provinces. Error bars indicate one standard deviation above and below the mean. Open circles indicate the national rebound effect. A rebound effect of 1 is indicated by the horizontal dashed line.

Figure B4. Province-level short-run macroeconomic growth rebound effect in 1989



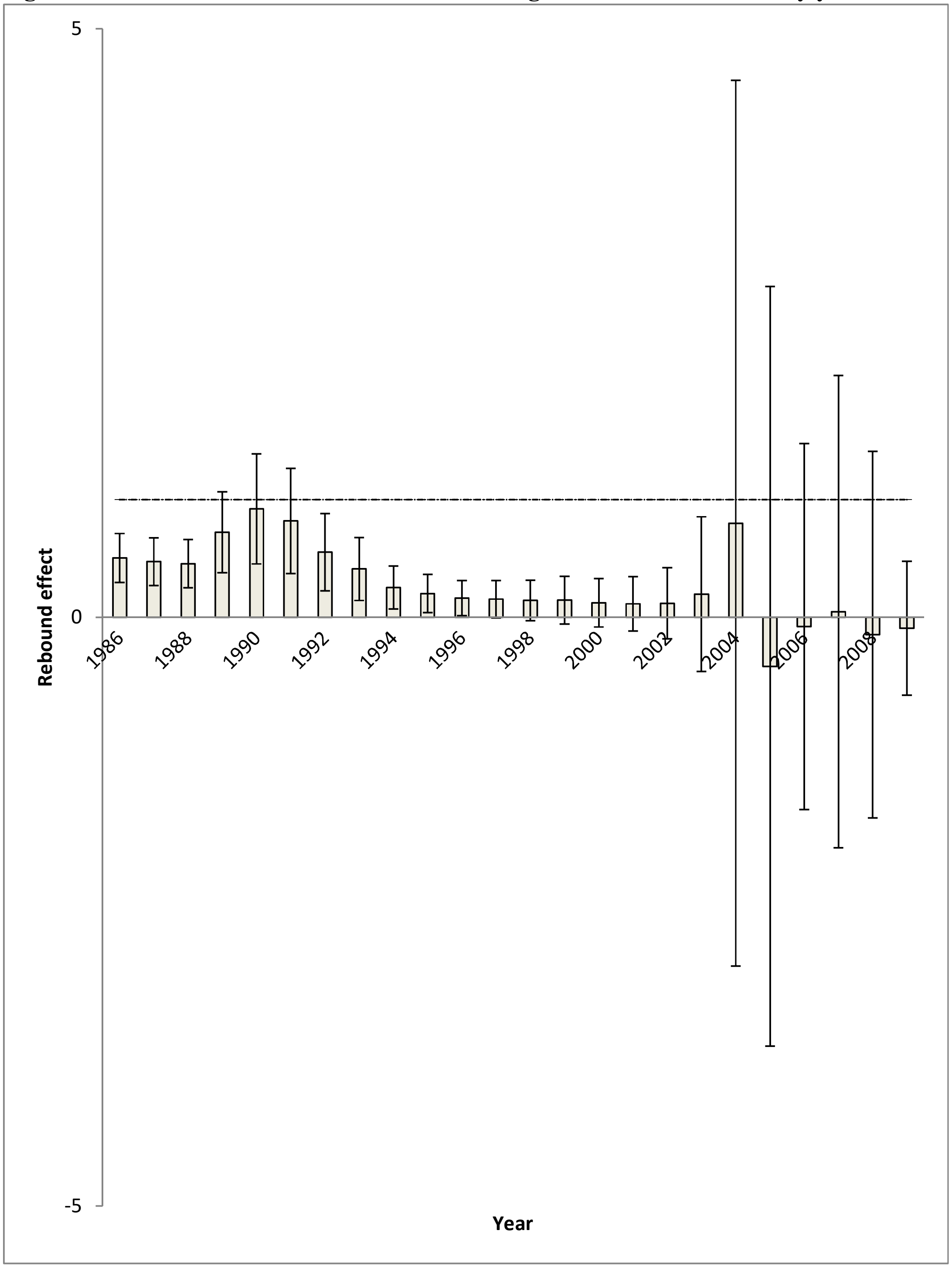
Note: Error bars indicate the 95% confidence interval. A rebound effect of 1 is indicated by the horizontal dashed line.

Table B1. Calculation of short-run macroeonomic growth rebound effect in 1989 for nation and for Shanghai

		National	Shanghai
GDP in 1988 (10^8 Yuan)	Y_t	8344.21	723.27
GDP in 1989 (10^8 Yuan)	Y_{t+1}	8683.26	744.97
Contribution of growth in technological progress to output growth in 1989	σ_{t+1}	0.300442	1.060772
Energy consumption in 1988 (10^4 tce)	F_t	929.97	2981
Energy consumption in 1989 (10^4 tce)	F_{t+1}	969.34	3070
Energy intensity in 1988	$EI_t = \frac{F_t}{Y_t}$	0.111451	4.121559
Energy intensity in 1989	$EI_{t+1} = \frac{F_{t+1}}{Y_{t+1}}$	0.111633	4.120971
Difference between potential energy savings and actual energy savings in 1989	$\sigma_{t+1} * (Y_{t+1} - Y_t) * (EI_{t+1})$	29.64558	94.85963

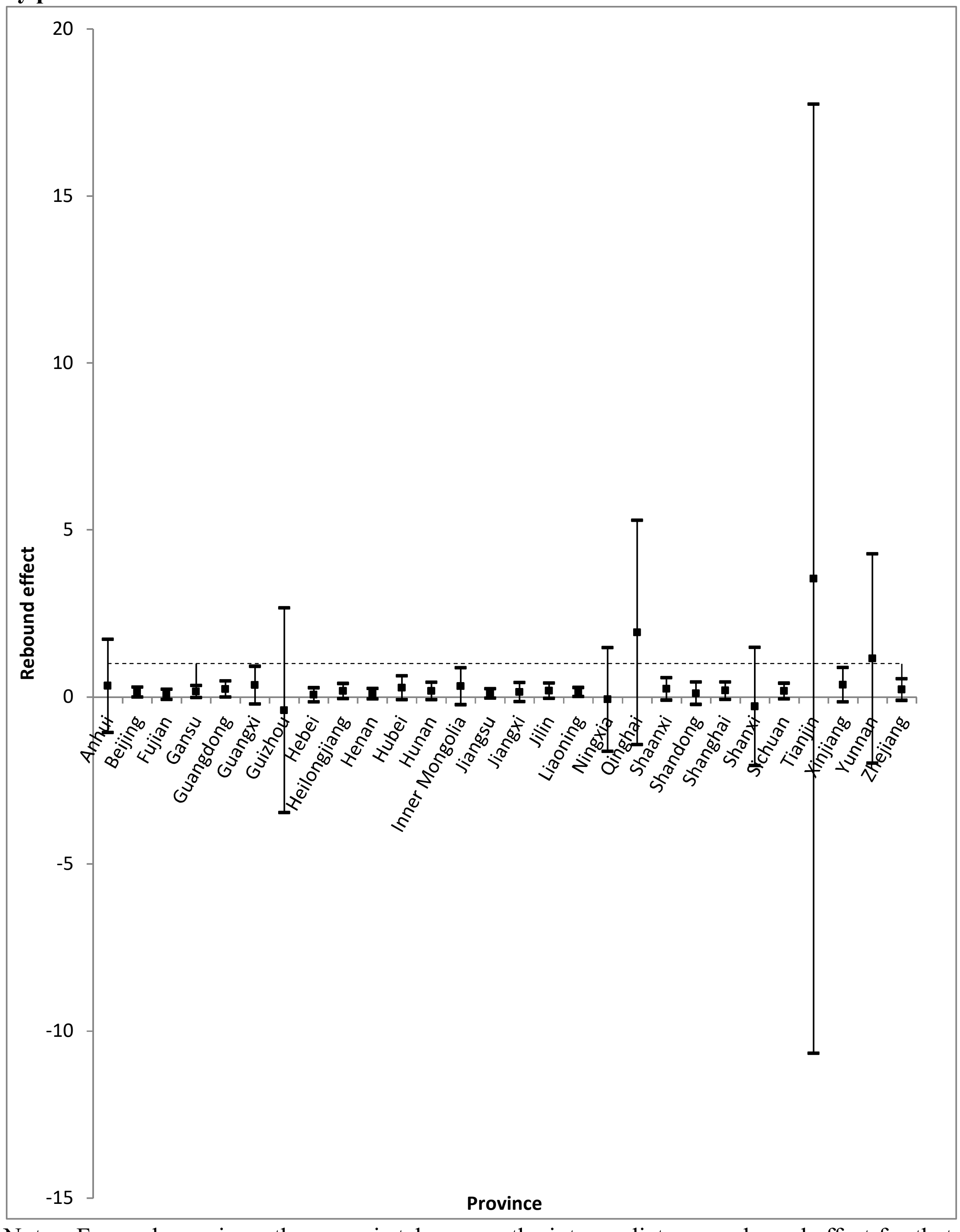
Potential energy savings in 1989	$Y_{t+1} * (EI_t - EI_{t+1})$	-1.58256	0.437831
Macroeconomic growth rebound effect in 1989	$R_{t+1} = \frac{\sigma_{t+1} * (Y_{t+1} - Y_t) * (EI_{t+1})}{Y_{t+1} * (EI_t - EI_{t+1})}$	-18.7327	216.6581

