Can Cooperation Stimulate Firms' Eco-Innovation? Firm-level Evidence from China

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Abstract

Firms' collaborative activities have created increasing opportunities for eco-innovation in modern society. Based on unbalanced panel data from the Chinese National Innovation Survey between 2011 and 2015, this paper explored the influences of different modes of cooperation, i.e., vertical cooperation, horizontal cooperation, and mixed cooperation, on the eco-innovation of Chinese manufacturing firms. Results indicated that three types of cooperation all had positive and statistically significant effects on the firms' eco-innovation, and mixed cooperation had promoted eco-innovation more dramatically. The extent of such impacts may vary depending on the heterogeneity of the characteristic of enterprises. We also verified that knowledge spillovers from cooperative partners have played a mediating role between cooperation and eco-innovation. Our results suggest the potential benefits of diversified collaborative activities and appropriate intellectual property protection for firms' eco-innovation in China.

1. Introduction

As a key to decoupling environmental pressure from economic growth, eco-innovation has gained increasing attention by governments, scientific communities, and firms, to uncover the underlying determinants for sustainable growth owing to its "double externalities" (Barbieri et al. 2016; Del Río et al. 2016). Eco-innovation can not only effectively reduce the environmental negative externalities, but also produce positive knowledge externalities (Rennings 2000). However, such positive knowledge externalities may render the firms, which are original with high enthusiasm in eco-innovation, less motivated, mainly because the knowledge and technology originated from eco-innovation can also benefit other firms or even its competitors by knowledge and technological spillovers. On the other side, the complex and uncertain nature of eco-innovation sets a higher standard for cross-disciplinary knowledge and diversified skills (Horbach et al. 2013). The multitudinous and wide-distributed knowledge, skills, and resources essential for eco-innovation are generally unavailable for one individual enterprise, but can only be obtained from external sources. As a consequence, firms concentrating on their internal environment may lose the opportunity for achieving the potential eco-innovation and the consequent benefits (Laursen and Salter 2006). Moreover, the high investment of diverse knowledge and resources for eco-innovation may bring about high risk inherently, and thus prevent one individual enterprise from the potential eco-innovation due to its high concern about the returns of investment (Acemoglu et al. 2016).

In this case, cooperation aimed to explore the innovation resources outside the firms has been regarded as an effective solution for the problems arising from the high and diverse requirements for knowledge for firms' eco-innovation (Marzucchi and Montresor 2017). Currently, open cooperation includes the horizontal collaboration with partners beyond the supply chain (such as universities, research institutions, the government, and even competitors, et, al.) and vertical collaboration with partners within the supply chain (including consumers and suppliers), and such collaborative activities for innovation has evolved as a new way that helps firms maintain their competitive advantage (Chesbrough 2003; Laursen and Salter 2006; Lichtenthaler 2011). Previous literature indicated that cooperating with heterogeneous

partners could be more accessible to the necessary but diversified knowledge for innovation (Cassiman and Veugelers 2006; Phelps 2010; Lichtenthaler 2011; Wang et al. 2014; Singh et al. 2016; Tumelero et al. 2019). Moreover, partners can also afford the cost- and risk- sharing in the presence of potentially high risk accompanied with innovation (Miotti and Sachwald 2003). Based on an investigation of 77 telecom equipment manufacturers in 13 countries, Phelps (2010) found that collaborative networks have benefited the innovative firms a lot from their partners with diversified technologies, and thus promoted their exploratory innovation.

Such benefits of open cooperation can also go for eco-innovation, which is characterized by complexity and high knowledge demands, for external knowledge (De Marchi 2012; Awan et al. 2021). In the face of increasingly stricter environmental regulation, heterogeneous partners can help innovative firms to much more rapid access to the diversified knowledge, resources, and the transformation and application of eco-innovation technologies (Del Río et al. 2016). As a consequence, increasingly more firms choose to develop their own inter-organizational collaborative networks to promote eco-innovation for better environmental and economic performances with relatively lower cost and risk (Doran and Ryan 2012; Cainelli et al. 2015). A case of the Spanish manufacturing industry in 2014 has demonstrated that cooperation can be conducive to the integration of environmental interests and knowledge for all stakeholders, and thus effectively promoted the implementation of eco-innovation activities (Garcés-Ayerbe et al. 2019). Extensive literature has also focused on the potential benefits of open collaboration with partners within or beyond the supply chain (Tether 2002; Miotti and Sachwald 2003; De Marchi 2012; Horbach 2014). As each partner has distinctive characteristics, the mixed operation could add an extra layer of value for enterprises to promote their eco-innovation through leveraging the collaboration advantages of external partners within and beyond the supply chain.

In the past decades, firms in China are facing “the strictest environmental regulation” ever, and thus have to seek their optimal behavior decisions to strive for a balance between economic outcomes and environmental performance. Eco-innovation has also been highly favored by firms and the Chinese government. However, the firm-level eco-innovation in China is difficult to meet the practical requirements, mainly due to the insufficient eco-innovation and achievement transformation activities (Miao et al. 2019; Song et al. 2020). Such mismatch of demand and supply of eco-innovation necessitates the scientific research of the leading motivating factors and the policy stimulus for eco-innovation in China. In 2019, the National Development and Reform Commission and Ministry of Science and Technology in China have issued the Guidelines on building an eco-innovation system, and aim to construct a market-oriented eco-innovation system by 2022 by enhancing the complementary collaboration among industries, universities, research institutions, financial service institutions, and intermediary agents. Hofman et al. (2020) collected data in the Chinese automotive, electronics, and textiles manufacturing sectors through a self-designed questionnaire, and found that cooperation with suppliers is conducive to green process innovation. Yang and Lin (2020) found that supply chain cooperation has played an important role in eco-innovation strategies by studying a case of an automobile firm in southwestern China. Although the effect of collaboration on the eco-innovation in China has been involved by previous literature, its inherent influencing mechanism, and the endogeneity problems accompanied by the lack of firm-level data, still

need further investigation. Such in-depth exploration may help to identify the key factors in promoting the eco-innovation practices, and further facilitate the win-win development of environmental improvement and economic outcomes in China.

To fill the above-mentioned gap in the existing literature, this paper contributes to the existing literature in the following ways. First, as a complement to the existing perspectives between collaboration and eco-innovation, mixed cooperation was also considered for innovation, rather than only that within or beyond the supply chain. Second, by constructing reliable two-period panel data from China National Innovation Survey, we constructed a panel fixed effect model to provide micro evidence of the impact of different types of cooperation on eco-innovation in China. Third, the mechanism of the impact of cooperation on eco-innovation at the micro-level has also been clarified by using knowledge spillover as the mediating channel.

The remainder of the paper is structured as follows. Section 2 proposes the inherent mechanism between cooperation and eco-innovation, and Section 3 introduces the estimation strategy and the data. Section 4 presents the main results of the baseline regression, the heterogeneous analysis, robustness analysis, and further analysis. The final section concludes with policy implications.

2. Theoretical Analysis And Hypothesis

2.1 Different types of cooperation and eco-innovation

Previous literature has summarized that cooperators for innovative firms mainly include partners beyond the supply chain and that within the supply chain, according to the benefits of cooperation for innovation with different types of organization (Tether 2002). Due to the diversities in knowledge type, management mode, and cooperative motivation, cooperation with different partners may affect innovative firms' eco-innovation differently (Awan et al. 2021; De Marchi 2012).

