



The path towards sustainable finance: Venture capital and air pollution in China

Yue Hua^a, Weizeng Sun^{b,*}, Danning Zhao^b

^a School of Economics and Trade, Hunan University, China

^b School of Economics, Central University of Finance and Economics, China

ARTICLE INFO

JEL classification:

G24
Q53
R11

Keywords:

Sustainable finance
Venture capital
Air pollution
Innovation
China

ABSTRACT

Financing sustainable growth has attracted global attention and discussion in recent years. This study investigates the effect of venture capital, as a potential source of sustainable finance, on air pollution in China from 2003 to 2016. Using the unique Government Guidance Fund as instrumental variable, we find that venture capital activities have significantly reduced local air pollution in cities of China. To be specific, a one standard deviation increase in the VC amount leads to 4% decrease in PM_{2.5} concentration and 6% reduction in industrial SO₂ emission. The effects are insensitive to a wide range of robustness tests. Cities characterized by more rigorous environmental supervision, superior business environments, and stronger innovation incentives benefit more from venture capital activities. We further show that venture capital helps improve local air quality by boosting general and green innovation, increasing the investment of new green enterprises, as well as crowding out the investment of polluting industries.

1. Introduction

Venture capital (VC) has been leaping forward in China in the past 20 years, featured by booming investment opportunities and greater availability in the supply of capital. According to the statistics of the Shanghai-Hongkong Development Institute, by 2018, 27,466 VC institutions were established in China, and the VC-managed capital reached 11.2 trillion yuan in total (1.72 trillion USD). China's VC has taken up 1/3 of the world's and 75.4% of Asia Pacific's total amount.¹ VC turns out to be the dominant source of finance for high-potential startups commercializing risky new ideas and technologies, and is considered to effectively boost innovative business (Arqué-Castells, 2012; Faria & Barbosa, 2014; Hellmann & Puri, 2002; Kortum & Lerner, 2000). Consistent with the United States, the VC amount managed by Chinese VC firms is small as compared with the national government investment.² However, several studies confirmed that VC is critical to facilitating regional innovation and optimizing local investment structure in China (Jin, Zhang, Shan, et al., 2015).

Taking environmental, social and governance (ESG) considerations into account, sustainable finance constantly arouses the

* Corresponding author at: School of Economics, Central University of Finance and Economics, 39 South College Road, Haidian District, Beijing 100081, China.

E-mail addresses: huayue@hnu.edu.cn (Y. Hua), sunweizeng@gmail.com (W. Sun), zhaodanning1998@126.com (D. Zhao).

¹ Data collected from the "Feasibility study report on China's venture capital market from 2019 to 2023" issued by Newsijie Industry Research Center (<http://www.newsijie.com/index.html>).

² As of 2020, the national VC amount was 243.7 billion RMB, which only accounts for 0.46% of the national total fixed asset investment 52,727 billion RMB.

attention of government and institutional investors worldwide. The harmful environmental effect of investment behavior is likely to adversely affect corporate performance, investor returns and social welfare (UN Annual Report on Responsible Investment). To cope with the rising concern from the general public over a better environment, China has aggressively rolled out “green finance” since 2012, marked by the “Green Credit Guidance” jointly released by the State Environmental Protection Administration, the People's Bank of China, and the China Banking Regulatory Commission. The “Green Credit Guidance” focuses almost exclusively on regulating the banking industry (Aizawa & Yang, 2010). To be specific, institutions in the banking industry are encouraged to finance environmental-friendly and low-carbon projects. Firms exhibiting poor energy conservation and pollution reduction are restricted from achieving bank loans (Yao, Pan, Sensoy, et al., 2021). New projects that do not pass the environmental assessment are prohibited from bank credit support, while ongoing projects that fail to meet certain environmental requirements are limited from receiving bank loans (Sun, Wang, & Yin, 2019).

However, existing green finance policies in China do not impose explicit environmental guidance on VC, implying that VCs do not necessarily function as “sustainable finance” and reduce pollution. In such background, discussion has emerged on whether VC would finance environment-friendly startups relying on cleaner inputs (e.g., renewable energy, pollution-free technology and new materials), which exhibit broad societal and environmental benefits (Lerner & Nanda, 2020). However, empirical evidence on the role of VC as a potential source of sustainable finance remains scarce. This study seeks to fill this gap by exploring the effects of VC on air pollution in China.

Based on the information acquired from Private Equity Database (PEDATA) built by Zero2IPO Group and the corresponding city-level air pollution data originating from $0.01^\circ \times 0.01^\circ$ grid data of ground-level $PM_{2.5}$, the effect of VC on air pollution at the city level in China between 2003 and 2016 is empirically examined. To tackle down the potential endogeneity issue, a unique city-level “Venture Capital Government Guidance Fund” (VC-GGF) is employed as the instrumental variable for the VC amount received by cities. VC-GGF refers to fiscal fundings set up by the central or local government that exogenously propels market VC activities.

This study reveals three main findings. First, VC is found to significantly improve local air quality. To be specific, a one standard deviation in the VC amount contributes to 3.97% and 6.25% declines in $PM_{2.5}$ concentration and industrial SO_2 emission, respectively. The result is robust when alternative measurements of VC activities and air pollutants are studied, the setting of instrumental variable is changed, potential outliers are dropped, and lagged effects are considered. Second, heterogeneous analysis indicates that the environmental effect of VC is larger in cities with more rigorous environmental supervision, better business environments, as well as stronger innovation incentives. Lastly, VC is found to effectively facilitates general and green innovation measured by patent numbers and an innovation index. Furthermore, VC can significantly increase the investment of new green enterprises and crowd out the investment of polluting enterprises, thereby contributing to the green urban industrial transformation.

This study contributes to the literature on three fronts. First, this study provides insights into the environmental effects of VC activities. In general, existing studies have focused on the effects of VC on industrial and firm innovation (Chemmanur, Loutschina, & Tian, 2014; Keuschnigg & Nielsen, 2004; Kortum & Lerner, 2000), employment and income (Engel & Keilbach, 2007), as well as enterprise value and business creation (Popov & Roosenboom, 2013; Samila & Sorenson, 2011). Shahbaz, Solarin, Mahmood, et al. (2013) found that financial development can reduce carbon emission by improving energy efficiency and enhancing environmental awareness. This study first links VC to local environments and presents the credible causal effect of VC on air pollution by exploiting VC-GGF as the instrumental variable, confirming the role of VC as a critical source of green credit and sustainable finance.

Second, this study is broadly connected with the literature on the environmental effects of firm investment. Existing studies largely discussed the effect of firm investment on environmental pollution from two perspectives, i.e., the purchase of environmental protection facilities and the introduction of clean technology. Moreover, most studies reported that firm environmental investment and pollution emissions are strongly correlated with the government's environmental regulation. If the local government carries out rigorous environmental supervision, firms will be encouraged to increase environmental investment and reduce environmental pollution (Gray & Deily, 1996; Liao, 2018). However, several studies indicated that environmental investment does not affect pollution. For instance, Zhou, Yang, Wan, et al. (2018) showed that the effects of environmental investment on industrial SO_2 emissions and dust emissions could be ignored. Inspired by the mentioned, this study provides novel evidence to the undetermined effect of firm investment on local environment.

Lastly, this study supplements the growing literature by highlighting the technological innovation and green investment effects of VC as influencing channels. Though the relationship between VC and innovation in the developed world has been extensively analyzed, the empirical evidence for China has not reached a consensus. According to Guo and Jiang (2013), and Sun, Zhao, and Sun (2020), VC exerts a significant positive effect on innovation at the firm and region levels. As opposed to their studies, Wen, Yang, Feng, et al. (2018) found a non-linear relationship between VC and innovation performance. VC can bring higher innovation performance only when reaching a certain amount. Lin, Xu, Zhang, et al. (2019) reported that VC does not impact early-stage innovation, but boosts innovation at the developing stage and hinders innovation at the expansion stage. Our findings support the general and green innovation effects of VC activities, and verify the investment preference of VC towards green industries.

The remainder of this study is organized as follows. Section 2 introduces the institutional background and two possible channels through which VC affects air pollution. Section 3 describes the data and empirical strategy. Section 4 presents the main results, robustness tests and heterogeneous analyses. Section 5 investigates the potential mechanisms. Section 6 concludes the study.

2. Institutional background

2.1. Venture capital in China

Since the “Reform and Opening-up” in 1978, the Chinese central government has recognized science and technology as a vital factor for economic development. To improve innovation capacity and cultivate emerging high-tech industries, the government incorporated the value of VC, a high-risk and high-yield professional equity investment, in its policy considerations and founded China's first VC institution in 1985. However, the development of VC during the 1980s was lagged, and the effect of VC on technological innovation was weak (Chen, Liu, & Liao, 2011). According to the China Venture Capital Yearbook, due to institutional obstacles, companies with venture financing as their main business failed to accelerate technological progress, and their market expansion has been extremely slow. In 1988, the VC took up only 3.7% of the total funds for China's R&D.