Figure B5. Intermediate-run macroeconomic growth rebound effect by year



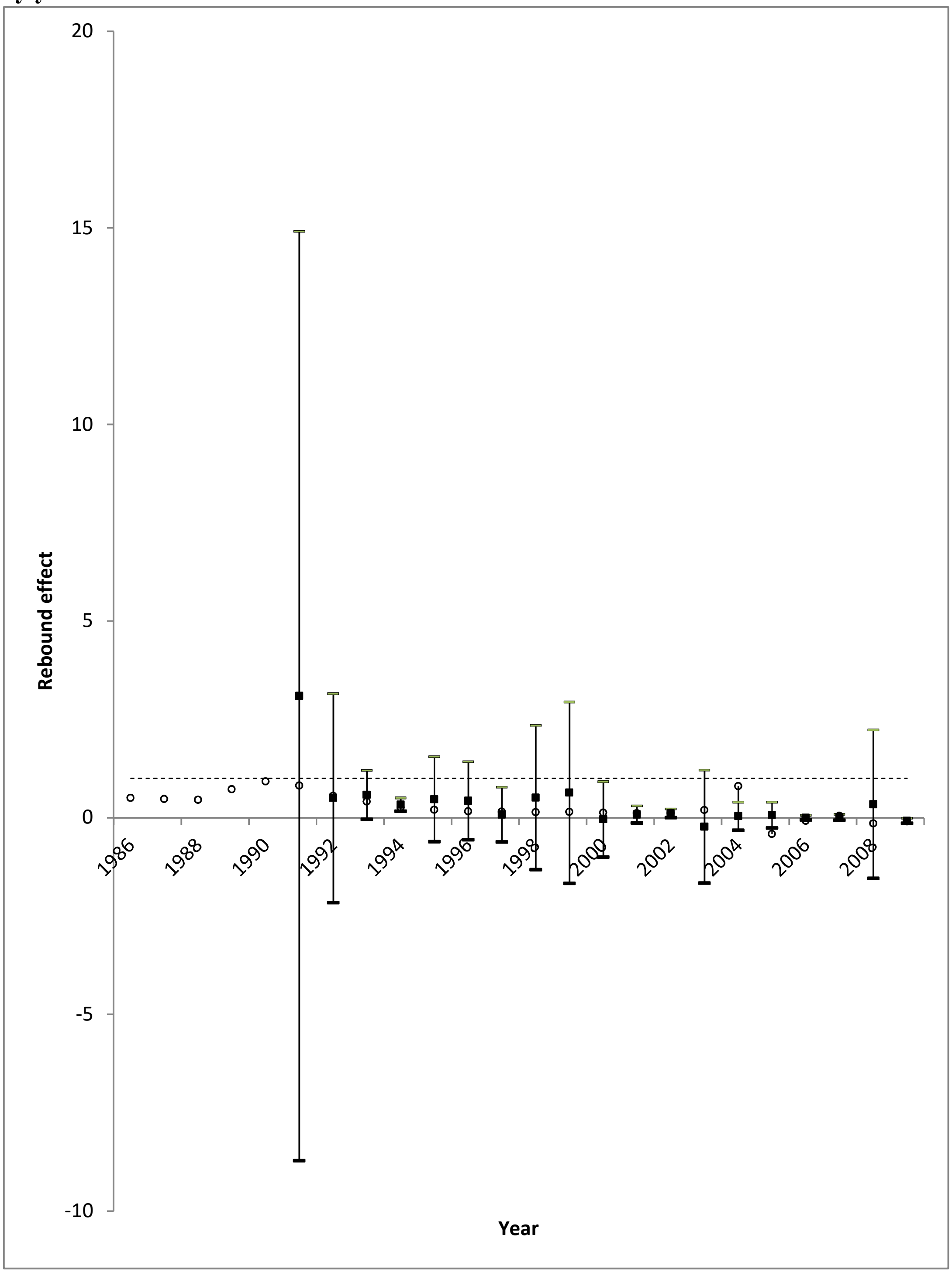
Note: Error bars indicate the 95% confidence interval. A rebound effect of 1 is indicated by the horizontal dashed line.

Figure B6. Mean intermediate-run province-level macroeconomic growth rebound effect by province



Notes: For each province, the mean is taken over the intermediate-run rebound effect for that province for all years over the period 1991-2009. Error bars indicate one standard deviation above and below the mean. A rebound effect of 1 is indicated by the horizontal dashed line.

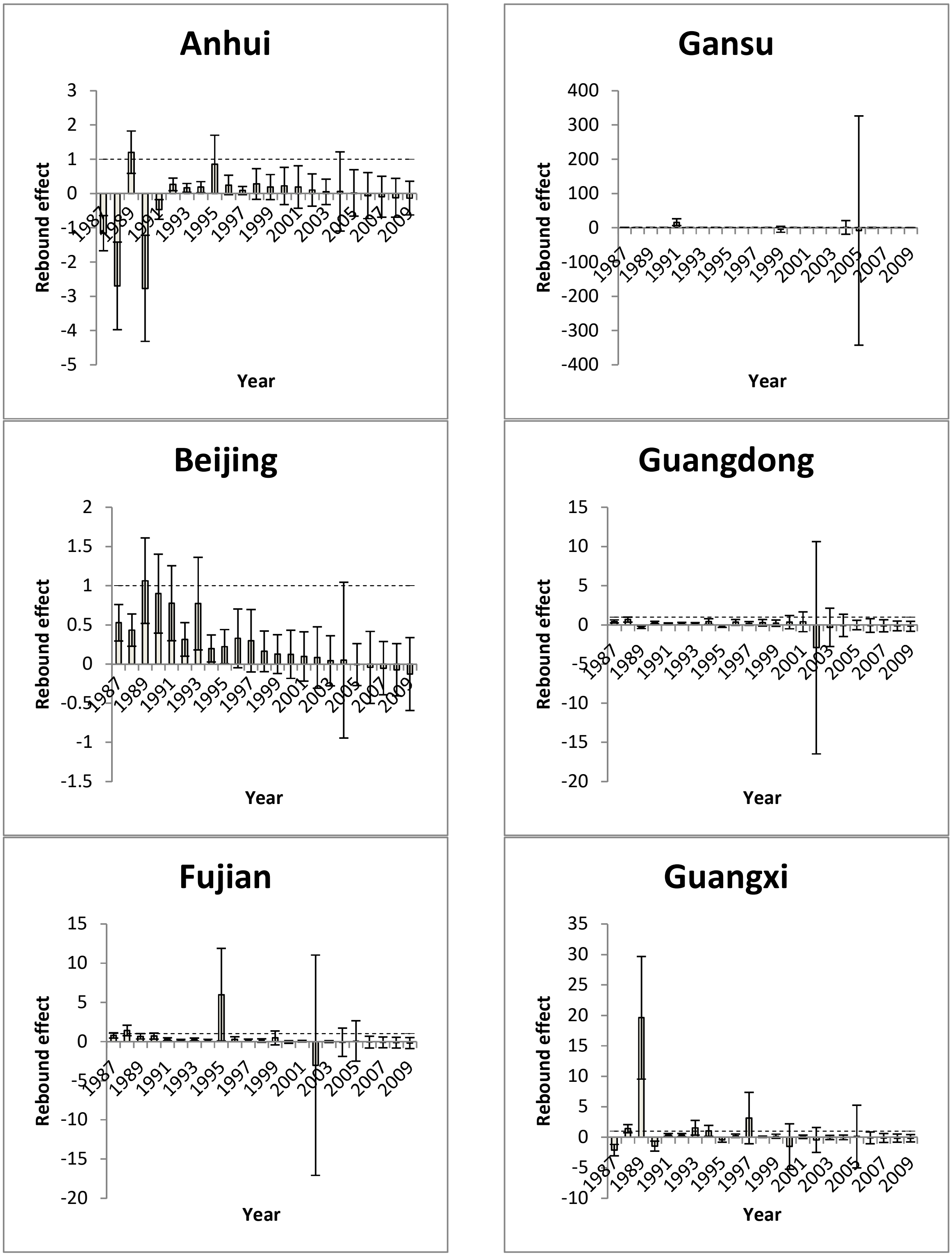
Figure B7. Mean province-level intermediate-run macroeconomic growth rebound effect by year