For partners within the supply chain, suppliers and consumers can help innovative firms to complement different types of resources for further eco-innovation. On one hand, due to suppliers' specialized resources of the technical requirements, component specifications, cooperation with suppliers can benefit the innovative firms with strategic knowledge and technologies for their internal green R&D efforts (Du et al. 2018; Hofman et al. 2020). In addition, their mutual technological dependence on skills and resources can make their collaborative activities with environmental-friendly factor inputs in the whole production process, to further reduce the adverse impact on the environment (De Marchi 2012). On the other hand, due to the potential uncertainties of consumer preferences of emerging technologies, consumers can contribute to obtaining complementary knowledge on users' behavior, and balancing the environmental and economic outcomes with lower prices (Kammerer 2009; Chatterji and Fabrizio 2014). Therefore, such vertical cooperation with partners along the supply chain may positively influence the propensity of firms to innovate because they can provide crucial information on technologies and markets (Miotti and Sachwald 2003).

In terms of horizontal cooperation with partners beyond the supply chain for innovation, various partners can contribute diversified resources and technical capabilities to supplement the limited internal resources of the innovative firms (Lichtenthaler 2011). Universities and research institutions can effectively guarantee the acquisition of cutting-edge knowledge and emerging technologies to complement their internal knowledge with much lower R&D expenditures (De Marchi 2012), and governmental partners can provide long-term research funding support and unique material resources for firms in technology development alliances (Doblinger et al. 2019). Especially, the industry-university-research cooperation can also deliver a lot of intellectual and human capital for firms' innovative activities (Horbach 2014). Based on a probit model analysis, Triguero et al. (2013) concluded that firms, which attached importance to the industry-university-research cooperation in European countries, are more active in eco-innovation activities. In addition, cooperating with other firms and institutions can help to share the high risks and costs of eco-innovation with firms, so that firms are more motivated to conduct the eco-innovation. However, it is noteworthy that innovative firms collaborated with competitors may be affected by their mutual competitive pressure and knowledge spillovers, which is not conducive to firms' eco-innovation (Cainelli et al. 2012).

It should be also noteworthy that the above-mentioned types of cooperators are more than substitutes, but can also be complements due to their potential additive effects (Howells 2006). Due to the huge requirements on the cutting-edge, diversified, and interdisciplinary knowledge and abilities, it is hard for one single firm to be proficient in all the skills required for eco-innovation (Doran and Ryan 2012). Cooperators beyond the supply chain, especially universities and research institutions, can provide innovative firms with the acquisition of advanced knowledge, but they are generally insensitive or less responsive to the market demand (Tether 2002). As a complementarity, partners within the supply chain can help to better understand the target market needs, and thus realize the most suitable exploitation of knowledge, skills, and resources necessary for eco-innovation. Using data from Community Innovation Surveys (CIS) conducted in the Netherlands, Belderbos et al. (2006) found that cooperation strategies with competitors and customers, and with customers and universities can play complementary roles in the innovation process. By such mixed cooperation, namely, complementing their respective collaboration advantages from both scientific communities and supply-chain partners, firms can be more motivated to the engagement in eco-innovation activities and the consequent transformation into new and high-quality products with responsive market orientation (Haus-Reve et al. 2019).

Thus, the first hypothesis was posited as follows:

H1: The establishment of various types of collaborative partnerships can help firms to develop eco-innovation in China.

2.2 The influencing mechanism of cooperation on eco-innovation

Cooperation can promote eco-innovation through knowledge spillovers. The establishment of stable collaborative networks can create the possibility for knowledge spillovers by the potential exchange of

information and resource, and thus improve knowledge networks (Wang et al. 2014). Specifically, cooperation between firms and different types of partners will directly trigger knowledge acquisition and knowledge integration, which can be easily achieved by their daily mutual communication (Wang 2016), to affect the innovation performance of firms (Hagedoorn et al. 2018; Liao and Liu 2021). Moreover, such knowledge spillovers can be sustainable, even under the situation that there is no cooperation at present, the researchers who have cooperated in the past may continue to exchange knowledge in an informal way (Frenken et al. 2010). The consequent complementarity of internal R&D activities and external knowledge acquisition is conducive to the firms' innovation activities (Cassiman and Veugelers 2006). Overall, such direct and sustainable knowledge spillovers from collaborative activities can promote firms' eco-innovation by knowledge sharing (Song et al. 2020). Chatterji and Fabrizio (2014) found that firms' external cooperation is conducive to the use of external knowledge from other firms, universities, and users to promote innovation. In particular, for the firms with more knowledge, which generally tend to have strong learning ability, the potential cooperation can not only enrich the firm's knowledge, but also enable them to quickly respond to changes in the market environment to reduce the uncertainty of eco-innovation (Liao 2018).

Cooperation can also make tacit knowledge explicit, thereby facilitating the exchange of knowledge. The complex technologies and technical know-how required by eco-innovation is generally tacit knowledge, which is difficult to be simply transferred by documents but more reliable on close social communication (Becerra et al. 2008). Gertner et al. (2011) concluded that cooperation based on personal social interaction generally contains more tacit knowledge, which could become more explicit and more easily transferred during collaborative engagements (Willoughby and Galvin 2005). Furthermore, successful innovative entrepreneurs are less likely to exchange their tacit knowledge with unfamiliar firms (Singh et al. 2016). Such a situation necessitates collaborative networks with these innovative entrepreneurs directly or indirectly with mutual trust to obtain the highly tacit knowledge, and such partners with the common purpose, are more inclined to share knowledge in a positive attitude to allow firms to absorb the knowledge.

Above all, the second hypothesis was formulated as follows:

H2: The cooperation between firms and partners generates knowledge spillovers, and thus promotes their potential eco-innovation.

3. Methods

3.1 Estimation strategy and the variables

To investigate the impact of cooperation on eco-innovation, a fixed-effects model, which can effectively address the statistical concerns that might not be tackled by an ordinary least squares method (Wooldridge 2013), has been applied to undertake the baseline regression analysis in this paper. The fixed-effects model is specified as follows:

$$eco_inno_{it} = \alpha_0 + \alpha_1 vertical_{it} + \alpha_2 horizontal_{it} + \alpha_3 mix_{it} + \beta_i \sum X_{it} + \gamma_c + \delta_y + \lambda_i + \mu_{it}$$

1

where, eco_inno_{it} is the number of types of eco-innovation introduced by firm i in year t . $vertical_{it}$, $horizontal_{it}$ and mix_{it} are dummy indicators that equal 1 if firm i conducts the vertical cooperation, horizontal cooperation, and mixed cooperation in year t , respectively, with α_1, α_2 and α_3 representing their coefficients. X_{it} is a vector of control variables (i.e., firm characteristics, entrepreneur characteristics, city characteristics). We also control for (a) industry fixed effects (λ_i), (b) year fixed effects (δ_y), and (c) city fixed effects (γ_c). μ_{it} is the error term. In addition, to modify the potential heteroscedasticity caused by the correlation among different firms in different sectors, we further clustered the standard errors at the industry level.