In 1995, the “Administrative Measures for the Establishment of Overseas Chinese Industrial Investment Funds” is established to initiate China's equity investment market. The governmental strategy on VC focused on supporting the industrialization of novel technologies. In 1999, the State Council issued the “Opinions on Establishing Risk Investment Mechanism”, which triggered a boom in establishing VC institutions. China's VC industry leaped forward ever since. From 1999 to 2002, the number of VC firms increased nearly fivefold. However, domestic VC still faced a series of difficulties relative to their foreign counterparts. VC overseas could tackle down the obstacles of policy restrictions on investment, and the firms they had invested in could enjoy benefits as Sino-foreign joint ventures. For this reason, the performance of foreign VC in China exceeded that of domestic VC, and most of China's VC activities were dominated by foreign VC (White, Gao, & Zhang, 2005). The revised Company and Security Law in 2006 significantly reduces the legal barriers to domestic VC in multiple aspects (e.g. organizational form and registration qualification). Since then, VC industry in China has been thriving. According to the Zero2IPO Research, there were 73,197 investment institutions in China by the end of 2020, among which 13,386 were VC institutions. In 2020, newly raised funds in the VC market reached 243.74 billion yuan in total.³ Fig. 1 presents the spatial distribution of VC amount in China for four specific years (Cheng et al., 2019), which shows the evolutionary pattern of VC. In the early years before 2005, VC primarily concentrated in Beijing, Shanghai, Hangzhou and other large cities in eastern China, and its spatial distribution was relatively discrete. After 2005, VC gradually spread to the central and western areas, as well as medium-sized and small cities.

Over the past decade, the Chinese government has issued several regulations to prevent executive distortions on VC market. In 2013, the “Securities Investment Fund Law” was amended to legally include “non-publicly raised funds”. The Securities Regulatory Commission of China further issued the “Interim Measures for the Supervision and Administration of Private Investment Funds” in 2014. Meanwhile, the Asset Management Association of China implemented “Measures for Registration of Private Investment Fund Managers and Fund Filing”. Private equity fund managers are required to update relevant information of non-securities funds they manage on a regular basis (within 10 working days from the end of each quarter), including the main directions of private equity investment funds. The implementation of these regulations has alleviated the information asymmetry between VC and the invested firms, and has effectively incentivized more VC-backed start-ups on the demand side.

2.2. Venture capital and pollution

Indifferent to any other private investment activities, VC can have environmental consequences by affecting the strategy and operation of target enterprises. VC is capable of reducing pollutant emission and improving local air quality by boosting the technological innovation of enterprises, especially the green technology innovation related to the generation and emission of pollutants. Existing studies have confirmed that VC can reduce carbon emissions by boosting technological innovation, improving energy efficiency and enhancing environmental awareness (Jalil & Feridun, 2011; Shahbaz et al., 2013; Tamazian, Chousa, & Vadlamannati, 2009). Green industry pertains to technology- and capital-intensive industries. For historical reasons, the green industry in China has undergone relatively slow development, and it remains an emerging industry with high growth potential and high risk profile, thereby making it difficult to obtain financial support from traditional channels. In the context above, VC serves as suitable financing source for green enterprises (Gompers & Lerner, 2001).

To be specific, VC is capable of providing funds for green enterprises to support the research and development of products and services, as well as enhancing the technological innovation ability by formulating the enterprise's development strategy and managing its operation (Faria & Barbosa, 2014). Through innovation involving green products and green processes, energy utilization efficiency can be effectively improved, and pollutant emission can be reduced (Chen, Lai, & Wen, 2006). Moreover, the development VC may offer high-quality financial services for environmental protection projects, as an attempt to reduce pollution (Halicioglu, 2009; Tamazian & Rao, 2010). In 2020, the China Venture Capital Inc. issued an environmental protection industry fund of 2 billion yuan to satisfy the investment and financing needs of environmental protection enterprises at different stages of development.

VC can also direct capital flow towards high-efficiency industries, thereby expediting the adjustment and upgrading of industrial structure (Fisman & Love, 2007; Wurgler, 2000). With rising concern on sustainable development from the government and the general public, green enterprises are increasingly encouraged given their potential environmental benefits. Accordingly, the investment direction of VC tends to switch from traditional high-tech enterprises to green enterprises (Petkova, Wadhwa, Yao, et al., 2014).

³ Data collected from the “China VC/PE Market Review 2020” issued by the Zero2IPO Research.

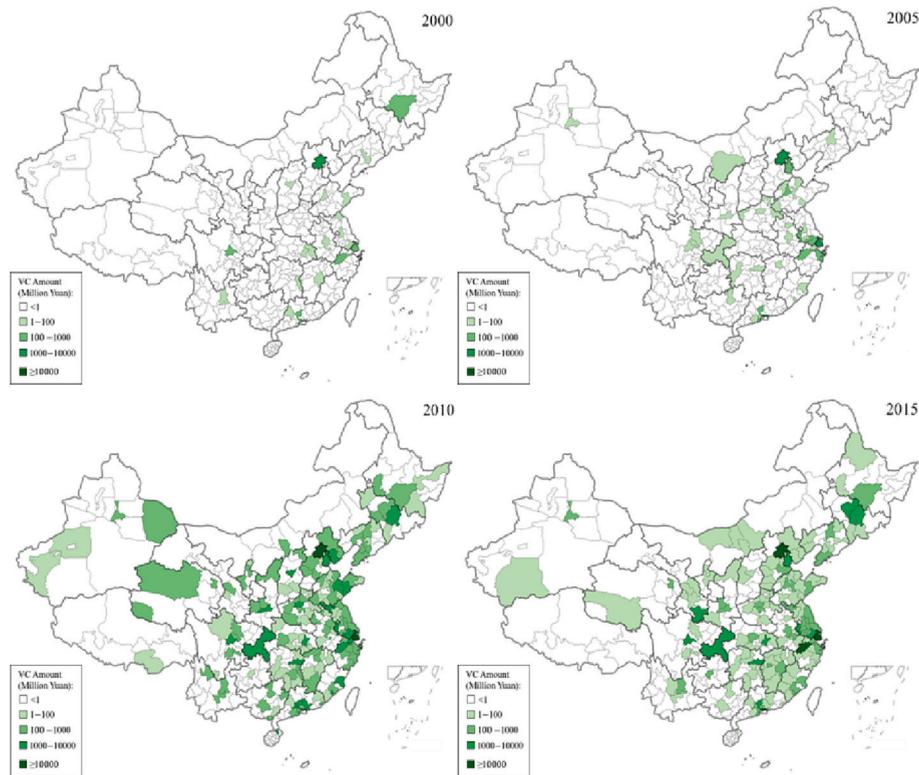


Fig. 1. Spatial distribution of VC amount in China.

Notes: The figure illustrates spatial distribution of VC amount (million RMB) from 2000 to 2015 in China. Five groups with shades from light to dark represent <1, 1–100, 100–1000, 1000–10,000, and > 10,000, respectively. The data is from the Private Equity Database (PEDATA) constructed by Zero2IPO Group.

Mrkajic, Murtinu, and Scalera (2019) reported that entrepreneurs who run green enterprises and position their enterprises in the green field are 7% more likely to obtain VC than other enterprises. From 2002 to 2008, VC on green technology increased significantly around the world, and the share of cleantech VC deals has risen from around 1% in 1996 to over 10% in 2010 (Cumming, Henriques, & Sadorsky, 2016). VC-backed green investments in China is also growing rapidly, with an amount of 22.8 billion yuan in the clean-tech industry in 2018.⁴ Consequently, the financial capital represented by VC progressively converges to green industries. As favorable institutional and market conditions are created for the development of green industries, capital financing intense pollution and high energy industries tends to be squeezed out, leading to a greener urban industrial structure.

3. Data and empirical specification

3.1. Data

Information regarding VC is acquired from one of the largest databases for VC and private equity in China, the Private Equity Database (PEDATA) constructed by Zero2IPO Group. The database records the investment dates, the total amounts of investment, names and geographical locations of both VC firms and investee companies and the affiliated industry of investee companies. Based on locational information, all invested companies at the prefecture-city level are first geocoded with Gaode Map API. Additionally, we convert investment amounts reported in foreign currency into yuan in accordance with the historical exchange rate.⁵ Through data cleaning and processing, the data on VC activities for 234 Chinese cities (79.6% of cities at prefecture-level and above) are obtained from 2003 to 2016.⁶

⁴ Data collected from the Private Equity Database (PEDATA).

⁵ Data on historical exchange rates are collected from CSMAR Database (www.gtarsc.com).

⁶ We restrict the research period to 2003–2016 mainly due to the accessibility of VC-GGF data, which we used as instrumental variable for VC throughout this study.

In terms of the air pollution data, we use PM_{2.5} concentration and SO₂ emission to indicate ambient air pollution level. The PM_{2.5} data originates from the 0.01° × 0.01° grid data of ground-level PM_{2.5} determined by van Donkelaar, Martin, Li, and Richard (2019).⁷ Next, a vectorization process is applied on the mentioned grid data by employing ArcGIS and Geoda to form a panel of city-level PM_{2.5} data from 2003 to 2016. A second data employed to indicate the local air pollution is the city-level industrial SO₂ emission, which has been extensively used to measure air pollution in existing studies (Popp, 2006; Streets & Waldhoff, 2000). The data on SO₂ emission are acquired from the China City Statistical Yearbook (2003–2016). Fig. 2 plots the dynamic relationship between air pollution and VC amount in Chinese cities from 2003 to 2016. VC amount and air pollution displayed similar trends before 2013. Since then, the positive relationship has somehow reversed, necessitating an in-depth analyses to reveal the true causal relationship of interest.