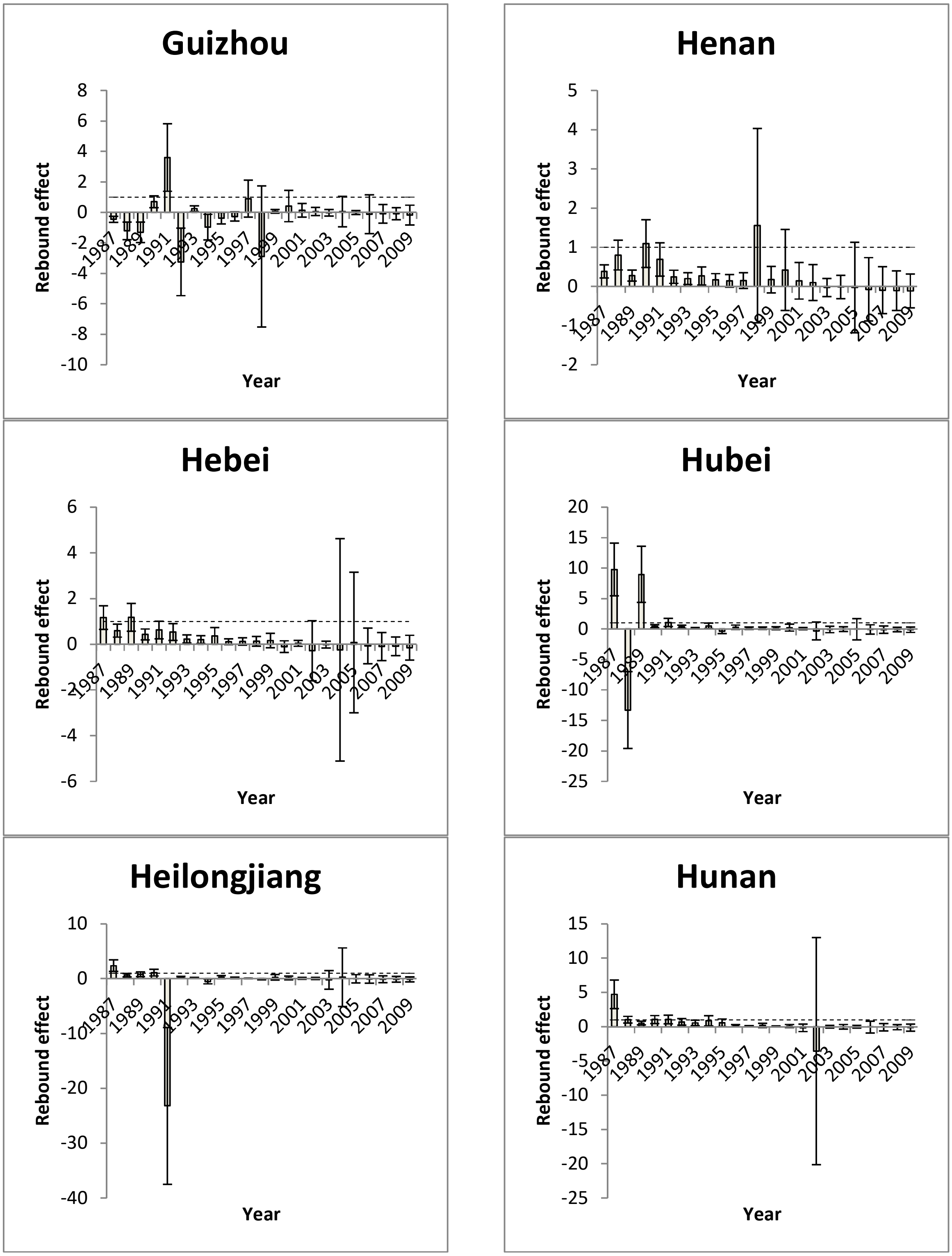
Notes: For each year, the mean is taken over all provinces. Filled squares indicate the mean over all provinces. Error bars indicate one standard deviation above and below the mean. Open circles indicate the national rebound effect. A rebound effect of 1 is indicated by the horizontal dashed line.

Appendix C

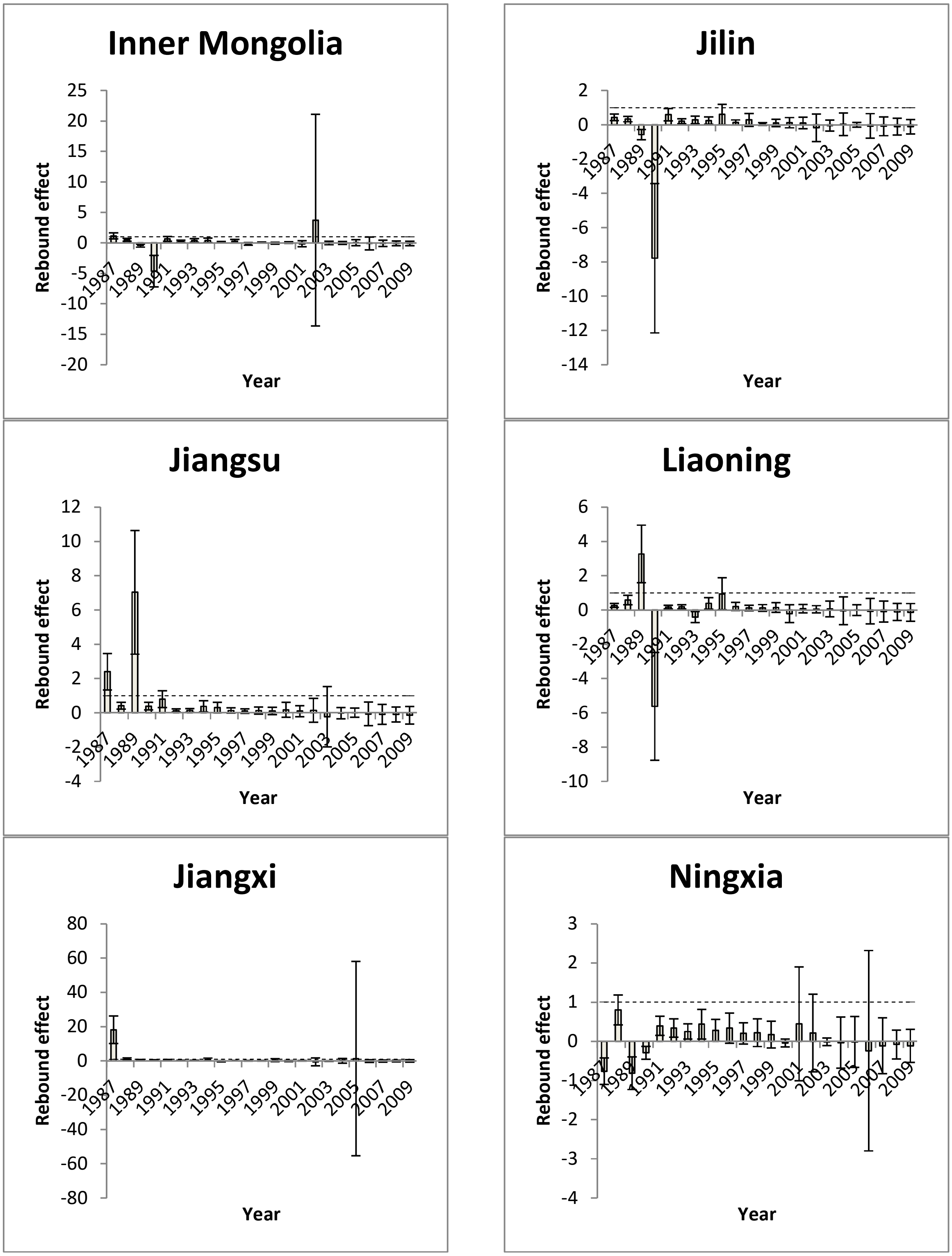
Figure C1. Short-run macroeconomic growth rebound effect