Dependent variable

In this study, the self-reported data about the impact of process innovation on the environmental benefits of firms from the CNIS have been employed to measure eco-innovation, as used in previous literature (Horbach et al. 2012; Antonioli et al. 2013). In the CNIS, which is similar to the widely used CIS, firms were requested to report their achieved benefits, mainly in material saving, energy saving, or emission reduction, from introducing process innovation. If one of the benefits in material saving, energy saving, or emission reduction has been achieved through the process innovation by firms, we defined this as eco-innovation, and we further used the sum of the values for each type of benefit as the eco-innovation variable, following the method in Ghisetti et al. (2015). Similar to the method in Horbach et al. (2012), for each type of the achieved benefits, the answer of “very high” receives a value of 1, and the answer of “medium”, “low”, or “none” receives a value of 0. It should be noted that the assignment of a value of “0”, rather than “1” in Horbach et al. (2012), to the answer of “medium” mainly aimed to prevent the entrepreneurs from overstating their potential achievements.

Independent variables

According to the response of which kind of partners firms cooperate with to innovate in the CNIS, we defined the key independent variables, i.e., different types of cooperation, as three dummy variables, following the method used by Haus-Reve et al. (2019). Horizontal cooperation is measured as a dummy with value 1 when the firms cooperate with any one of the following partners, including other firms, universities, research institutions, governments, associations, competitors, consultants, intermediaries, venture capital institutions, or other partners in their affiliated group. Similarly, the vertical cooperation is represented as a dummy with value 1 if the firms’ partner is one of their suppliers or customers. Furthermore, if firms’ partners include both the above horizontal and vertical partners, we defined this kind of cooperation as the mixed cooperation with the dummy value as 1, otherwise with the value as 0.

Control variables

In this paper, several firm-, entrepreneur-, and city-level variables, which may potentially affect the exploratory innovation, have been controlled to isolate the marginal effects of the explanatory variables only.

Firm-level control variables. (a) Generally speaking, larger firms have more capital and human resources to support the implementation of eco-innovation (Rehfeld et al. 2007; Liao and Liu 2021). We measured the firm size as the natural logarithm of the number of employees by firm i in year t . (b) The firm age is expected to influence the knowledge base, thus affecting the development of eco-innovation (Barbieri et al. 2016). Firm age is defined as the natural logarithm of the differences between the foundation date of firm i with its surveyed date in the CNIS. (c) Previous studies have shown that the ownership of a company, state-owned or private-owned, is increasingly considered as a key factor, which may significantly affect the development of technology innovation (Clò et al. 2020). In this paper, we controlled for firm ownership by using three dummy variables, i.e. state-owned enterprises (SOEs), domestic private, and foreign-invested, that take the value of 1 if a firm belongs to the corresponding firm type or 0 otherwise. (d) Firms with more fixed assets tend to operate more stably, which is more conducive to the adoption of eco-innovation, and we defined the per capita fixed assets as the natural logarithm of the total fixed assets per employee. (e) Previous studies have shown that exports have little influence or negative influences on eco-innovation for European firms (De Marchi 2012), while firms in China are more motivated to carry out eco-innovation to meet the increasingly strict environmental standards of the foreign market for exports. Therefore, export is considered as another important control variable, and is defined as a dummy variable, with the value as 1 if the export delivery value of firm i in year t is not 0.

Entrepreneur-level control variables

Factors related to entrepreneurs will create innovation (Larson 2000). (a) Gender is measured as a dummy with a value of 1 when the entrepreneur is male according to the relevant survey response. (b) To control for entrepreneurs' age, five dummy variables (i.e. younger than 29 years, 30-39 years old, 40-49 years old, 50-59 years old, and that older than 60 years) have been used, which receive the value 1 if they fall under the corresponding interval, or 0 otherwise. (c) Similar method has been employed for controlling entrepreneurs' education level by using five dummy variables, namely, Ph.D., master, undergraduate, junior college, and others.

City-level control variables

(a) Previous studies have shown that environmental regulation is the main driving factor of eco-innovation (Horbach 2008). In this paper, a city-level comprehensive indicator has been designed by incorporating the city-level air pollutants (SO_2 , and soot and dust) removal rate, the water pollutant treatment rate, and the industrial solid waste utilization rate to represent the city-level environmental regulation (regulation) in the studied cities, by following the approach in Cheng et al. (2018). (b) The urban economic level is also an external factor that affects the firms' eco-innovation (Horbach 2014), and

the natural logarithm of satellite nightlight density is used as a proxy to reflect urban economic level (nightlight) in this paper, mainly because that the nightlight data can not be confounded by the price factors among different regions (He et al. 2020).

3.2 Sample and data

To investigate the effect of cooperation on firm eco-innovation, we constructed data samples from three major sources. First, data on the innovation activities of Chinese manufacturing firms are from two waves of innovation surveys on manufacturing firms in four developed regions (namely Jiangsu, Zhejiang, Guangdong, and Shanghai) in the China National Innovation Survey (CNIS)¹. Two surveys were jointly conducted by China's National Bureau of Statistics and the Ministry of Science and Technology in 2011 and 2015. According to the requirements of the survey, all "above-scale" manufacturing firms, with annual sales income above 5 million CNY before 2011 and 20 million CNY thereafter, were required to respond to the questionnaire. Consistent with the CIS and OECD's Oslo manual, the survey consisted of a firm innovation questionnaire and an entrepreneur questionnaire. The former includes detailed coverage of firm-level information on innovation activities (inputs, outputs, sources, effects, obstacles, modalities, etc.), and the latter asked the entrepreneurs to provide personal information like gender, age, education levels, and their attitudes and perception of government policies to support innovation. Therefore, the survey is the fundamental data source to identify the impact of cooperation on firms' eco-innovation.

Second, data from the Annual Survey of Industrial Firms (ASIF), conducted by China's National Bureau of Statistics for the period from 1998 to 2013, can provide information on firm-level control variables. ASIF has been widely used in the extant literature to estimate the productivity of Chinese manufacturing firms, and the total output of its covered firms accounts for approximately 90% of all industrial output in China. The information contained in the data includes basic firm information (firms' legal identification code, industry classification, name, address, etc.) and the major financial indicators (number of employees, annual sales income, assets, annual industrial output, etc.).

Third, we collect city-level environmental regulation data of 2010-2013 from the China City Statistical Yearbooks, and China Environmental Statistical Yearbooks (Cheng et al. 2018). The satellite nightlight densities data are from the Chinese Research Data Services Platform (CNRDS).

Based on the above-mentioned data sources, we first obtain our sample by selecting firms located in Jiangsu Province, Zhejiang Province, Guangdong Province, and Shanghai City according to their administrative location codes at the city level. Then, we use both the legal identification code and the firms' names to match the samples between the CNIS and ASIF. In the regression model, firm-level control variables, environmental regulation, and satellite nightlight densities are lagged by one year to alleviate problems from the potential reverse causality to the best as we can.

Finally, we construct unbalanced panel data regarding firm eco-innovation, cooperation innovation, and other covariates both at the firm and the city level in two years: 2011, and 2015. The total data for 2011

and 2015 consist of 43,132 observations, and the number of observations from Jiangsu, Zhejiang, Guangdong province, and Shanghai city is 17185, 14414, 8660, and 2873, respectively.