3.2. Empirical model

We adopt a standard two-way fixed-effects model to explore the effect of VC on local air pollution. The model takes the form as follows:

$$Pollution_{ijt} = \beta_0 + \beta_1 \cdot VC_{it} + \beta_2 \cdot Controls_{it} + \delta_i + \rho_{jt} + \varepsilon_{ijt} \tag{1}$$

where $Pollution_{ijt}$ represents the air pollution level in city i of province j in year t , measured by PM_{2.5} concentration and industrial SO₂ emission, both in the log form. VC_{it} denotes the log of VC amount (million yuan) received by city i in year t . $Controls$ incorporate a set of city characteristics such as GDP per capita (in log form), GDP share of the secondary sector, GDP share of the tertiary sector, total employment (in log form), fiscal spending (in log form), area of paved roads (in log form), as well as coverage rate of green space (in log form). δ_i represents city fixed effects, capturing all city-level time-invariant characteristics (e.g., geographical features). ρ_{jt} stands for provincial year fixed-effects capturing common shocks to cities in the same province (e.g., provincial environmental policy). ε_{ijt} is the error term. Standard errors are clustered at the city level to solve potential heteroscedasticity and serial correlation.

Table 1 lists the summary statistics for the variables adopted in Eq. (1). From 2003 to 2016, the average PM_{2.5} concentration of 234 Chinese cities reached 43.37 μg/m³, with the largest city-year observation over 100 μg/m³. The average SO₂ emission was approximately 66.6 million tons. For the VC, the average city hosted 4.4 VC-backed firm and received 8.84 invested cases with 253.41 million yuan of VC investment. The summary statistics are also reported for different city characteristics.

3.3. Endogeneity issue and instrumental variable

VC activities are by no means randomly distributed, triggering two endogeneity issues for the empirical analysis. First, environmental pollution has been reported to be correlated with lower potential in economic growth and innovation (Grimaud & Rougel, 2005), so VC tends to avoid cities encountering serious pollution. It is possible that urban air pollution will affect the VC obtained by the city, yielding a reverse causality problem. Second, some city-level unobserved factors (e.g. fiscal policy and business environment) may simultaneously affect VC activities and local air quality, thereby causing the omitted variable bias. If the unobservable factors exert identical (opposed) effect on VC and air pollution, the coefficient β_1 in Eq. (1) will be overestimated (underestimated).

This study introduces a unique policy-based instrumental variable to address the potential endogeneity problem. To be specific, the amount of city-level “Venture Capital Government Guidance Fund” (VC-GGF) is employed as the instrumental variable for the VC amount received by the city. VC-GGF is set up by the local government and operates in a market-oriented manner, functioning essentially as “funds on funds” or “master fund”. VC-GGF aims to use fiscal spending to guide private capital into the field of VC, as an attempt to improve regional innovation capacity and to facilitate the industrial upgrading. VC-GGF is a flow of funding scheduled in advance in the previous year’s fiscal budget. Since the Beijing Zhongguancun Management Committee established the first domestic VC-GGF in 2002, China’s VC-GGF has witnessed rapid growth in the past two decades. By the end of 2016, 980 GGFs have been established in China, covering 152 prefecture-level cities with a fund scale of 3300.46 billion yuan. Although in some underdeveloped regions, the guiding effect of VC-GGF is not fully exploited due to lower returns and higher risks of local industrial projects, VC-GGF in general is highly effective in expanding the scale of social financing (Wang & Liu, 2019).

Fig. 3 presents the positive correlation between the total amount of VC-GGF and VC amount in the study period. Since the sole purpose of VC-GGF is to support and complement private VC activities, other channels that relate VC-GGF with air pollution are unlikely.

Taking VC-GGF as an instrument, we estimate the model following a standard two-stage least square (2SLS) process:

$$VC_{ijt} = \alpha_0 + \alpha_1 \cdot GGF_{ijt} + \alpha_2 \cdot Controls_{it} + \delta_i + \rho_{jt} + \varepsilon_{ijt} \tag{2}$$

$$Pollution_{ijt} = \beta_0 + \beta_1 \cdot \widehat{VC}_{ijt} + \beta_2 \cdot Controls_{it} + \delta_i + \rho_{jt} + \varepsilon_{ijt} \tag{3}$$

GGF_{ijt} in Eq. (2) denotes the log of VC-GGF amount (million yuan) of city i in year t , which serves as the instrumental variable of VC. \widehat{VC}_{ijt} in Eq. (3) is the predicted value of VC. Other model specifications are identical to Eq. (1).

⁷ The methodology for estimating ground-level PM_{2.5} “combines Aerosol Optical Depth (AOD) retrievals with the GEOS-Chem chemical transport model, and subsequently calibrated to regional ground-based observations of both total and compositional mass using Geographically Weighted Regression (GWR).” See <https://sites.wustl.edu/acag/datasets/surface-pm2-5/>.

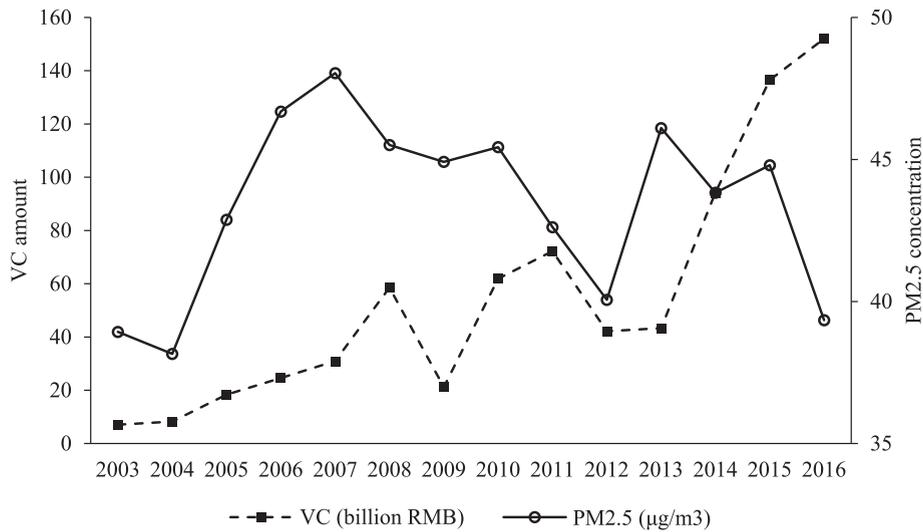


Fig. 2. VC amount and PM_{2.5} concentration in China (2003–2016).

Notes: The figure illustrates the trend of VC amount (billion RMB) and PM_{2.5} concentration (µg/m³) from 2003 to 2016 in China. The VC amount data is from the Private Equity Database (PEDATA). The PM_{2.5} data originates from the 0.01° × 0.01° grid data of ground-level PM_{2.5} determined by van Donkelaar et al. (2019).

Table 1
Summary statistics.

Variables	Obs.	Mean	Std. Dev.	Min	Max
Dependent variables					
PM _{2.5} concentration (µg/m ³)	3276	43.37	16.14	9.36	100.25
SO ₂ emission (ton)	3276	66,568.21	65,637.16	64.08	683,010
Variables of interest					
Money amount of VC (million RMB)	3276	253.41	2232.95	0.00	57,128.43
Number of VC events	3276	8.84	69.41	0.00	2096
Number of VC-backed firms	3276	4.40	29.81	0.00	809
Instrumental variable					
Government Guidance Fund (million RMB)	3276	42.73	482.90	0.00	1977.83
Control variables					
GDP per capita (10,000 RMB)	3276	3.67	4.18	0.15	20.63
GDP share of the secondary sector	3276	49.22	10.68	14.95	85.92
GDP share of the tertiary sector	3276	37.12	8.93	11.05	80.23
Total employment (10,000)	3276	53.74	78.34	4.05	986.87
Fiscal spending (million RMB)	3276	23,200	43,800	33,050	692,000
Area of paved road (10,000 m ²)	3276	1572.162	2092.282	14	21,490
Coverage rate of green space	3276	38.67	9.21	4.66	91.27

4. Empirical results

4.1. Baseline results

Table 2 shows the IV estimates for model (1) as the baseline results. First-stage results presents a significant and positive relationship between the VC-GGF and VC amount, which complies with the descriptive evidence. The F-statistic of the first-stage regression is significantly larger than the critical value 16.38, which demonstrates the non-existence of the weak instrumental variable. Columns (1) and (2) show regression results controlling only for city fixed effects and province-year fixed effects. In Columns (3) and (4), city characteristics are further included. All the coefficients of VC amount are negative and statistically significant at the 1% level, confirming the reduction effect of VC on air pollution. To be specific, the results in Columns (3) and (4) indicate that a one standard deviation increase in the VC amount contributes to a 3.97% ($[\log(253.41 + 2232.95) - \log(253.41)] \times (-0.04)$) decrease in PM_{2.5} concentration and a 6.25% ($[\log(253.41 + 2232.95) - \log(253.41)] \times (-0.063)$) decrease in SO₂ emission. Considering that VC amount of an average city during our research period (2003–2016) increased from 73.6 million RMB to 610.9 million RMB, we can calculate that the overall increase in VC amount contributed to a 3.68% decrease in PM_{2.5} and a 5.79% decrease in industrial SO₂ emission from 2003 to 2016.