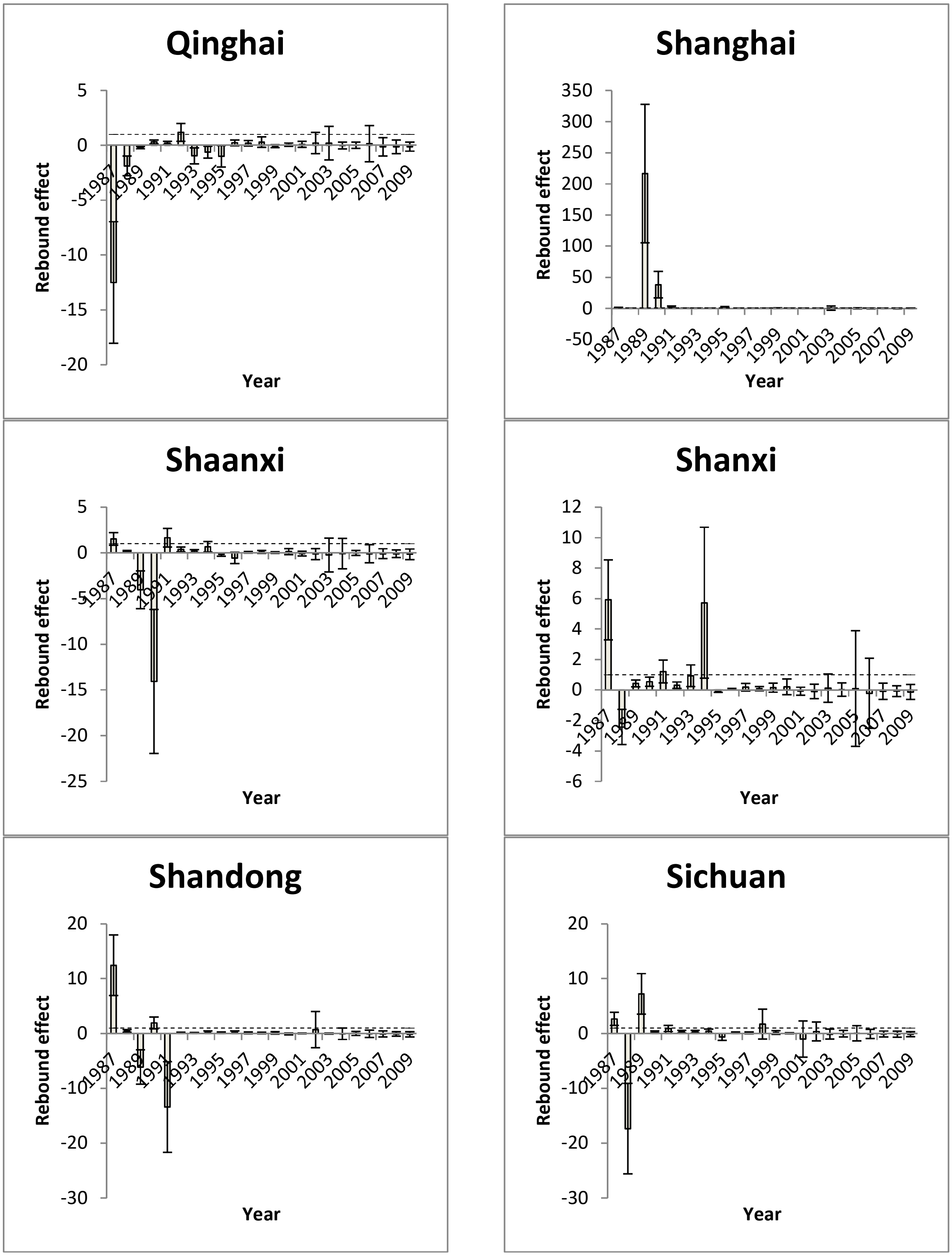
Note: Error bars indicate the 95% confidence interval. A rebound effect of 1 is indicated by the horizontal dashed line.



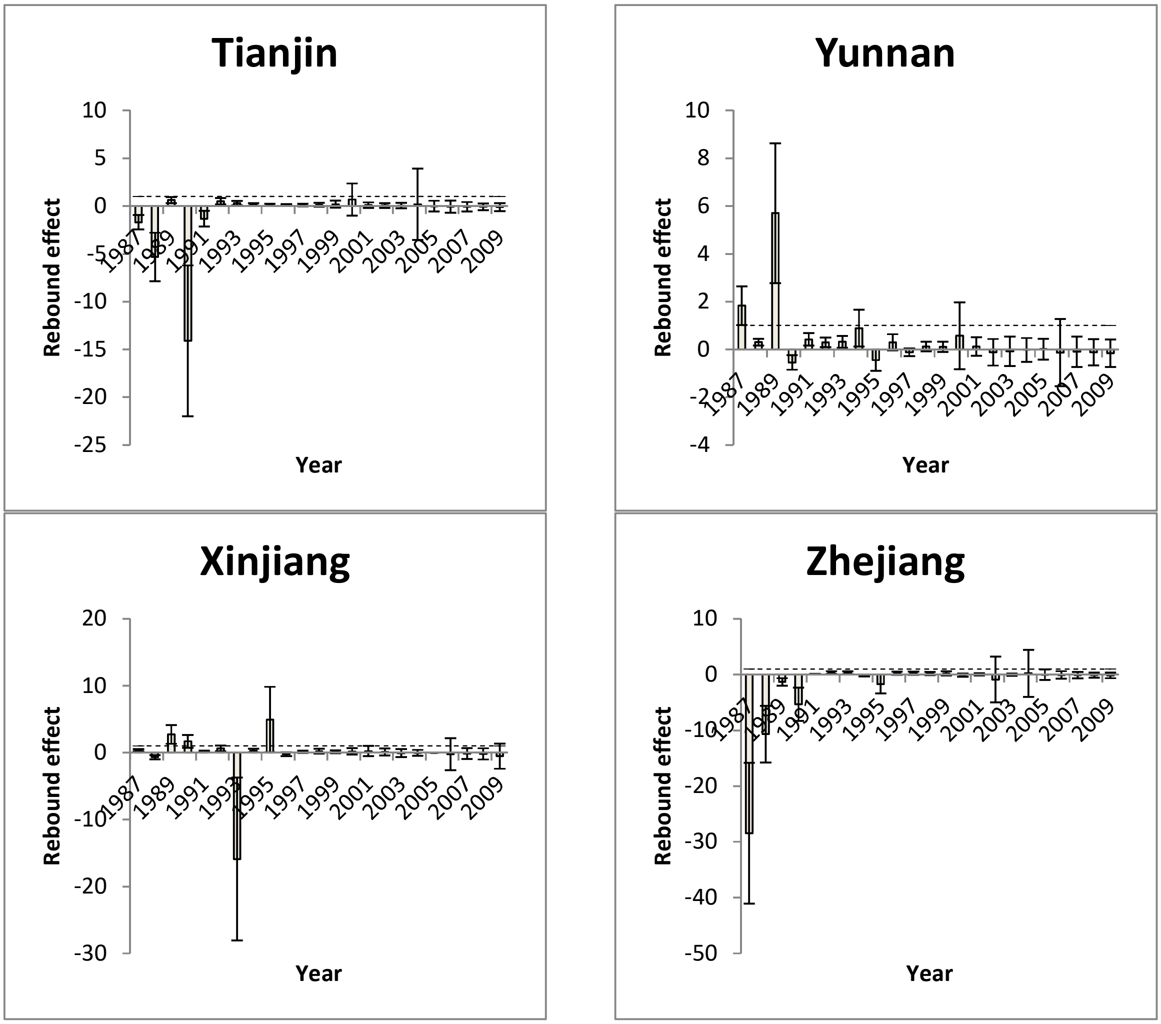
Note: Error bars indicate the 95% confidence interval. A rebound effect of 1 is indicated by the horizontal dashed line.