3.3 Descriptive statistics

Table 1 presents a summary of descriptive statistics for dependent and main independent variables. Eco-innovation (*ei* for short in the following) has a mean of 0.981, suggesting that all covered firms have a relatively low level of eco-innovation between 2011 and 2015. For main independent variables, on average, vertical, horizontal, and mix are about 0.066, 0.149, and 0.178, respectively, indicating a visible difference among various types of cooperation.

Table 1
Descriptive statistics

Variable	Obs	Mean	Std.Dev.	Min	Max
<i>ei</i>	43,132	0.981	1.226	0	3
<i>vertical</i>	43,132	0.066	0.248	0	1
<i>horizontal</i>	43,132	0.149	0.356	0	1
<i>mix</i>	43,132	0.178	0.382	0	1
<i>gender</i>	43,132	0.604	0.489	0	1
<i>Entrepreneurs' age: taking "younger than 29 years" as reference</i>					
<i>younger than 29 years</i>	43,132	0.0855	0.280	0	1
<i>30-39 years old</i>	43,132	0.289	0.454	0	1
<i>40-49 years old</i>	43,132	0.365	0.481	0	1
<i>50-59 years old</i>	43,132	0.217	0.412	0	1
<i>older than 60 years</i>	43,132	0.0425	0.202	0	1
<i>Entrepreneurs' education level: taking "others" as reference</i>					
<i>others</i>	43,132	0.202	0.402	0	1
<i>junior college</i>	43,132	0.434	0.496	0	1
<i>undergraduate</i>	43,132	0.306	0.461	0	1
<i>master</i>	43,132	0.0504	0.219	0	1
<i>Ph.D.</i>	43,132	0.0074	0.0856	0	1
<i>size</i>	43,132	5.420	0.915	0	11.90
<i>firmage</i>	43,132	2.263	0.613	0	6.023
<i>Firm ownership: taking "SOEs" as reference</i>					
<i>SOEs</i>	43,132	0.173	0.379	0	1
<i>domestic private</i>	43,132	0.534	0.499	0	1
<i>foreign-invested</i>	43,132	0.292	0.455	0	1
<i>percapita</i>	43,132	3.926	1.523	-6.073	15.74
<i>export</i>	43,132	0.490	0.500	0	1
<i>regulation</i>	43,132	0.799	0.070	0.343	0.925
<i>nightlight</i>	43,132	2.977	0.729	0.678	4.043

Furthermore, considering the regional distribution of eco-innovation activities, Table 2 shows the eco-innovation activities in each province during the two waves of investigation. Firms introducing eco-innovation, which achieved material-saving, energy-saving, and emission reduction, accounted for about 45% of the total surveyed firms, and firms that introduce innovation to obtain all the three types of benefits, accounted for more than 20% for each province, indicating that firms have paid more attention to the innovative technologies that can achieve material-saving, energy-saving, and emission reduction, simultaneously.

Table 2
Eco-innovation of firms in various provinces/municipalities in China

<i>Types of eco-innovation activities</i>	<i>Shanghai</i>	<i>Jiangsu</i>	<i>Zhejiang</i>	<i>Guangdong</i>	<i>Total</i>
<i>Number of firms not introducing any type of ei</i>	1535	9407	7956	4703	23601
<i>Number of firms introducing one type of ei</i>	413	2449	1967	1195	6024
<i>Number of firms introducing two types of ei</i>	286	1621	1420	920	4247
<i>Number of firms introducing three types of ei</i>	639	3708	3071	1842	9260
<i>Total</i>	2873	17185	14414	8660	43132

[¹] The China National Innovation Survey covered the innovation activities nationwide in 2011 and 2015. In this paper, only the data from Jiangsu, Zhejiang, Shanghai, and Guangdong has been used, mainly due to the data limitation and the representativeness of active innovation engagements in these four developed regions of China.

4. Results And Discussion

4.1 Cooperation and eco-innovation

Table 3 reports the impact of cooperation on eco-innovation. From columns (1) to (3), control variables, industry-year joint fixed effect, and city fixed effect are gradually added. Results indicate that vertical cooperation, horizontal cooperation, and mixed cooperation all have positive influences on eco-innovation. Furthermore, as shown in columns (2) and (3), the estimated coefficients remained positive and statistically significant for three types of cooperation, regardless of the control of industry-year interaction, indicating that cooperation has significantly positive effects on the firms' eco-innovation. More precisely, horizontal cooperation and mixed cooperation are statistically significant (at the 1% level), while vertical cooperation is statistically significant (at the 10% level). Firms that choose cooperation display a stronger likelihood to introduce eco-innovation. Therefore, H1 was verified.

Mixed cooperation had a more dramatic impact on promoting eco-innovation. As shown in Table 1, mixed cooperation has a mean score of 0.178, which is greater than that of the other two modes, suggesting that firms covered in our sample tended to choose mixed cooperation. Such choice has also shown better performance on eco-innovation promotion. By comparing the coefficients of vertical cooperation (0.042), horizontal cooperation (0.1874), and mixed cooperation (0.2682), we found that mixed cooperation has the highest positive impact on eco-innovation, suggesting that mixed cooperation can reap the benefits of collaboration from external partners within and beyond the supply chain to the fullest.

In addition, we also found that gender, age, and education of entrepreneurs are important drivers of eco-innovation, as shown in Column (3) of Table 3, and younger, highly-educated male entrepreneurs are more inclined to conduct eco-innovation statically. At the firm level, the firm size has positive impacts on eco-innovation statistically, and economies of scale would make firms more active in the development of eco-innovation with the expansion of firms' scale. Moreover, the per capita fixed assets also have positive impacts on eco-innovation statistically, and its potential increase may bring more new energy-saving and emission-reduction equipment to firms and promote eco-innovation. In terms of firms' ownership, foreign-invested firms may have a negative influence on eco-innovation statistically. Although these foreign-invested firms can provide firms with opportunities to learn and imitate, the knowledge and technologies cannot be utilized due to the limitations of the firm's absorptive capacity. Such high dependence on foreign technologies also inhibits their inherent willingness and activities to conduct innovation.

Table 3
Cooperation and eco-innovation

	(1)	(2)	(3)
	Fixed effect	Fixed effect	Fixed effect
<i>vertical</i>	0.0372*	0.0405*	0.0420*
	(0.0199)	(0.0232)	(0.0230)
<i>horizontal</i>	0.2464***	0.1892***	0.1874***
	(0.0197)	(0.0190)	(0.0188)
<i>mix</i>	0.3105***	0.2679***	0.2682***
	(0.0176)	(0.0183)	(0.0182)
<i>gender</i>		0.0600***	0.0588***
		(0.0096)	(0.0096)
<i>30-39 years old</i>		-0.0963**	-0.0957**
		(0.0368)	(0.0368)
<i>40-49 years old</i>		-0.1187***	-0.1178***
		(0.0350)	(0.0350)
<i>50-59 years old</i>		-0.1395***	-0.1392***
		(0.0427)	(0.0429)
<i>older than 60 years</i>		-0.0430	-0.0437
		(0.0462)	(0.0465)
<i>junior college</i>		0.0779***	0.0760***
		(0.0216)	(0.0215)
<i>undergraduate</i>		0.1754***	0.1722***
		(0.0221)	(0.0221)
<i>master</i>		0.3052***	0.3012***
		(0.0265)	(0.0260)
Note: Robust standard errors in parentheses are clustered at the industry level.			
*** p<0.01, ** p<0.05, * p<0.1.			