In terms of the control variables, we find that GDP per capita, GDP share of the secondary sector, total employment, fiscal spending,

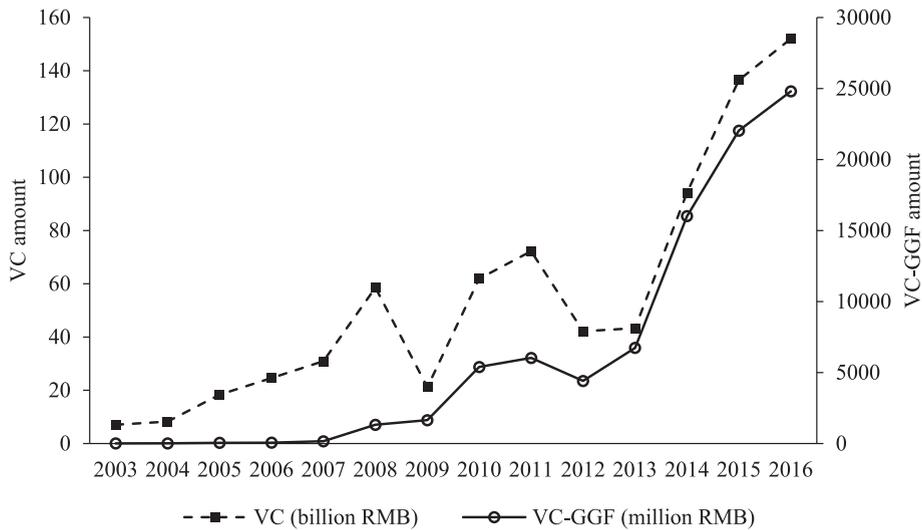


Fig. 3. VC amount and VC-GGF amount in China (2003–2016).

Notes: The figure illustrates the dynamic changes of VC amount and “Venture Capital Government Guidance Fund” (VC-GGF) from 2003 to 2016 in China. Relevant data are collected from the Private Equity Database (PEDATA).

Table 2

Baseline IV results.

	(1)	(2)	(3)	(4)
	log($PM_{2.5}$)	log(SO_2)	log($PM_{2.5}$)	log(SO_2)
log(<i>VC amount</i>)	-0.053*** (0.016)	-0.075*** (0.015)	-0.040*** (0.015)	-0.063*** (0.018)
log(<i>GDP per capita</i>)			0.051*** (0.011)	0.034** (0.016)
<i>GDP share of manufacturing</i>			0.011** (0.005)	0.047*** (0.019)
<i>GDP share of service</i>			-0.011*** (0.001)	-0.025*** (0.006)
log(<i>Total employment</i>)			0.141*** (0.022)	0.173*** (0.018)
log(<i>Fiscal spending</i>)			0.039*** (0.012)	0.120*** (0.032)
log(<i>Area of paved road</i>)			0.040*** (0.011)	0.067** (0.030)
log(<i>Coverage of green space</i>)			-0.023*** (0.007)	-0.031*** (0.005)
City fixed-effects	Yes	Yes	Yes	Yes
Province-year effects	Yes	Yes	Yes	Yes
Observation	3276	3276	3276	3276
First-stage results				
log(<i>VC-GGF</i>)	0.875*** (0.091)	0.875*** (0.091)	0.590*** (0.098)	0.590*** (0.098)
Observation	3276	3276	3276	3276
R ²	0.460	0.460	0.471	0.471
K-P rk Wald F statistic	109.07	109.07	35.33	35.33

Notes: Robust standard errors clustered at city level are in parentheses. * $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$.

and area of paved road are all positively correlated with local air pollution. A larger GDP share of service and a higher coverage rate of green space contributes to better air quality. Most of these results are consistent with findings of existing studies (An, Zhou, Yu, Shi, & Wang, 2021; Bernauer & Koubi, 2006; Hang, Wang, Zhou, & Zhang, 2019; Lopez, Galinato, & Islam, 2011).

4.2. Validity tests of IV

We further validate the use of VC-GGF as an instrument from four aspects. First, if the local government decides the amount of VC-

GGF after the city receives VC, then VC-GGF does not generate exogenous variation in VC. We hence examine whether VC-GGF is correlated with the VC amount in the previous year. Results in Column (1) of Table 3 show that the lagged term of VC amount does not predict the VC-GGF, indicating no reverse causality between VC-GGF and VC.

Second, following the common practice (e.g. Acemoglu, Johnson, & Robinson, 2001; Dittmar & Meisenzahl, 2020), we include VC amount and VC-GGF in the model simultaneously. As shown in Columns (2) and (3) of Table 3, we find that the coefficient of IV is insignificant for both the PM_{2.5} and the SO₂ model after controlling for the VC amount, which, to some extent, supports that the IV will not directly affect air pollution in ways other than VC amount.

Third, we add more controls that can be highly correlated with both VC-GGF and VC, including population, annual sales revenue of state-owned enterprises and number of local VC firms. Columns (4) and (5) of Table 3 show that for both the PM_{2.5} and the SO₂ model, such additional controls do not alter the magnitude and significance of the coefficients of VC.

Lastly, we directly test whether VC-GGF released by local government is related to local environmental regulation stringency. Follow studies by Zhao, Dong, Wang, et al. (2022) and Huang and Tian (2023), we use the amount of environmental governance investment (in log), which is collected from the China City Statistical Yearbook, to measure the environmental regulation stringency. Column (6) of Table 3 shows that after controlling city's characteristics and fixed effects, the VC-GGF is insignificantly correlated with local environmental regulation stringency, indicating that VC-GGF can't affect the local air quality through environmental regulation.

4.3. Robustness checks

We next conduct an array of robustness checks to verify our main finding. First, the explanatory variable is replaced with two alternative measurements, i.e., the number of VC events and the number of VC-backed firms. The results using VC-GGF as IV are presented in Panel A and Panel B of Table 4. The estimates indicate that a one standard deviation increase in the VC event leads to a 5.21% decline in PM_{2.5} concentration and a 6.53% decline in industrial SO₂ emission; and one more standard deviation of VC-financed firm contributes to a 6.41% decline in PM_{2.5} concentration and a 7.30% decline in industrial SO₂ emission. The results confirm that VC activities have negative and statistically significant effects on local air pollution.

Second, some cities in the sample are hosting more than one VC-GGF. This variation of numbers of VC-GGF is not captured by the amount of VC-GGF, which may cause bias in determining the LATE (Local Average Treatment Effect) estimates. In Panel C, Eq. (1) is re-estimated by adopting number of VC-GGF established in a city as an alternative IV for VC amount. The estimates are found to be mostly unchanged in the PM_{2.5} model and decrease slightly in magnitude in the SO₂ model. The results confirm the validity and robustness of the main IV estimates.

Third, several star cities, including Beijing, Shanghai, Tianjin, and Chongqing, accommodate large interest groups with strong political power which is critical to resource allocation. Hangzhou and Shenzhen are two other super VC centers in China that receive massive amount of VC investment (Giroud, 2013). These cities also encounter special urban planning schemes and extraordinarily rigorous environment regulations. We test if the bulk of estimates are driven by these VC outliers. Panel D lists the estimation results obtained by dropping the 6 VC star cities. The effects of VC on PM_{2.5} concentration (−0.044) and industrial SO₂ emission (−0.033) remain statistically significant.

Our main model considers the province-year fixed-effects and city fixed-effects. However, such setting may absorb the variations of both VC and air pollution. As another robustness check, Eq. (1) is re-estimated by only including city fixed-effects and year fixed-effects. The estimates presented in Panel E are mostly unchanged both in the PM_{2.5} model and in the SO₂ model. The results confirm that trends at the provincial level have trivial impact on the pollution effect of VC. As a placebo test, we include the one-year lead VC amount as the explanatory variable in Panel F. We find no significant effects when adding leads of VC, indicating the reverse causality problem between VC and air pollution could be trivial.

Next, to rule out the impact of environmental regulation, we use the compulsory emission reduction formula announced by the Ministry of Ecology and Environment during the Eleventh Five-Year Plan (2006–2010) and the Twelfth Five-Year Plan (2011–2015) to calculate two city-level pollution reduction quotas (Chen, Yu, et al., 2018).⁸ Results in Panel G and Panel H of Table 4 show that after controlling for the official pollution reduction quota (interacted with time fixed-effects), the negative impact of VC on air pollution remains largely unchanged.