Note: Error bars indicate the 95% confidence interval. A rebound effect of 1 is indicated by the horizontal dashed line.

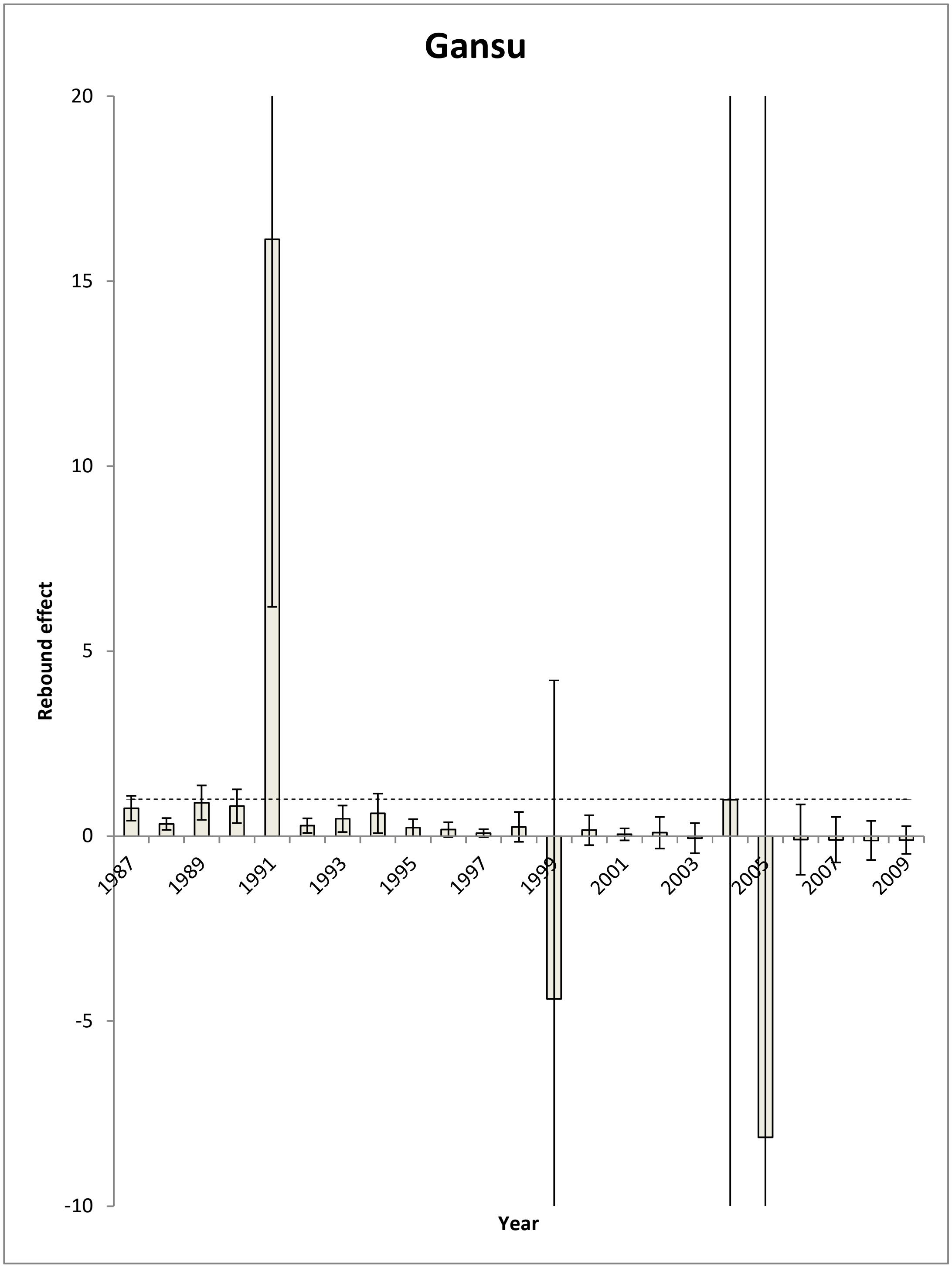


Note: Error bars indicate the 95% confidence interval. A rebound effect of 1 is indicated by the horizontal dashed line.



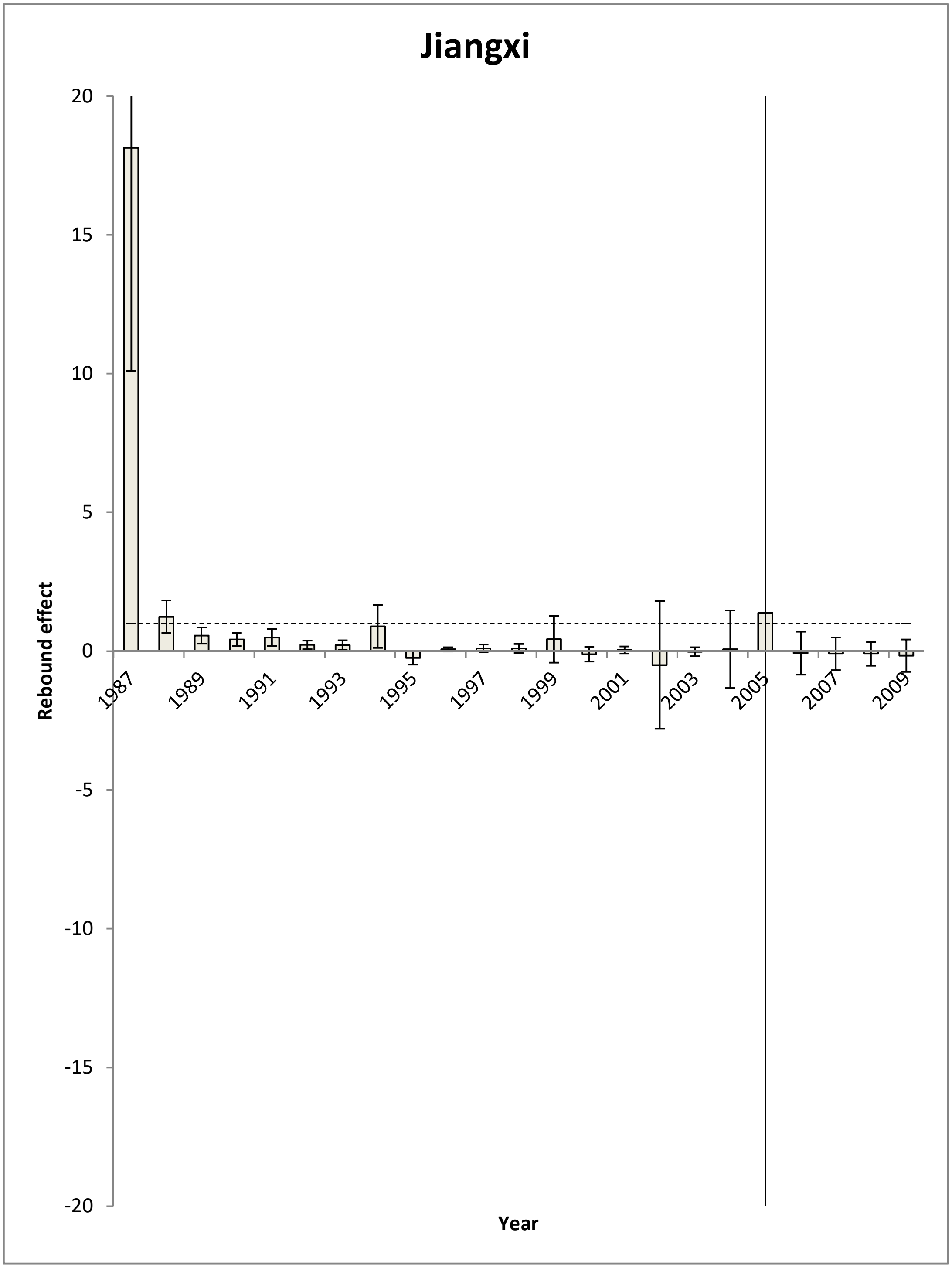
Note: Error bars indicate the 95% confidence interval. A rebound effect of 1 is indicated by the horizontal dashed line.