	(1)	(2)	(3)
<i>Ph.D</i>		0.4463***	0.4427***
		(0.0456)	(0.0458)
<i>size</i>		0.0425***	0.0421***
		(0.0075)	(0.0076)
<i>firmage</i>		-0.0082	-0.0079
		(0.0113)	(0.0114)
<i>percapital</i>		0.0493***	0.0492***
		(0.0077)	(0.0077)
<i>export</i>		0.0159	0.0155
		(0.0171)	(0.0169)
<i>regulation</i>		0.2668	0.2037
		(0.2821)	(0.2442)
<i>nightlight</i>		0.8191	0.7240
		(0.5011)	(0.4942)
<i>private</i>		-0.0153	-0.0149
		(0.0147)	(0.0146)
<i>foreign-invested</i>		-0.0899***	-0.0899***
		(0.0147)	(0.0146)
<i>industry fixed effect</i>	No	Yes	No
<i>year fixed effect</i>	No	Yes	No
<i>industry*year fixed effect</i>	Yes	No	Yes
<i>city fixed effect</i>	Yes	Yes	Yes
<i>constant</i>	0.8095***	-2.3177	-1.9743
	(0.0123)	(1.5144)	(1.5064)
<i>N</i>	38666	37802	37801
Note: Robust standard errors in parentheses are clustered at the industry level.			
*** p<0.01, ** p<0.05, * p<0.1.			

	(1)	(2)	(3)
<i>F</i>	134.0451	128.3235	133.8949
<i>R-squared</i>	0.0222	0.0325	0.0327
Note: Robust standard errors in parentheses are clustered at the industry level.			
*** p<0.01, ** p<0.05, * p<0.1.			

4.2 Robustness checks

4.2.1 Alternative independent variables

To test the robustness of our findings, we consider different partners of horizontal cooperation as alternative independent variables of our model (Awan et al. 2021), given the heterogeneous influences of the different partners on eco-innovation. In this section, the influences of partners of horizontal cooperation on eco-innovation have been detailed into that of other firms in the affiliated group (*otherfirms*), universities and research institutions (*school*), associations (*association*), governments (*government*), competitors (*competitor*), intermediaries (*consultant*), venture capital institutions (*venturecap*) and other partners (*otherpartners*). Column (1) of Table 4 shows that other firms, universities and research institutions, associations, governments, competitors and consultants, and intermediaries all play an important role in promoting eco-innovation. This alternative measure produces similar results as our baseline results in Table 3. It can be explained by the following aspects. Other firms in the affiliated group and competitors often have the same goals and similar resources, which is conducive to the exchange of resources in eco-innovation. In particular, when the information from competitors is very important, firms are more likely to become followers of innovation (Cassiman and Veugelers 2006). The universities and research institutions in industry-university-research cooperation can better provide firms with the human capital and professional knowledge needed for eco-innovation (De Marchi 2012). The associations and intermediaries can also provide legal advice, financing, and other services for it. In addition, the financial incentives and relevant policy information provided by the governments bring the resource to support and point out the future direction for firms, to boost eco-innovation (Tsai and Liao 2017).

4.2.2 Alternative dependent variable

We perform the basic regression by using the dependent variable defined by the number of eco-innovation introduced. However, this measurement does not consider its specific classification. Previous studies have shown that different types of eco-innovation may also bring heterogeneous economic performance to firms (Ghisetti and Rennings 2014), and consequently, cooperation may also have heterogeneous effects on different types of eco-innovation, given the profit-maximization goal of firms. Here, the eco-innovation has been further classified into two types, i.e., the Energy and Resource Efficiency Innovation, for the reduction in material and energy input per unit of output, and the Externality Reducing

Innovation, for reducing production externalities, by following Ghisetti and Rennings (2014). Specifically, the Energy and Resource Efficiency Innovation (*erei*) is measured as a dummy with a value of 1, if the firms have introduced innovation with a high impact on material and energy reduction. The Externality Reducing Innovation (*reei*) is also assigned as a dummy with a value of 1, if firms have introduced the innovation with a high impact on emission reduction, otherwise with a value of 0. As shown in columns (2) and (3) of Table 4, we found that the impacts of three types of cooperation on the Energy and Resource Efficiency Innovation and the Externality Reducing Innovation are both positively significant, in line with the results in Table 3, indicating that the results are robust.

4.2.3 Alternative estimation method

According to the descriptive statistics in Table 1, the dependent variable is a count variable, and its variance is significantly greater than the mean value. Such overdispersion makes the negative binomial regression model also applicable (Cameron and Trivedi 2005). Therefore, we have also applied the negative binomial regression as another robustness check. As shown in column (4) of Table 4, the coefficient of vertical cooperation is insignificant, but it is still positive. This alternative method produces results similar to the results of the panel fixed-effect model in Table 3. It is proved that vertical cooperation, horizontal cooperation, and mixed cooperation are important drivers for eco-innovation.

Table 4
Robustness checks

	(1)	(2)	(3)	(4)
	Fixed effect	Fixed effect	Fixed effect	Negative binomial regression
	ei	erei	reei	ei
<i>vertical</i>		0.0217**	0.0200*	0.0445
		(0.0091)	(0.0099)	(0.0280)
<i>horizontal</i>		0.0686***	0.0706***	0.2077***
		(0.0074)	(0.0089)	(0.0192)
<i>mix</i>		0.1007***	0.1006***	0.2879***
		(0.0066)	(0.0074)	(0.0197)
<i>otherfirms</i>	0.0505***			
	(0.0185)			
<i>school</i>	0.1505***			
	(0.0294)			
<i>association</i>	0.1560***			
	(0.0174)			
<i>governments</i>	0.2042***			
	(0.0401)			
<i>competitor</i>	0.1014***			
	(0.0193)			
<i>consultant</i>	0.1280***			
	(0.0225)			
<i>venturecap</i>	-0.2114**			
	(0.0807)			

Note: Robust standard errors in parentheses are clustered at the industry level.

*** p<0.01, ** p<0.05, * p<0.1.

	(1)	(2)	(3)	(4)
<i>otherpartners</i>	-0.0066			
	(0.0239)			
<i>gender</i>	0.0642 ^{***}	0.0281 ^{***}	0.0219 ^{***}	0.0629 ^{***}
	(0.0137)	(0.0031)	(0.0053)	(0.0110)
<i>30-39 years old</i>	-0.0956 ^{**}	-0.0219	-0.0398 ^{***}	-0.0920 ^{***}
	(0.0408)	(0.0137)	(0.0132)	(0.0326)
<i>40-49 years old</i>	-0.1144 ^{***}	-0.0306 ^{**}	-0.0440 ^{***}	-0.1172 ^{***}
	(0.0371)	(0.0137)	(0.0116)	(0.0325)
<i>50-59 years old</i>	-0.1377 ^{***}	-0.0399 ^{***}	-0.0481 ^{***}	-0.1395 ^{***}
	(0.0433)	(0.0135)	(0.0165)	(0.0408)
<i>older than 60 years</i>	-0.0436	-0.0170	-0.0068	-0.0334
	(0.0525)	(0.0167)	(0.0205)	(0.0427)
<i>junior college</i>	0.0696 ^{**}	0.0299 ^{***}	0.0337 ^{***}	0.0925 ^{***}
	(0.0304)	(0.0100)	(0.0071)	(0.0234)
<i>undergraduate</i>	0.1717 ^{***}	0.0756 ^{***}	0.0543 ^{***}	0.1896 ^{***}
	(0.0249)	(0.0077)	(0.0091)	(0.0232)
<i>master</i>	0.2834 ^{***}	0.1227 ^{***}	0.1065 ^{***}	0.2989 ^{***}
	(0.0379)	(0.0103)	(0.0096)	(0.0234)
<i>Ph.D</i>	0.4719 ^{***}	0.1852 ^{***}	0.1542 ^{***}	0.4108 ^{***}
	(0.0578)	(0.0214)	(0.0213)	(0.0354)
<i>size</i>	0.0422 ^{***}	0.0179 ^{***}	0.0128 ^{***}	0.0392 ^{***}
	(0.0088)	(0.0030)	(0.0028)	(0.0072)
<i>firmage</i>	-0.0180	-0.0048	-0.0000	-0.0087
	(0.0142)	(0.0048)	(0.0052)	(0.0112)