To examine whether our findings are robust at a finer spatial resolution, we use county-level data (instead of prefecture-level data) to inspect the environmental effects of VC. Both the VC and pollution data are reproduced for county panel dataset using the same method discussed in Section 3.1. Results in Panel I of Table 4 consistently support the pollution-reduction effects of VC.⁹ Concerning the potential LATE bias of IV estimates, we further examine the plain OLS model as a comparison. As shown by the results in Panel J of Table 4, the OLS estimates are smaller in magnitude relative to the IV estimates, but the differences are not substantial (especially for

⁸ In this study, city-level pollution reduction quota is calculated by the following formula: $\Delta S_{c, 05-10} = \Delta S_{p, 05-10} \times \frac{P_{c, 2005}}{\sum_{j=1}^J P_{j, 2005}}$, where $\Delta S_{p, 05-10}$ is province p 's SO₂ reduction mandate; the second term represents the proportion of province p 's SO₂ emissions in 2005 that is contributed by industries located in city c , while $P_{c, 2005}$ is the total industrial SO₂ emissions in city c in 2005 and J represents the number of cities in the province. The pollution reduction quota for the Twelfth Five-Year Plan is calculated using the similar approach. The provincial SO₂ quota are recorded in two national policies (See http://www.gov.cn/gongbao/content/2006/content_394866.htm and http://www.gov.cn/govweb/zwggk/2011-09/07/content_1941731.htm for details).

⁹ Based on the geographical locations provided by the dataset, only 16.7% of the investment cases can be identified at the country level.

Table 3
Validity tests of IV.

	(1)	(2)	(3)	(4)	(5)	(6)
	log(VC-GGF)	log(PM _{2.5})	log(SO ₂)	log(PM _{2.5})	log(SO ₂)	log(Env_invest)
lagged log(VC amount)	0.031 (0.045)					
log(VC-GGF)		0.015 (0.014)	0.022 (0.013)			
log(VC amount)		-0.041*** (0.009)	-0.061*** (0.012)	-0.043*** (0.010)	-0.061*** (0.013)	-0.028 (0.022)
Controls	Yes	Yes	Yes	Yes	Yes	Yes
Additional controls	No	No	No	Yes	Yes	No
City fixed-effects	Yes	Yes	Yes	Yes	Yes	Yes
Province-year effects	Yes	Yes	Yes	Yes	Yes	Yes
Observation	3042	3276	3276	3276	3276	3012
R ²	0.294	0.377	0.410	N/A	N/A	0.426

Note: City fixed-effects, province-year fixed-effects and control variables (GDP per capita (in log form), GDP share of the secondary sector, GDP share of the tertiary sector, total employment (in log form), fiscal spending (in log form), area of paved road (in log form), and coverage rate of green space (in log form)) are included in all regressions. Additional control variables including population of the build-up area, sales revenue of state-owned enterprises and number of local VC firms (all in log form) are included in Columns (4) and (5), with total employment dropped to avoid multicollinearity. Robust standard errors clustered at city level are in parentheses.

* p < 0.10, ** p < 0.05, *** p < 0.01.

SO₂), which could result from undetermined omitted variables.

Lastly, to promote a more comprehensive understanding on VC's environmental impacts, we investigate other major air pollutants as the outcome variables. Additional data on city-level nitrogen oxide (NO_x) and industrial dust emissions are collected from China City Statistical Yearbook. When replacing the dependent variable with the above alternative pollution measures, the results presented in Panel K of Table 4 show that VC reduce NO_x and industrial dust emission, indicating a robust negative impact of VC on air pollution.

4.4. Heterogeneity analysis

In this section we conduct several heterogeneity analyses to gain more insights into the idiosyncratic effect of VC on local air pollution. First, we explore whether the pollution effect of VC differs across cities with varying intensities of environmental regulation. The central government initiated the monitoring of 113 Key Environmental Monitoring (KEM) cities in 1997. This group of cities is subject to more stringent environmental regulations, in which VCs tend to select cleaner firms or projects for investment. Otherwise, the VC investment in KEM cities would encounter a higher regulatory cost, thereby causing lower returns. The heterogeneous effects of VC on PM_{2.5} concentration and SO₂ emission in 113 KEM cities and 121 non-KEM cities are presented in Panel A of Table 5, respectively. As expected, VC induces more air pollution reduction in cities with more stringent environmental regulations. To be specific, a one standard deviation increase in the VC amount will lower the PM_{2.5} concentration and SO₂ emission in KEM cities and non-KEM cities by 5.16%, 8.03% and 3.07%, 5.16%, respectively.

Next, we investigate whether city's business environment affects the impact of VC on local air pollution, since the choice and performance of VC can be directly impacted by the local business environment. In cities with more superior business environment, the mechanism of VC injection, participation and exit is smoother, and the odds of target enterprise's survive and success are higher. In this case, VC is more likely to invest in projects with sustainable development potential and firms with more rigorous standards on production technologies and energy efficiency. Using the 2011 China City Commercial Credit Environment Index (CEI), we divided all the 234 cities into two groups: superior business environment (115 cities above the median) and inferior business environment (119 cities below the median).¹⁰ Panel B of Table 5 presents the subsample regression results. As expected, VC has a larger impact on air quality in cities with better commercial environments. With additional one standard deviation of VC amount, the PM_{2.5} concentration and industrial SO₂ emission are reduced by 4.66% and 7.04% in superior-commercial-environment cities, respectively, as compared with 2.98% and 6.45% in inferior-commercial-environment cities.

Next, the pollution effects of VC across cities of differentiated innovation incentives are examined. Based on previous analysis, encouraging innovation is a vital feature that differs VC from traditional capital investment, and is also a salient channel for VC to facilitate energy efficiency and environmental quality. Thus, we expect VC to play a more significant role in improving air quality in cities with stronger innovation incentives. Since 2010, the National Development and Reform Commission has promoted the formation of regional development engines through the establishment of innovative pilot cities.¹¹ These designated innovative cities are

¹⁰ CEI index (see <http://www.chinacei.org/>) is a comprehensive evaluation index on Chinese city's business environment developed by leading research groups from the Chinese Academy of Management Sciences. The index has been a "wind vane" to show the construction progress and operation effect of China's city credit system, offering an objective measurement of the advantages and disadvantages of city's business environment. In this study, we use the 2011 CEI data that best suits our research period. Results using the 2016 CEI index are very similar.

¹¹ Source: http://www.gov.cn/zwqk/2010-01/11/content_1507703.htm.

Table 4
Robustness checks.

	(1)	(2)
	log($PM_{2.5}$)	log(SO_2)
Panel A. use VC events log(<i>VC events</i>)	-0.055*** (0.019)	-0.069*** (0.017)
Panel B. use VC-backed firms log(<i>VC-backed firms</i>)	-0.072*** (0.026)	-0.082** (0.038)
Panel C. use no. of GGF log(<i>VC amount</i>)	-0.040*** (0.015)	-0.052*** (0.019)
Panel D. drop outlier cities log(<i>VC amount</i>)	-0.044*** (0.017)	-0.033* (0.018)
Panel E. use city and year fixed effects log(<i>VC amount</i>)	-0.041*** (0.015)	-0.060*** (0.017)
Panel F. lead impact log(<i>VC amount</i>) _{lead}	0.007 (0.013)	-0.008 (0.020)
	-0.041*** (0.016)	-0.058*** (0.017)
Panel G. control for environmental regulation during the 11th Five-Year Plan log(<i>VC amount</i>)	-0.032*** (0.011)	-0.060*** (0.015)
Panel H. control for environmental regulation during the 12th Five-Year Plan log(<i>VC amount</i>)	-0.036*** (0.013)	-0.067*** (0.019)
Panel I. use county-level data log(<i>VC amount</i>)	-0.067*** (0.014)	-0.105*** (0.021)
Panel J. plain OLS model log(<i>VC amount</i>)	-0.026 (0.018)	-0.043*** (0.017)
Panel K. other air pollutants log(<i>VC amount</i>)	log(<i>NOx</i>) -0.045*** (0.017)	log(<i>Dust</i>) -0.063*** (0.020)

Notes: The table reports IV estimates except for Panel J. Control variables including GDP per capita (in log form), GDP share of the secondary sector, GDP share of the tertiary sector, total employment (in log form), fiscal spending (in log form), area of paved road (in log form), and coverage rate of green space (in log form) are in all regressions. City fixed-effects and province-year fixed effects are included in all regressions except for Panel E and Panel I. Panel E controls for city fixed effects and year fixed effects; Panel I controls for county fixed effects and province-year fixed effects. Outlier cities in Panel D are Beijing, Shanghai, Tianjin, Chongqing, Hangzhou and Shenzhen. Robust standard errors are clustered at the county level in Panel I and are clustered at the city level in other panels, which are reported in parentheses. * $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$.

supported by central and local governments to attract high-tech firms and high-skill workers. In this study, the 61 innovation pilot cities are denoted as cities with stronger innovation incentives, and the other 173 cities are denoted as cities with relatively weaker innovation incentive. As revealed by the results in Panel C of Table 5, the reduction of air pollution due to a one standard deviation increase in the VC in cities with stronger innovation incentives (4.07% for $PM_{2.5}$ concentration, 6.45% for SO_2 emission) is larger than cities with lower innovation incentive (3.47% for $PM_{2.5}$ concentration, 4.96% for SO_2 emission).