Figure C2a. Zoomed in version of Figure C1 for Gansu



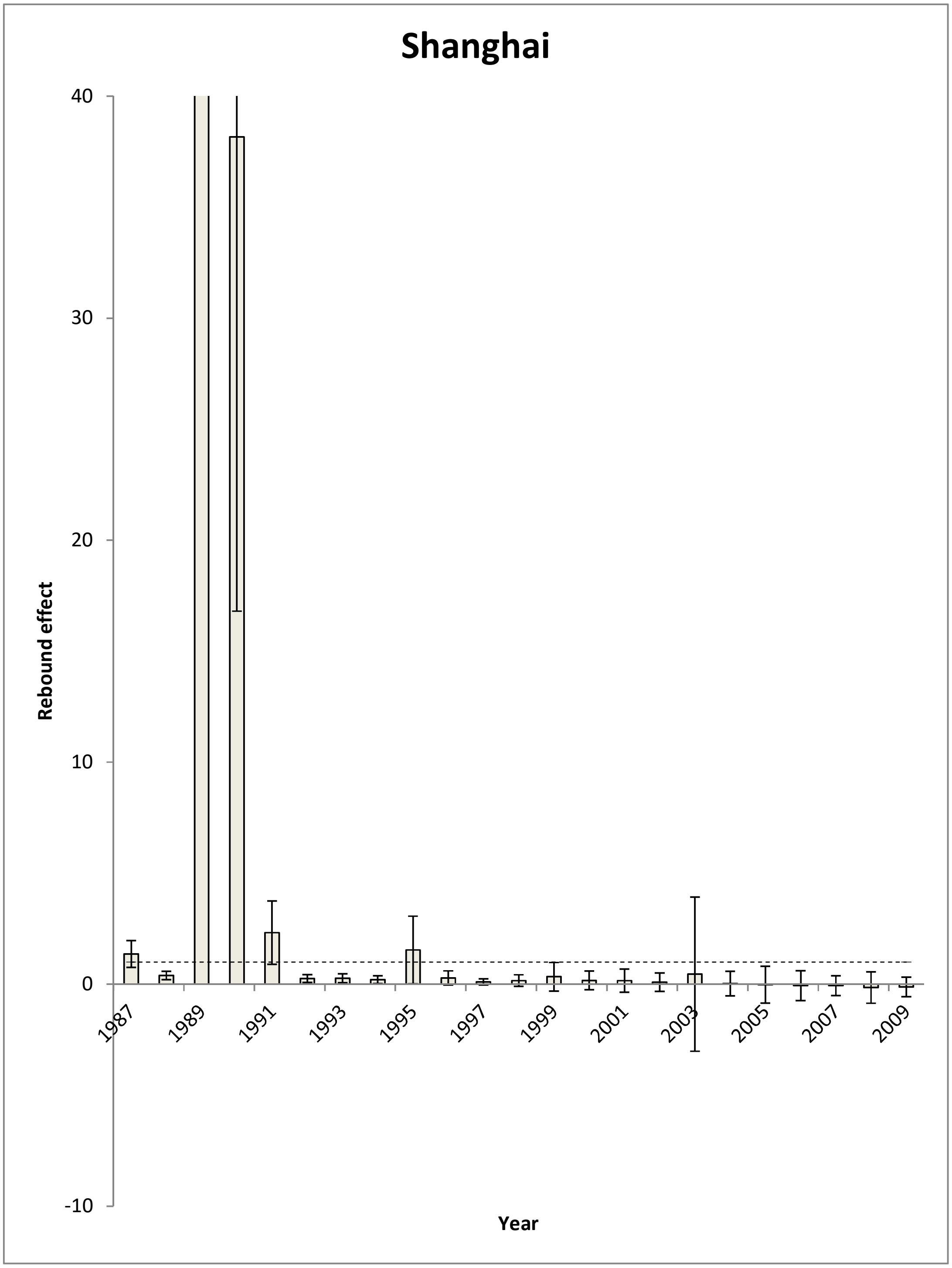
Note: Error bars indicate the 95% confidence interval. A rebound effect of 1 is indicated by the horizontal dashed line.

Figure C2b. Zoomed in version of Figure C1 for Jiangxi



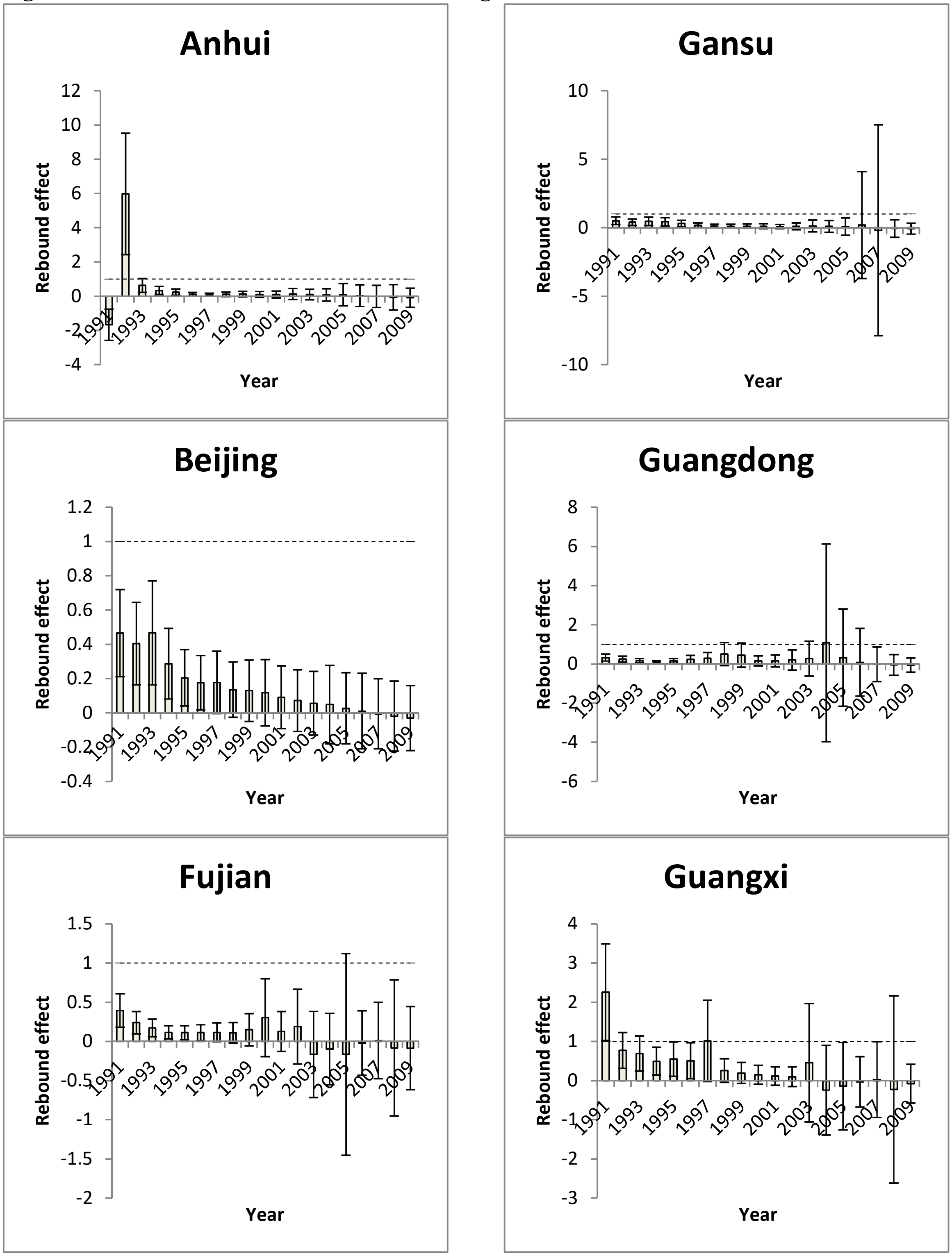
Note: Error bars indicate the 95% confidence interval. A rebound effect of 1 is indicated by the horizontal dashed line.