Note: Robust standard errors in parentheses are clustered at the industry level.

*** p<0.01, ** p<0.05, * p<0.1.

	(1)	(2)	(3)	(4)
<i>percapita</i>	0.0521 ^{***}	0.0195 ^{***}	0.0166 ^{***}	0.0491 ^{***}
	(0.0085)	(0.0029)	(0.0032)	(0.0084)
<i>export</i>	0.0291	-0.0001	0.0041	0.0125
	(0.0204)	(0.0062)	(0.0067)	(0.0166)
<i>regulation</i>	0.4032	0.0561	0.0765	0.2247
	(0.2584)	(0.1005)	(0.1086)	(0.2614)
<i>nightlight</i>	1.0014 ^{**}	0.3081	0.1556	0.6743
	(0.4605)	(0.1941)	(0.1599)	(0.5531)
<i>private</i>	-0.0484 ^{**}	-0.0112 ^{**}	-0.0045	-0.0120
	(0.0226)	(0.0054)	(0.0085)	(0.0150)
<i>foreign-invested</i>	-0.1251 ^{***}	-0.0339 ^{***}	-0.0321 ^{***}	-0.0852 ^{***}
	(0.0190)	(0.0064)	(0.0064)	(0.0152)
<i>industry*year fixed effect</i>	Yes	Yes	Yes	Yes
<i>city fixed effect</i>	Yes	Yes	Yes	Yes
<i>constant</i>	-3.0506 ^{**}	-0.8391	-0.3924	-3.3392
	(1.4394)	(0.5931)	(0.4509)	(2.1081)
<i>lnalpha</i>				-0.1121
				(0.0691)
<i>N</i>	28138	37801	37801	37802
<i>F</i>	201.6460	328.1163	102.7393	
<i>R-squared</i>	0.0329	0.0299	0.0302	
Note: Robust standard errors in parentheses are clustered at the industry level.				
*** p<0.01, ** p<0.05, * p<0.1.				

4.3 Heterogeneity analyses

Generally, firms in energy-intensive and emission sectors may be more likely to conduct eco-innovation, which is also highly impacted by the level of intellectual property protection (Del Río et al. 2016;

Brüggemann et al. 2016). Therefore, in this section, heterogeneous analyses have been further conducted.

Firms with different energy intensities. Based on the Statistical Communique of the People's Republic of China on the 2010 National Economic and Social Development, six high energy-consuming industries², have been identified. Firms have been then classified into high energy-consuming firms and low energy-consuming firms according to their sector attributes. The high energy-consuming firm is measured as a dummy with a value of 1, if the firm belongs to one of the six high energy-consuming industries, otherwise with a value of 0, representing a low energy-consuming firm. As shown in column (1) of Table 5, there is a statistically significant and positive association between the horizontal/mixed cooperation and eco-innovation, consistent with the results in Table 3. However, the coefficient of vertical cooperation is insignificantly positive. The statistically significant and positive coefficients of interaction between the three types of cooperation and high energy-consuming firms indicated that, in comparison to low energy-consuming firms, three types of cooperation in high energy-consuming firms could have higher influences on promoting eco-innovation.

Firms with different emission intensities. Generally, firms with higher emission intensities may pay much more attention to their emission reduction and thus the consequent eco-innovation, leading to the sector heterogeneities. Therefore, we have classified all the samples into heavy-pollution firms and light-pollution firms, based on their sectoral attributes according to the definition of high pollution sectors in the Guidelines for Environmental Information Disclosure of Listed Companies 2010 in China. The heavy-pollution firm is measured as a dummy with a value of 1, if the firm belongs to one of the heavy-pollution industries³, otherwise with a value of 0, indicating a light-pollution firm. As shown in column (2) of Table 5, we can obtain statistically significant and positive relations between vertical/horizontal/mixed cooperation and eco-innovation, respectively. Furthermore, the significantly negative coefficients of interaction between horizontal/mixed cooperation and heavy-pollution firms have shown that the promotion of horizontal cooperation and mixed cooperation on eco-innovation will be weakened in heavy-pollution firms, compared with that in light-pollution firms. This may be attributable to the reason that, in comparison to light-pollution firms, heavy-pollution firms are always reliable to their emission-intensive production patterns, and thus less motivated to conduct eco-innovation of production technology due to the existed technology lock-in and the potentially high costs. In addition, the cooperation may cause technology spillovers and make their innovative technology been easily imitated and even copied, and thus lead to relatively lower returns on investment, and further, alleviate the motivation for cooperation on eco-innovation.

Firms with different levels of intellectual property protection. In collaborative activities, knowledge can be spread and further be used by firms to meet their requirements of eco-innovation. However, the quantity and quality of such knowledge spillovers may be highly affected by the level of intellectual property protection in the city, where firms are located (Arora et al. 2021). Therefore, we measured the level of city-level intellectual property protection (*intproperty*) by the number of documents on intellectual property protection in each city, and then we interacted that with the different types of cooperation. As displayed in

column (3) in Table 5, we found that vertical cooperation, horizontal cooperation, and mixed cooperation all have statistically significant and positive effects on eco-innovation. We also observed the statistically significant and negative association between vertical cooperation and intellectual property, while statistically insignificant and negative coefficients of interaction between horizontal/mixed cooperation and intellectual property. In other words, the improvement of the level of intellectual property protection in a city may weaken the promotion of cooperation on eco-innovation. The main reason is that overstrict intellectual property protection may not be conducive to knowledge and technology sharing in cooperation by inhibiting the imitation and learning of firms. Such circumstances would make firms more reliable on their previous innovation, and have adverse effects on the engagements of more complex and valuable innovation (Brüggemann et al. 2016).