We proceed to examine the environmental effects of VC among different geographical regions. The sampled cities are divided by coastal ones (89 cities) and inland ones (145 cities) in accordance with the consensual divisions of China's economic macro-regions. Given the differed endowment and unbalanced development across space in China, the role of regional heterogeneity can be assessed from multiple aspects such as local climate, resource endowment, degree of openness, infrastructure and initial industrial conditions. As shown by the results in Panel D of Table 5, in the eastern region, a one standard deviation in the VC amount contributes to a 5.65% decline in $PM_{2.5}$ concentration and a 7.93% reduction in SO_2 emission. The corresponding pollution-reduction effects are much smaller within the inland area and only identified for $PM_{2.5}$ concentration.

Execution distortions in attracting and using venture capital can generate unexpected results. Firms may deliberately decorate their projects in order to achieve VC investments. To formally investigate this possibility, we divide VCs by their geographic distance to the invested companies. It is believed that proximity to invested companies makes it easier for VC to monitor and acquire information about the companies (Giroud, 2013). We first geocode all investors and investees at the city level using Gaode Map API based on their location information. Then we calculate the distance between each investment pair. City-year observations are divided into long-distance group and short-distance group by median investor-investee distance. The results are shown in Panel E of Table 5. We find similar pollution effects of VC with longer or shorter investment distance, implying that the execution distortion, even if existed, does

Table 5
Heterogeneous effects.

	log(PM _{2.5})		log(SO ₂)	
	(1)	(2)	(3)	(4)
Panel A. by environmental regulation				
	KEM	Non-KEM	KEM	Non-KEM
log(<i>VC amount</i>)	-0.052*** (0.013)	-0.031** (0.014)	-0.081*** (0.017)	-0.052** (0.022)
Observation	1582	1694	1582	1694
Two-sample <i>t</i> -tests	-5.120***		-2.317**	
Panel B. by business environment				
	High CEI	Low CEI	High CEI	Low CEI
log(<i>VC amount</i>)	-0.047*** (0.013)	-0.030*** (0.011)	-0.071*** (0.021)	-0.065*** (0.019)
Observation	1610	1666	1610	1666
Two-sample <i>T</i> -tests	-7.903***		-1.485	
Panel C. by innovation incentives				
	Innov	Non-Innov	Innov	Non-Innov
log(<i>VC amount</i>)	-0.041*** (0.011)	-0.035*** (0.013)	-0.065*** (0.019)	-0.050** (0.022)
Observation	854	2422	854	2422
Two-sample <i>T</i> -tests	-3.462***		-5.923***	
Panel D. by geographical region				
	Eastern	Central & Western	Eastern	Central & Western
log(<i>VC amount</i>)	-0.057*** (0.013)	-0.039*** (0.011)	-0.080*** (0.023)	-0.032 (0.021)
Observation	1246	1316	1246	1316
Two-sample <i>T</i> -tests	-7.840***		-11.667***	
Panel E. by investment distance				
	Long	Short	Long	Short
log(<i>VC amount</i>)	-0.042*** (0.010)	-0.039*** (0.012)	-0.059** (0.023)	-0.064*** (0.021)
Observation	1472	1804	1472	1804
Two-sample <i>T</i> -tests	-1.045		1.210	
Panel F. by types of VC				
log(<i>Green VC amount</i>)	-0.014** (0.007)		-0.023** (0.011)	
log(<i>Dirty VC amount</i>)	-0.051*** (0.010)		-0.065*** (0.021)	
Observation	3276		3276	

Note: The table reports IV estimates. City fixed-effects, province-year effects and control variables including GDP per capita (in log form), GDP share of the secondary sector, GDP share of the tertiary sector, total employment (in log form), fiscal spending (in log form), area of paved road (in log form), and coverage rate of green space (in log form) are in all regressions. Robust standard errors clustered at city level are in parentheses. * $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$.

not disturb the environmental effect of VC.

Next, we make efforts to better understand the pollution impacts from different types of VC. VCs are divided into green VC and dirty VC according to the “Listed companies’ environmental protection inspection industry classification management directory” issued by the Ministry of Ecology and Environment in 2008.¹² To be specific, if a VC is invested in industries that are defined as heavy pollution industry in the directory such as thermal power, steel, chemical, petrochemical, etc., it is divided into dirty VC, otherwise, it is divided into green VC. Results presented in Panel F of Table 5 show that a one standard deviation increase in the green VC amount will reduce the PM_{2.5} concentration and SO₂ emission by 1.53% and 2.51%, respectively, and the effect of dirty VC on PM_{2.5} concentration and SO₂ emission are 7.51% and 9.58%, respectively. The pollution-reduction effect from dirty VC is much larger than that from green VC, indicating that VC is indeed making dirty firms and industries cleaner. The results also imply that the impact of VC on air pollution is not driven exclusively by green firms, which once again suggests that VC is not selecting into cleaner industries under any “green

¹² According to the policy, 16 industries including thermal power, steel, cement, electrolytic aluminum, coal, metallurgy, chemical, petrochemical, building materials, papermaking, brewing, pharmaceutical, fermentation, textile, tanning and mining are defined as heavy industry.

guidance”.

Lastly, we examine the dynamic effects of VC on local air pollution over time. Specifically, we investigate the effects of one-year lag to five-year lag of VC investment by estimating the following equation:

$$Pollution_{ijt} = \beta_0 + \sum_{n=0}^5 \beta_1^n \cdot VC_{ij, t-n} + \beta_2 \cdot Controls_{it} + \delta_i + \rho_{jt} + \varepsilon_{ijt} \quad (4)$$

where $VC_{ij, t-n}$ denotes the log of VC amount (million yuan) received by city i in year $t-n$. Thus, the coefficient β_1^n measures the effects of VC on local air pollution n years after the investment. The results are plotted in Fig. 4. We find that the impact of VC on air pollution is declining over time. The statistical significance lasted 1 year for $PM_{2.5}$ and 3 years for SO_2 . The evolution of the effects from VC is consistent with the findings in the literature that the impact of VC on the innovation and development of invested firms is more obvious in the short term than long term (Arqué-Castells, 2012; Inderst & Mueller, 2009; Wadhwa, Phelps, & Kotha, 2016).

5. Mechanisms

In this section, we explore the mechanisms of the identified pollution-reduction effect of VC, and explain why VC can be recognized as a form of sustainable finance in China. Corresponding to the analysis in Section 2.2, two possible channels, i.e., technological innovation and structural improvement, are empirically tested.

5.1. Technological innovation

We first examine the relationship between VC and city-level innovation. Three measurements on urban innovation are used for analysis. First, we follow the common practice to employ the number of patent grants as proxy for city innovation. The patent data are obtained from the State Intellectual Property Office (SIPO). Second, we use the number of *invention* patents as a more rigorous and stronger measurement of urban innovation.¹³ Third, an urban innovation index constructed by Kou and Liu (2017) is adopted to indicate the comprehensive innovation level of cities.¹⁴

Columns (1) to (3) of Table 6 list the estimation results achieved by applying the above three variables as the dependent variables in Eq. (1). Overall, the coefficients of VC amount in the three regressions are significantly positive, which reveals that VC has robustly facilitated the technological innovation of Chinese cities. The finding above complies with that achieved by Florida and Kenney (1988) and Sun et al. (2020). According to the estimation results, with an additional 1% VC amount, the number of authorized patents will be elevated by 0.31%, the number of authorized invention patents will be up-regulated by 0.70%, and the innovation index of the city will rise by 0.69 (13.2% of the mean).

To place more focus on the environmental externality of VC activities, we further use the number of green patents to indicate the level of city's green innovation. By employing the “International Patent Classification Green Inventory” managed by the World Intellectual Property Organization, we extract the city-level green patent data using the international patent classification number. Green patent can also be divided into green invention patent and green utility-model patent, while the former is in general more innovative than the latter.

Columns (4)–(6) of Table 6 list the results of the effects of VC on green innovation. It is demonstrated that VC significantly facilitate the occurrence of green innovation. As indicated by the results, in response to a 1% increase in the VC amount, the number of green patents will be elevated by 0.67%, the number of green invention patents will increase by 0.99%, and the number of green utility-model patents will increase by 0.52%. Furthermore, the effects of VC on green innovation are significantly higher than those of general patents, thereby verifying the role of VC in improving local environmental quality through technological innovation.

5.2. Structural improvement

Next, we investigate whether VC reduces air pollution by altering the industrial investment structure. The analysis is conducted from two aspects, i.e., how VC affects cleaner capital investment, and how VC affects pollution-related investment. Data on the registered capital and the number of newly registered enterprises are adopted, both at the industry level, to indicate the scale of industrial investment in the city. The information of newly registered enterprises is acquired from the industrial and commercial registration data of Chinese enterprises, provided by the National Enterprise Credit Information Publicity System (<http://www.gsxt.gov.cn/index.html>) (e.g., the registration date, address, registered capital and other information of all enterprises in China). In the research period of this study (2003–2016), the number of newly registered units reaches 9.8 million, with a total registered capital of 840 trillion yuan. By complying with the industry codes of registered enterprises, three types of green industries are selected, i.e., environmental protection, public service and other special equipment manufacturing (“green equipment”, code 359), environmental

¹³ Patents in China are officially categorized into three types: invention, utility model, and industrial design. To qualify for “invention”, the patent must contribute to major improvement on certain product or technology. Utility model and industrial design are less innovative patents that focus on the new shape, structure or design patterns of the products.