Figure C2c. Zoomed in version of Figure C1 for Shanghai

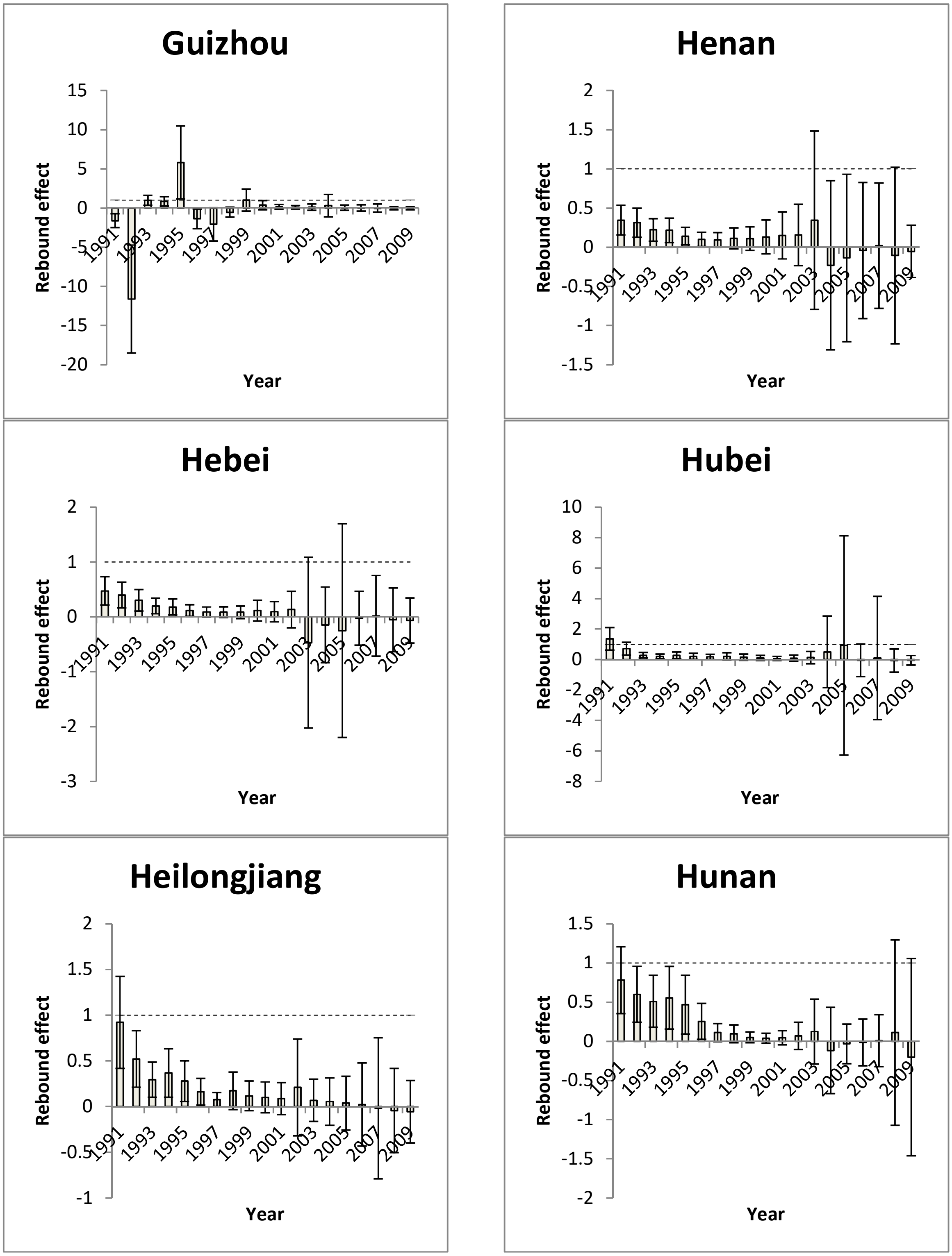


Note: Error bars indicate the 95% confidence interval. A rebound effect of 1 is indicated by the horizontal dashed line.

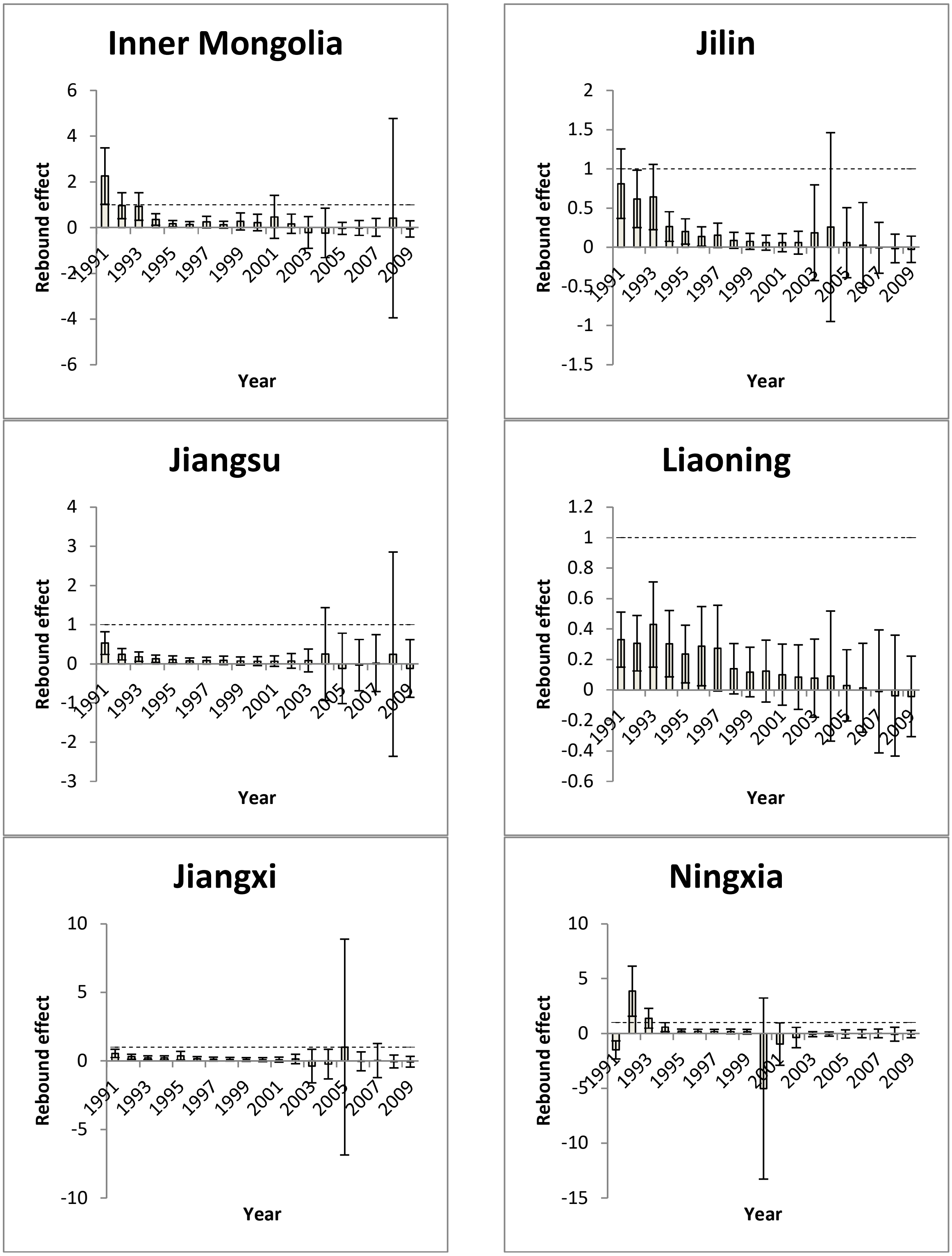
Figure C3. Intermediate-run macroeconomic growth rebound effect