Table 5
Heterogeneity analysis

	(1)	(2)	(3)
	Fixed effect	Fixed effect	Fixed effect
	enersector	pollsector	intproperty
<i>vertical</i>	0.0239	0.0726**	0.1079**
	(0.0266)	(0.0303)	(0.0397)
<i>horizontal</i>	0.1736***	0.2267***	0.2027***
	(0.0212)	(0.0229)	(0.0378)
<i>mix</i>	0.2514***	0.3233***	0.2774***
	(0.0193)	(0.0184)	(0.0291)
<i>vertical*sector</i>	0.1068**		
	(0.0453)		
<i>horizontal*sector</i>	0.0744**		
	(0.0286)		
<i>mix*sector</i>	0.0943**		
	(0.0442)		
<i>vertical*sector1</i>		-0.0430	
		(0.0395)	
<i>horizontal*sector1</i>		-0.0552*	
		(0.0300)	
<i>mix*sector1</i>		-0.0778***	
		(0.0259)	
<i>vertical*intproperty</i>			-0.0001*
			(0.0001)
<i>horizontal*intproperty</i>			-0.0000

Note: Robust standard errors in parentheses are clustered at the industry level.

*** p<0.01, ** p<0.05, * p<0.1.

	(1)	(2)	(3)
			(0.0001)
<i>mix*intproperty</i>			-0.0000
			(0.0000)
<i>gender</i>	0.0590 ^{***}	0.0587 ^{***}	0.0588 ^{***}
	(0.0096)	(0.0096)	(0.0096)
<i>30-39 years old</i>	-0.0958 ^{**}	-0.0960 ^{**}	-0.0955 ^{**}
	(0.0368)	(0.0369)	(0.0368)
<i>40-49 years old</i>	-0.1179 ^{***}	-0.1181 ^{***}	-0.1174 ^{***}
	(0.0351)	(0.0351)	(0.0352)
<i>50-59 years old</i>	-0.1392 ^{***}	-0.1394 ^{***}	-0.1389 ^{***}
	(0.0430)	(0.0431)	(0.0433)
<i>older than 60 years</i>	-0.0428	-0.0435	-0.0433
	(0.0465)	(0.0468)	(0.0468)
<i>junior college</i>	0.0755 ^{***}	0.0760 ^{***}	0.0760 ^{***}
	(0.0216)	(0.0216)	(0.0213)
<i>undergraduate</i>	0.1716 ^{***}	0.1724 ^{***}	0.1721 ^{***}
	(0.0222)	(0.0221)	(0.0218)
<i>master</i>	0.3002 ^{***}	0.3017 ^{***}	0.3011 ^{***}
	(0.0262)	(0.0261)	(0.0260)
<i>Ph.D</i>	0.4418 ^{***}	0.4437 ^{***}	0.4417 ^{***}
	(0.0458)	(0.0457)	(0.0457)
<i>size</i>	0.0422 ^{***}	0.0421 ^{***}	0.0422 ^{***}
	(0.0075)	(0.0076)	(0.0076)
<i>firmage</i>	-0.0080	-0.0080	-0.0079

Note: Robust standard errors in parentheses are clustered at the industry level.

*** p<0.01, ** p<0.05, * p<0.1.

	(1)	(2)	(3)
	(0.0114)	(0.0113)	(0.0113)
<i>percapital</i>	0.0492***	0.0492***	0.0492***
	(0.0077)	(0.0076)	(0.0077)
<i>export</i>	0.0151	0.0161	0.0156
	(0.0168)	(0.0169)	(0.0169)
<i>regulation</i>	0.2009	0.1999	0.1921
	(0.2438)	(0.2429)	(0.2449)
<i>nightlight</i>	0.7389	0.7234	0.7791
	(0.4961)	(0.4948)	(0.4671)
<i>intproperty</i>			0.0006
			(0.0021)
<i>private</i>	-0.0151	-0.0151	-0.0148
	(0.0146)	(0.0146)	(0.0146)
<i>foreign-invested</i>	-0.0896***	-0.0898***	-0.0896***
	(0.0147)	(0.0146)	(0.0146)
<i>industry*year fixed effect</i>	Yes	Yes	Yes
<i>city fixed effect</i>	Yes	Yes	Yes
<i>constant</i>	-2.0162	-1.9689	-2.4877
	(1.5116)	(1.5114)	(1.9600)
<i>N</i>	37801	37801	37801
<i>F</i>	121.8186	239.5229	292.2168
<i>R-squared</i>	0.0328	0.0328	0.0327
Note: Robust standard errors in parentheses are clustered at the industry level.			
*** p<0.01, ** p<0.05, * p<0.1.			

4.4 Further analysis

Based on the benchmark analysis, this paper constructs a mediating effect model to investigate how cooperation affects firms' eco-innovation. Based on the question "Which kind of information and

knowledge have high impacts on firms' innovation activities" in the CNIS, the knowledge spillovers were defined as the mediating variable to conduct mechanism analysis. Given the fact that the knowledge spillovers may be affected by different types of partners, the knowledge spillovers were further classified based on the above-mentioned different types of cooperation, by following the method in Martínez-Ros and Kunapatarawong (2019). Vertical knowledge spillover (*verknow*) is measured as a dummy with a value of 1, if the firms' knowledge comes from any one of suppliers and customers, otherwise with a value of 0. Similarly, horizontal knowledge spillover (*horknow*) is represented as a dummy with a value of 1, if the firms' knowledge comes from any of the firm's horizontal partners, otherwise with a value of 0. In addition, if firms have obtained knowledge both from vertical and horizontal partners, we defined mixed knowledge spillover (*mixknow*) as a dummy with a value 1, otherwise with a value of 0. Furthermore, we first constructed a regression model to test whether these three types of cooperation can promote the corresponding knowledge spillovers, and then we verified whether knowledge spillovers can promote eco-innovation, as follows:

2

$$verknow_{it} = \alpha_0 + \alpha_1 vertical_{it} + \beta_i \sum X_{it} + \gamma_c + \delta_y + \lambda_i + \mu_{it}$$

3

$$horknow_{it} = \alpha_0 + \alpha_2 horizontal_{it} + \beta_i \sum X_{it} + \gamma_c + \delta_y + \lambda_i + \mu_{it}$$

4

$$mixknow_{it} = \alpha_0 + \alpha_3 mix_{it} + \beta_i \sum X_{it} + \gamma_c + \delta_y + \lambda_i + \mu_{it}$$

verknow_{it}, *horknow_{it}* and *mixknow_{it}* refers to vertical, horizontal, and mixed knowledge spillovers useful for the innovation of firm *i* in the year *t*, respectively. The other variables are consistent with the definition in the benchmark model, and the standard errors are also clustered at the industry level.

As shown in columns (1) - (3) of Table 6, we observed statistically significant and positive associations between vertical/horizontal/mixed cooperation and vertical/horizontal/mixed knowledge spillovers, respectively, demonstrating that cooperation can generate knowledge spillovers, as we discussed in the theoretical analysis. Cooperation can be regarded as the co-production of knowledge, and knowledge spillovers are generated as a by-product (Frenken et al. 2010). In addition, business contacts and exchanges among partners could enable firms to timely grasp the most advanced tacit knowledge needed for eco-innovation. Furthermore, in combination with the extant literature on the promotion of knowledge to eco-innovation (Chatterji and Fabrizio 2014; Marzucchi and Montresor 2017; Liao 2018; Song et al. 2020), it can be proved that knowledge spillovers acted as a mediating role between cooperation and eco-innovation. H2 was verified.