¹⁴ Kou and Liu (2017) use the patent data of the State Intellectual Property Office of China and the registered capital data from the State Administration for Industry and Commerce of China to calculate the annual innovation index of Chinese cities from 2001 to 2016 based on the parameter estimation method (see <http://www.cbnri.org/news/5389402.html>).

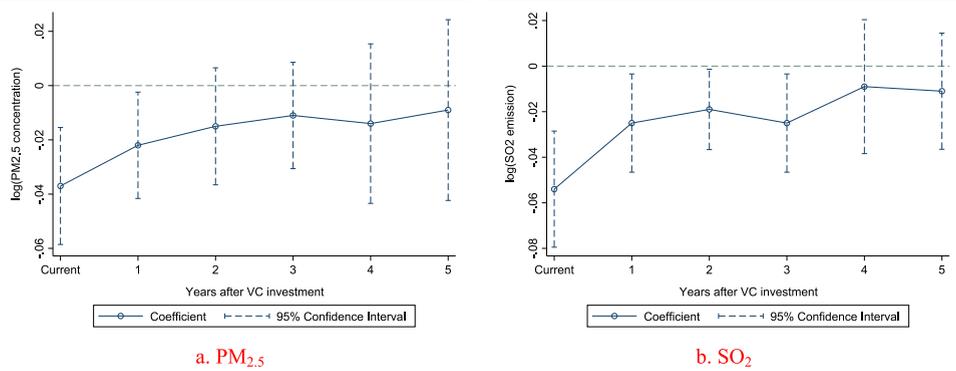


Fig. 4. The dynamic effects of VC on air pollution.

Notes: The figure illustrates the coefficients and the corresponding 95% confidence intervals for β_1^i in Eq. (4).

Table 6

Mechanism: promoting innovation.

	(1)	(2)	(3)	(4)	(5)	(6)
	log (Patent)	log(Patent-invention)	Innovation index	log(Green patent)	log(Green invention)	log(Green utility model)
log(VC amount)	0.307** (0.133)	0.696* (0.367)	0.685** (0.314)	0.671*** (0.118)	0.989*** (0.137)	0.519*** (0.123)
Controls	Yes	Yes	Yes	Yes	Yes	Yes
City fixed-effects	Yes	Yes	Yes	Yes	Yes	Yes
Province-year fixed effects	Yes	Yes	Yes	Yes	Yes	Yes
Observation	3276	3276	3276	2897	2897	2897

Note: Dependent variables are in log form except for the innovation index. The table reports IV estimates. City fixed-effects, province-year fixed effects and control variables including GDP per capita (in log form), GDP share of the secondary sector, GDP share of the tertiary sector, total employment (in log form), fiscal spending (in log form), area of paved road (in log form), and coverage rate of green space (in log form) are in all models. Robust standard errors clustered at city level are in parentheses. * $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$.

and ecological detection (“environmental detection”, code 746), as well as environmental governance (code 772). Likewise, three types of polluting industries are adopted, i.e., coal mining, smelting and construction.¹⁵

Table 7 lists the regression results of effects of VC on the six industries above. Panel A relates to green investment, in which VC amount is found to be correlated with a larger investment of green industries. To be specific, if VC amount is raised by 1%, the newly registered capital in the industries of green equipment, environmental detection and environmental governance will rise by 0.11%, 0.21% and 0.72%, respectively, and the newly registered enterprises of the three industries will significantly increase by 0.46%, 0.28% and 0.87%, respectively.

Panel B lists the effects of VC on the three heavy pollution industries. As opposed to the green industries, VC investment is found to significantly crowd out heavy pollution investment in the city. With a 1% increase in the VC amount, the newly registered capital in the industries of coal, smelting and construction will be reduced by 0.16%, 0.75% and 0.64%, respectively, and the newly registered enterprises of the three industries will decline by 0.13%, 0.33% and 0.07%, respectively. In general, we confirm that VC facilitates new green investment and discourages polluting investment, which contributes to the improvement of air quality.

6. Conclusion

China's VC has been surging since the beginning of the new millennium, accompanied by the establishment of thousands of Government Guidance Funds that guide and support the prevalence of VC activities. High-potential startups commercializing risky novel ideas are offered a source of finance, which translated into the driving forces of technological innovation and economic development. However, concerns have emerged regarding the sustainability of such a substantial economic gain. This study provides novel evidence on the role of VC as sustainable finance, by evaluating the impact of VC activities on local air pollution in China.

¹⁵ The industry of coal mining includes bituminous and anthracite mining and washing (code 610), lignite mining and washing (code 620), other coal mining and washing (code 690). The industry of smelting includes ironmaking (code 311), steelmaking (code 312), common non-ferrous metal smelting (code 321). The industry of construction includes cement, lime and gypsum manufacturing (code 301), gypsum, cement products, and similar products manufacturing (code 302), bricks, stones, and other building materials manufacturing (code 303).

Table 7
Mechanism: improving investment structure.

	log(Registered capital)			log(Registered firms)		
	(1)	(2)	(3)	(4)	(5)	(6)
Panel A. green investment						
	Green equipment	Environment detection	Environment governance	Green equipment	Environment detection	Environment governance
log(VC amount)	0.113 (0.277)	0.212** (0.085)	0.717** (0.347)	0.459*** (0.176)	0.281*** (0.079)	0.873*** (0.300)
Observation	3061	2179	2899	3061	2179	2899
Panel B. polluting investment						
	Coal	Smelting	Construction	Coal	Smelting	Construction
log(VC amount)	-0.158*** (0.032)	-0.753** (0.314)	-0.643*** (0.220)	-0.134 (0.122)	-0.329*** (0.120)	-0.072 (0.099)
Observation	6307	7911	9623	6307	7911	9623

Note: The table reports the IV estimates. City fixed-effects, province-year fixed effects and control variables including GDP per capita (in log form), GDP share of the secondary sector, GDP share of the tertiary sector, total employment (in log form), fiscal spending (in log form), area of paved road (in log form), and coverage rate of green space (in log form) are in all models. Robust standard errors clustered at city level are in parentheses. * $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$.

Relying on the Government Guidance Fund as a valid instrumental variable, and using city-level data between 2003 and 2016, we find that VC has robustly improved local air quality in Chinese cities. With a one standard deviation in the VC amount, the city's $PM_{2.5}$ concentration and industrial SO_2 emission will significantly decrease by 3.97% and 6.25%, respectively. The pollution-reduction effect of VC is larger for green VCs, in cities with more rigorous environmental supervision, superior business environments, stronger innovation incentives, and in eastern cities. Lastly, the effect of interest is realized via technological innovation and structural improvement. In general, our findings suggest that the development of VC complies with the global trend on encouraging green credit and sustainable finance. The positive environmental externality of VC can be achieved and augmented by enhancing innovative motivations, strengthening environmental supervision, creating more desirable business climate, and taking the cons out of fiscal expenditure to better guide and support VC activities.

A few concerns on extended research are worth noting. First, although we conduct several validity tests of the IV, the exercise on validating the exclusion restriction can never be exhaustive. Second, the channels through which VC can promote (green) innovation and improve investment structure deserves more discussion. For instance, VC can promote (green) innovation by directly providing capital to enhance the R&D activities of the target firms, by acquiring certain decision-making authority in the financed firms and motivate more innovative investments, or by promoting firm innovation via the provision of services on cooperate finance, law and management. Third, it would be practically beneficial to check whether early-stage VC and late-stage VC exhibit different impacts on air pollution. Future studies built on improved methods and detailed data are in order.

Data availability

Data will be made available on request.

Acknowledgements

Weizeng Sun acknowledges funding support from the National Science Foundation of China (No. 72274228, No. 71903210), the Beijing Social Science Fund Project (No. 21DTR010), and the Program for Innovation Research in Central University of Finance and Economics. Yue Hua acknowledges funding support from the National Science Foundation of China (No. 71803043) and Social Science Foundation of Hunan Province (No. 18JD14). All errors are ours.