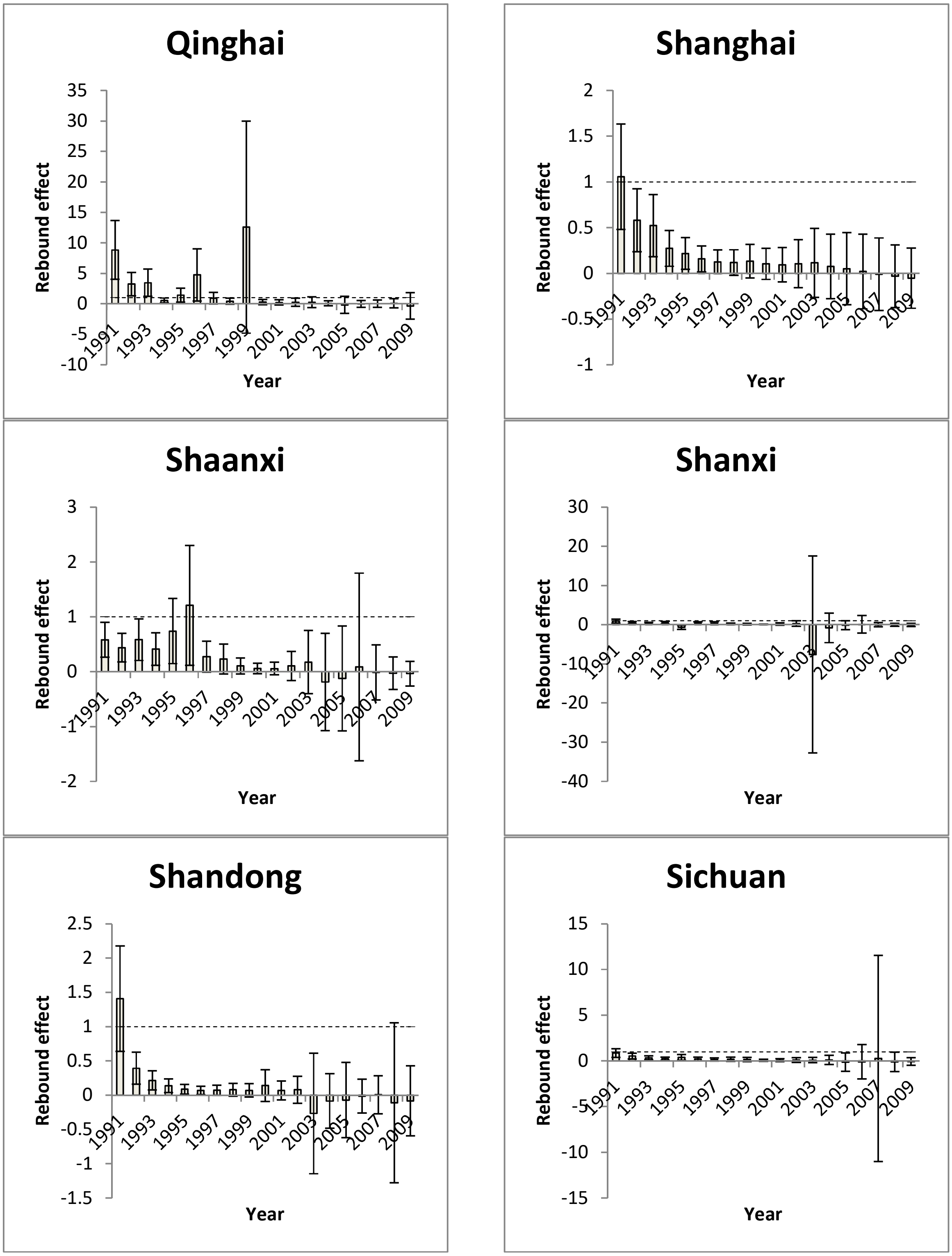
Note: Error bars indicate the 95% confidence interval. A rebound effect of 1 is indicated by the horizontal dashed line.



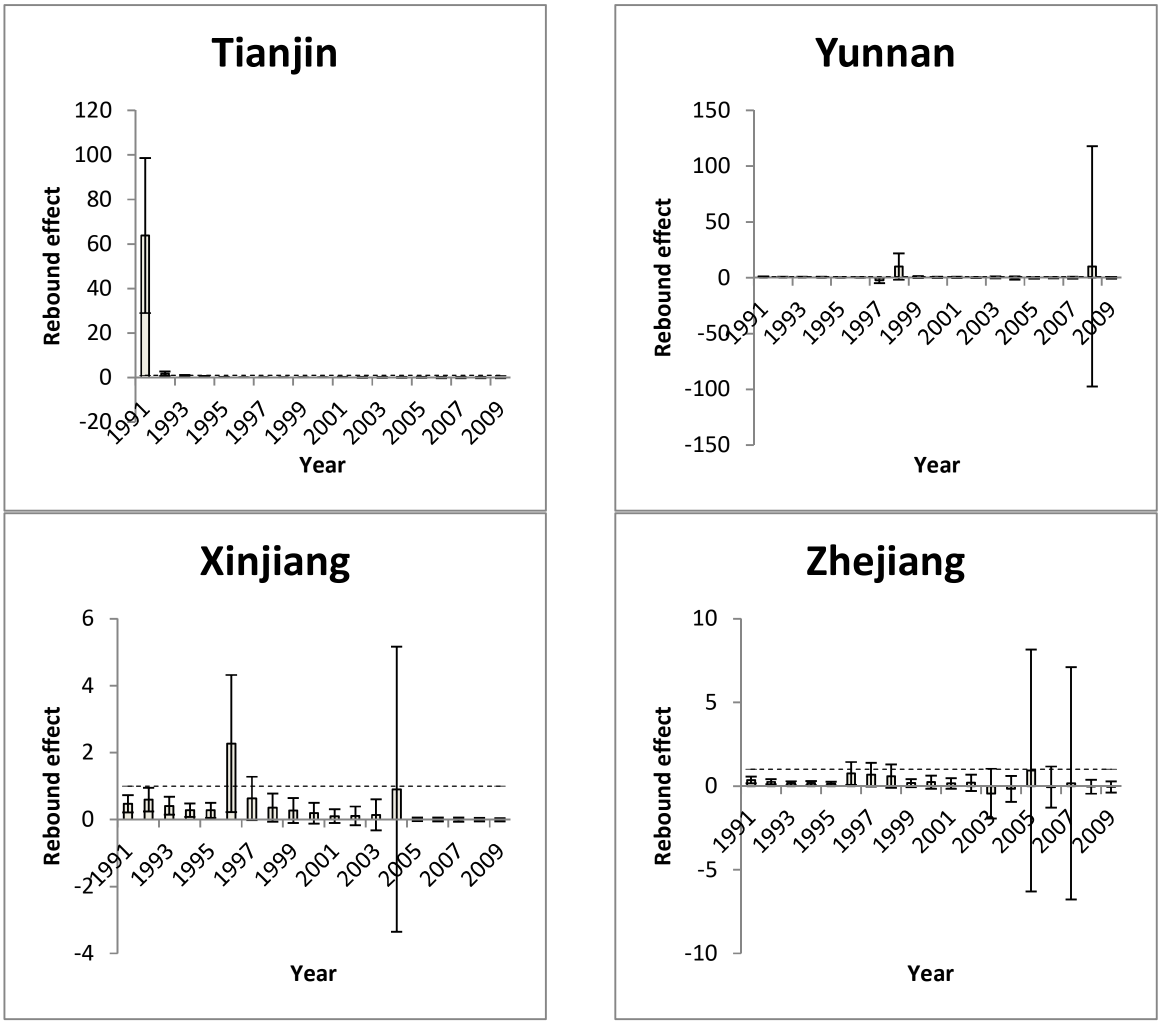
Note: Error bars indicate the 95% confidence interval. A rebound effect of 1 is indicated by tshe horizontal dashed line.



Note: Error bars indicate the 95% confidence interval. A rebound effect of 1 is indicated by the horizontal dashed line.



Note: Error bars indicate the 95% confidence interval. A rebound effect of 1 is indicated by the horizontal dashed line.



Note: Error bars indicate the 95% confidence interval. A rebound effect of 1 is indicated by the horizontal dashed line.