Table 6
Results of further analysis

	(1)	(2)	(3)
	Fixed effect	Fixed effect	Fixed effect
	vertical knowledge spillovers	horizontal knowledge spillovers	mixed knowledge spillovers
<i>vertical</i>	0.1686 ^{***}		
	(0.0047)		
<i>horizontal</i>		0.2832 ^{***}	
		(0.0088)	
<i>mix</i>			0.1691 ^{***}
			(0.0038)
<i>gender</i>	-0.0028	-0.0189 ^{**}	0.0176 ^{***}
	(0.0028)	(0.0075)	(0.0059)
<i>30-39 years old</i>	-0.0052	-0.0080	0.0188 [*]
	(0.0060)	(0.0094)	(0.0095)
<i>40-49 years old</i>	0.0075	-0.0295 ^{**}	0.0287 ^{**}
	(0.0060)	(0.0120)	(0.0113)
<i>50-59 years old</i>	0.0047	-0.0089	0.0117
	(0.0073)	(0.0105)	(0.0109)
<i>older than 60 years</i>	0.0084	-0.0326 [*]	0.0383 ^{**}
	(0.0107)	(0.0180)	(0.0181)
<i>junior college</i>	-0.0213 ^{***}	0.0219 ^{***}	-0.0095
	(0.0067)	(0.0066)	(0.0079)
<i>undergraduate</i>	-0.0314 ^{***}	0.0144 [*]	-0.0039
	(0.0059)	(0.0075)	(0.0082)

Note: Robust standard errors in parentheses are clustered at the industry level.

*** p<0.01, ** p<0.05, * p<0.1.

	(1)	(2)	(3)
<i>master</i>	-0.0422 ^{***}	0.0176	-0.0038
	(0.0072)	(0.0158)	(0.0134)
<i>Ph.D</i>	-0.0444 ^{***}	-0.0071	0.0203
	(0.0121)	(0.0198)	(0.0170)
<i>size</i>	-0.0068 ^{***}	0.0063 ^{**}	-0.0051
	(0.0013)	(0.0031)	(0.0033)
<i>firmage</i>	0.0011	-0.0088 ^{***}	0.0073 [*]
	(0.0030)	(0.0026)	(0.0039)
<i>percapital</i>	-0.0070 ^{***}	0.0113 ^{***}	-0.0096 ^{***}
	(0.0010)	(0.0021)	(0.0022)
<i>export</i>	-0.0063 [*]	-0.0273 ^{***}	0.0324 ^{***}
	(0.0033)	(0.0056)	(0.0057)
<i>regulation</i>	-0.0704	0.1728 [*]	-0.0453
	(0.0829)	(0.0930)	(0.1228)
<i>nightlight</i>	0.2445	0.3076	-0.6417 ^{**}
	(0.1603)	(0.2256)	(0.2991)
<i>private</i>	0.0014	0.0178 ^{***}	-0.0108 [*]
	(0.0035)	(0.0064)	(0.0063)
<i>foreign-invested</i>	0.0085 ^{**}	0.0031	-0.0005
	(0.0038)	(0.0075)	(0.0070)
<i>industry*year fixed effect</i>	Yes	Yes	Yes
<i>city fixed effect</i>	Yes	Yes	Yes
<i>constant</i>	-0.5185	-0.7545	2.3921 ^{**}

Note: Robust standard errors in parentheses are clustered at the industry level.

*** p<0.01, ** p<0.05, * p<0.1.

	(1)	(2)	(3)
	(0.4710)	(0.6840)	(0.9038)
<i>N</i>	43132	43132	43132
<i>F</i>	275.8003	447.1885	302.8196
<i>R-squared</i>	0.0502	0.0953	0.0493
Note: Robust standard errors in parentheses are clustered at the industry level.			
*** p<0.01, ** p<0.05, * p<0.1.			

^[2] Six high energy-consuming industries in China include the petroleum processing, the coking & nuclear fuel processing industry, chemical raw material & chemical product manufacturing, the manufacture of non-metallic minerals, ferrous metal smelting & rolling, non-ferrous metal smelting & rolling, and electricity & heating power generation & supply.

^[3] The heavy-pollution industries in China include coal fire, iron & steel, cement, electrolytic aluminum, coal, metallurgy, chemical, petrochemical, building materials, paper making, brewing, pharmaceutical, fermentation, textile, tanning and mining industries.

5. Conclusions

Based on the unique two waves of the Chinese National Innovation Survey on manufacturing firms in 2011 and 2015, we run an unbalanced panel fixed-effect model to test the influence of different types of cooperation on firms' eco-innovation. Empirical results have shown that vertical cooperation, horizontal cooperation, and mixed cooperation all significantly contributed to eco-innovation, and mixed cooperation has shown a more dramatic promotion of eco-innovation than the other two modes. The results remain robust after our robustness check. Observations by different types of firms (e.g., energy intensities, emissions intensities, and levels of intellectual property protection) indicated heterogeneous effects of cooperation on eco-innovation. Finally, the further analysis has explained how knowledge spillovers acted as a mediating variable in the promotion of different types of cooperation on eco-innovation.

Results have highlighted the importance of cooperation on firms' eco-innovation. Firms, aiming to conduct eco-innovation, should actively seek cooperation with different organizations with new ideas on eco-innovation. Through the establishment of a long-term and stable relationship, firms can make full use of the relevant professional knowledge generated by diversified partners to supplement the internal knowledge base, and thus their internal resource allocation can be further optimized and the eco-innovation can be carried out more smoothly with relatively low cost and risk. In addition, the government should accelerate the promotion of horizon cooperation, especially the industry-university-research cooperation, which can provide diversified talents and resources for firms' eco-innovation, by supporting the construction of university talent incubation bases and science and technology industrial parks.

Finally, the Chinese government has proposed that in the 14th five-year plan period (2021-2025), intellectual property rights should be protected, with both public interests and innovation incentives guaranteed. The heterogeneous analysis on different levels of intellectual rights protection has indicated that, the future intellectual property protection system should not only protect the core knowledge and technology of the firms from being leaked, but also ensure partners being not constrained by overstrict content of intellectual property protection for further knowledge and technology share.

As an initial attempt to explore the relations between different types of cooperation and eco-innovation in China, there are several limitations in this study. First, due to the data limitation, firms' eco-innovation in China has been measured by using the self-reported data of entrepreneurs in the China National Innovation Survey, which may be subjective to some extent. Further measurement can be extended by using more objective data, such as green patent data. Secondly, although the merge of surveys allows a time lag between the dependent variable and the independent variables to alleviate endogeneity issues to the best of our abilities, there may still exist endogenous problems in the regression model caused by missing variables, reverse causality, etc. However, the selection of appropriate instrumental variables for three types of cooperation is really difficult and can be further explored in future works. Finally, this paper is based on two waves of innovation surveys in 2011 and 2015, and the future extension of long-time series data can provide more valuable policy insights for the eco-innovation in China.

Declarations

Ethical Approval: The manuscript does not report on or involve the use of any animal or human data.

Consent to Participate: Not applicable.

Consent to Publish: Not applicable.

Authors Contributions: All authors contributed to the study conception and design. Sanfeng Zhang focuses on data collection, data processing, conceptualization, methodology, writing-original draft and writing-review. Xinyue Xu focuses on the data processing, writing-original draft, writing-review and editing. Feng Wang focuses on the analysis, writing-original draft, writing-review and editing. Jian Zhang focuses on analysis, writing-review and editing. All authors commented on previous versions of the manuscript. All authors read and approved the final manuscript.

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