References

- Acemoglu, D., Johnson, S., & Robinson, J. A. (2001). The colonial origins of comparative development: An empirical investigation. *American Economic Review*, 91(5), 1368–1401.
- Aizawa, M., & Yang, C. F. (2010). Green credit, Green stimulus, Green revolution? China's mobilization of banks for environmental cleanup. *The Journal of Environment & Development*, 19(2), 119–144.
- An, Y., Zhou, D., Yu, J., Shi, X., & Wang, Q. (2021). Carbon emission reduction characteristics for China's manufacturing firms: Implications for formulating carbon policies. *Journal of Environmental Management*, 84(15), 112055.1–112055.12.
- Arqué-Castells, P. (2012). How venture capitalists spur invention in Spain: Evidence from patent trajectories. *Research Policy*, 41(5), 897–912.
- Bernauer, T., & Koubi, V. (2006). States as providers of public goods: How does government size affect environmental quality?. Available at SSRN <https://ssrn.com/abstract=900487>.
- Chemmanur, T. J., Loutskina, E., & Tian, X. (2014). Corporate venture capital, value creation, and innovation. *The Review of Financial Studies*, 27(8), 2434–2473.
- Chen, Y., Liu, M., & Liao, J. (2011). *20 years of China's venture capital* (pp. 15–18). Beijing: China Development Press.
- Chen, Y. S., Lai, S. B., & Wen, C. T. (2006). The influence of green innovation performance on corporate advantage in Taiwan. *Journal of Business Ethics*, 67(4), 331–339.

- Chen, Z., Kahn, M. E., Yu, L., et al. (2018). The consequences of spatially differentiated water pollution regulation in China. *Journal of Environmental Economics and Management*, 8, 468–485.
- Cumming, D., Henriques, I., & Sadorsky, P. (2016). “Cleantech” venture capital around the world. *International Review of Financial Analysis*, 44(3), 86–97.
- Dittmar, J. E., & Meisenzahl, R. R. (2020). Public goods institutions, human capital, and growth: Evidence from German history. *Review of Economic Studies*, 87(2), 959–996.
- van Donkelaar, A., Martin, R. V., Li, C., & Richard, T. (2019). Regional estimates of chemical composition of fine particulate matter using a combined geoscientific-statistical method with information from satellites, models, and monitors. *Environmental Science & Technology*, 53(5), 2595–2611.
- Engel, D., & Keilbach, M. (2007). Firm-level implications of early stage venture capital investment—An empirical investigation. *Journal of Empirical Finance*, 14(2), 150–167.
- Faria, A. P., & Barbosa, N. (2014). Does venture capital really Foster innovation. *Economics Letters*, 122(2), 129–131.
- Fisman, R., & Love, I. (2007). Financial dependence and growth revisited. *Journal of the European Economic Association*, 5(2–3), 470–479.
- Florida, R. L., & Kenney, M. (1988). Venture capital, high technology and regional development. *Regional Studies*, 22(1), 33–48.
- Giroud, X. (2013). Proximity and investment: Evidence from plant-level data. *The Quarterly Journal of Economics*, 128(2), 861–915.
- Gompers, P., & Lerner, J. (2001). The venture capital revolution. *Journal of Economic Perspectives*, 15(2), 145–168.
- Gray, W. B., & Deily, M. E. (1996). Compliance and enforcement: Air pollution regulation in the US steel industry. *Journal of Environmental Economics and Management*, 31(1), 96–111.
- Grimaud, A., & Rougel, L. (2005). Pollution non-renewable resources, innovation and growth: Welfare and environment policy. *Resource and Energy Economics*, 27(2), 109–129.
- Guo, D., & Jiang, K. (2013). Venture capital investment and the performance of entrepreneurial firms: Evidence from China. *Journal of Corporate Finance*, 22, 375–395.
- Haliçioğlu, F. (2009). An econometric study of CO₂ emissions, energy consumption, income and foreign trade in Turkey. *Energy Policy*, 37(3), 1156–1164.
- Hang, Y., Wang, Q., Zhou, D., & Zhang, L. (2019). Factors influencing the progress in decoupling economic growth from carbon dioxide emissions in China’s manufacturing industry. *Resources, Conservation and Recycling*, 146, 77–88.
- Hellmann, T., & Puri, M. (2002). Venture capital and the professionalization of start-up firms: Empirical evidence. *The Journal of Finance*, 57, 169–197.
- Huang, X., & Tian, P. (2023). How does heterogeneous environmental regulation affect net carbon emissions: Spatial and threshold analysis for China. *Journal of Environmental Management*, 330, Article 117161.
- Inderst, R., & Mueller, H. M. (2009). Early-stage financing and firm growth in new industries. *Journal of Financial Economics*, 93(2), 276–291.
- Jalil, A., & Feridun, M. (2011). The impact of growth, energy and financial development on the environment in China: A cointegration analysis. *Energy Economics*, 33(2), 284–291.
- Jin, Y., Zhang, Q., Shan, L., et al. (2015). Characteristics of venture capital network and its correlation with regional economy: Evidence from China. *PLoS One*, 10(9), Article e0137172.
- Keuschnigg, C., & Nielsen, S. B. (2004). Start-ups, venture capitalists, and the capital gains tax. *Journal of Public Economics*, 88(5), 1011–1042.
- Kortum, S., & Lerner, J. (2000). Assessing the contribution of venture capital to innovation. *RAND Journal of Economics*, 31(4), 674–692.
- Kou, Z., & Liu, X. (2017). *FIND report on city and industrial innovation in China (2017)*. Shanghai: Fudan Institute of Industrial Development, School of Economics, Fudan University.
- Lerner, J., & Nanda, R. (2020). Venture Capital’s role in financing innovation: What we know and how much we still need to learn. *Journal of Economic Perspectives*, 34(3), 237–261.
- Liao, X. (2018). Public appeal, environmental regulation and green investment: Evidence from China. *Energy Policy*, 119, 554–562.
- Lin, X., Xu, W., Zhang, B., et al. (2019). Does venture capital spur innovation or the other way around? Evidence on the significance of investment timing from China. *Growth and Change*, 50(1), 90–113.
- Lopez, R., Galinato, G., & Islam, A. (2011). Fiscal spending and the environment: Theory and empirics. *Journal of Environmental Economics and Management*, 62, 180–198.
- Mrkajic, B., Murtinu, S., & Scalera, V. G. (2019). Is green the new gold? Venture capital and green entrepreneurship. *Small Business Economics*, 52(4), 929–950.
- Petkova, A. P., Wadhwa, A., Yao, X., et al. (2014). Reputation and decision making under ambiguity: A study of US venture capital firms’ investments in the emerging clean energy sector. *Academy of Management Journal*, 57(2), 422–448.
- Popov, A., & Roosenboom, P. (2013). Venture capital and new business creation. *Journal of Banking & Finance*, 37(12), 4695–4710.
- Popp, D. (2006). International innovation and diffusion of air pollution control technologies: The effects of NOX and SO₂ regulation in the US, Japan, and Germany. *Journal of Environmental Economics and Management*, 51(1), 46–71.
- Samila, S., & Sorenson, O. (2011). Venture capital, entrepreneurship, and economic growth. *The Review of Economics and Statistics*, 93(1), 338–349.
- Shahbaz, M., Solarin, S. A., Mahmood, H., et al. (2013). Does financial development reduce CO₂ emissions in Malaysian economy? A time series analysis. *Economic Modelling*, 35, 145–152.
- Streets, D. G., & Waldhoff, S. T. (2000). Present and future emissions of air pollutants in China: SO₂, NO_x, and CO. *Atmospheric Environment*, 34(3), 363–374.
- Sun, J., Wang, F., & Yin, H. (2019). Money talks: The environmental impact of China’s green credit policy. *Journal of Policy Analysis and Management*, 38(3), 653–680.
- Sun, W., Zhao, Y., & Sun, L. (2020). Big data analytics for venture capital application: Towards innovation performance improvement. *International Journal of Information Management*, 50, 557–565.
- Tamazian, A., Chousa, J. P., & Vadlamannati, K. C. (2009). Does higher economic and financial development lead to environmental degradation: Evidence from BRIC countries. *Energy Policy*, 37(1), 246–253.
- Tamazian, A., & Rao, B. B. (2010). Do economic, financial and institutional developments matter for environmental degradation? Evidence from transitional economies. *Energy Economics*, 32(1), 137–145.
- Wadhwa, A., Phelps, C., & Kotha, S. (2016). Corporate venture capital portfolios and firm innovation. *Journal of Business Venturing*, 31(1), 95–112.
- Wang, J., & Liu, M. (2019). Current situation analysis and policy suggestions of China’s government guidance fund. *Journal of Fujian Normal University (Philosophy and Social Sciences Edition)*, 219(6), 78–86.
- Wen, J., Yang, D., Feng, G. F., et al. (2018). Venture capital and innovation in China: The non-linear evidence. *Structural Change and Economic Dynamics*, 46(C), 148–162.
- White, S., Gao, J., & Zhang, W. (2005). Financing new ventures in China: System antecedents and institutionalization. *Research Policy*, 34(6), 894–913.
- Wurgler, J. (2000). Financial markets and the allocation of capital. *Journal of Financial Economics*, 58, 187–214.
- Yao, S., Pan, Y., Sensoy, A., et al. (2021). Green credit policy and firm performance: What we learn from China. *Energy Economics*, 101, Article 105415.
- Zhao, C., Dong, K., Wang, K., et al. (2022). How does energy trilemma eradication reduce carbon emissions? The role of dual environmental regulation for China. *Energy Economics*, 116, Article 106418.
- Zhou, W., Yang, W., Wan, W., et al. (2018). The influences of industrial gross domestic product, urbanization rate, environmental investment, and coal consumption on industrial air pollutant emission in China. *Environmental and Ecological Statistics*, 25(4), 429–442.