Does the Complexity and Embeddedness of Knowledge Recombination Contribute to Economic Growth?

——Observations from prefecture cities in China

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1. Knowledge and economic growth theory

(1) Neoclassical growth theory

- Classical growth theory demonstrates that cumulative physical capital and division of labor are the main factors of economic growth (Piętak, 2014; Smith, 1776), while also acknowledging the role of technological innovation in the process of economic growth (Piętak, 2014). However, from the perspective of these traditional economists, technological progress was not considered independent, only passively following the accumulation of capital.
- Neoclassical theory asserts that knowledge creation is critical for long-run economic growth (Solow, 1956; Swan, 1956).
- According to the Solow growth model, the "residual effect" of economic growth, referring to the part that cannot be explained by the increased use of labor force and capital, is attributable to technology improvement (Sredojević et al., 2016).

1. Knowledge and economic growth theory

(2) Endogenous growth theory

- Endogenous growth theory proposes that knowledge is an internally determinant of economic growth (Piętak, 2014).
- Arrow (1962) questioned the results derived from neoclassical models and assumed that the obtained knowledge is the result of "learning by doing" (Piętak, 2014).
- Romer (1986) and Lucas (1988) found that economic growth is driven by technological change, deriving from knowledge-related investments in R&D and human capital. Spillover effect.
- Lucas (1988) found that economic growth is driven by technological change generated by knowledge-related investments and human capital.

Bai Chong'en talks about China's potential economic growth rate in the next 15 years

Forecasting China's economic growth and China's high growth: China population growth rate; Productivity gap between China and the US (Bai Chongen, 2021.01.03).

On the one hand, as the economic development level approaches the United States, *the* ***growth rate of labor productivity*** *in the economy gradually declines; on the other hand,* ***with the advent of aging****, the working-age population and* ***employment rate*** *have reached their peaks, both of which will restrict future economic development.*

Note: The farther to the right the horizontal axis is, the closer it is to the level of development in the United States.
When the gap with developed countries is relatively large, labor productivity grows faster. When the gap with developed countries continues to narrow, labor productivity growth will gradually decline.

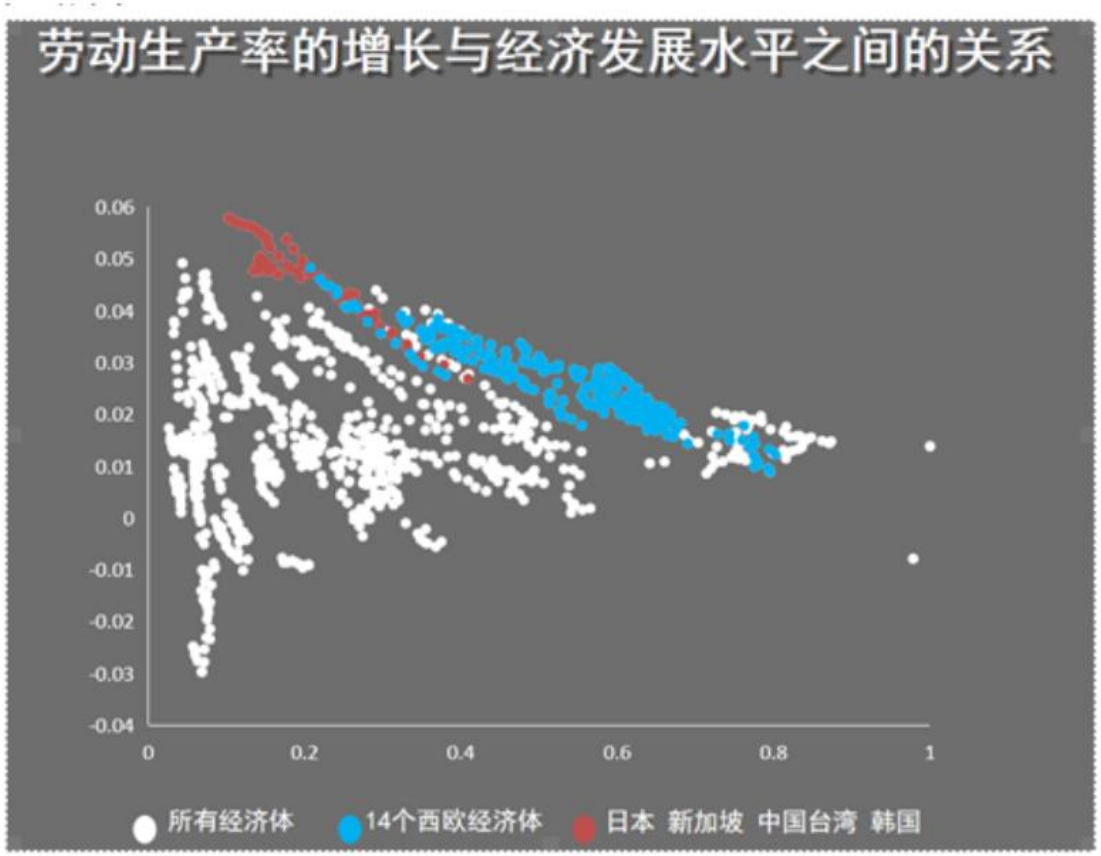

Figure 1 The relationship between labor productivity growth and economic development

Note: Y axis is the growth rate of the economy's labor productivity, and the X axis is the ratio of the economy's per capita GDP/labor productivity to U.S. GDP. The red points represent the historical data of four East Asian economies, including Japan, Singapore, South Korea and Taiwan, and the blue points are the historical data of 14 Western European Economies

1. Knowledge and economic growth theory

(3) Research gap

- From classical growth theory to endogenous growth theory, **knowledge was an elementary driver of economic growth of countries.**
- There are always black boxes containing the "new knowledge creation" (Weitzman, 1998).
- Traditional economic growth theory has not changed its assumption that all knowledge is valuable and equivalent, ignoring the differences between simple knowledge and complex knowledge in the process of knowledge spillover and their differentiated impacts on economic growth (Yan et al., 2023).

2. Knowledge Recombination: Schumpeterian Innovation Economics

- The Schumpeterian growth theory is a variant of endogenous economic growth theory: **(1) the main source of technological progress is innovation; (2) innovation is driven by the prospect of monopoly rents; (3) new innovations can replace old technologies, making economic growth involve disruptive innovation** (Schumpeter, 1911, Schumpeter, 1939, p.88).
- The core idea of the Schumpeterian growth theory is that the endogenous capability for technological innovation is a decisive factor in economic growth, and innovation arises from the recombination of knowledge pieces. Knowledge recombination, innovation, and economic growth can be connected (Cooke and Leydesdorff, 2006).
- Weizmann (1998), began the quantitative research on the knowledge recombination, and also introduced the recombinant theory to explore the determinants of long-term economic growth.
- In Weitzman's (1998) model, knowledge generation mechanism is driven by three steps, the formation of new ideas, turning a potentially fruitful idea into useful knowledge and the internalization of new knowledge (Tsur and Zemel, 2007; Marchese et al., 2019).

2. Knowledge recombination: Technological distance

Adjacent knowledge recombination for incremental innovation

- Adjacent knowledge combination will typically enjoy a high level of recognizability and "cognitive legitimacy", making it more prone to yielding incremental innovation (Keijl et al., 2016; Yayavaram and Chen, 2015).

Distant knowledge recombination for radical innovation

- Radical technologies are linked with recombination that combines new components that typically originate from distant knowledge domains (Rosenkopf and Nerkar, 2001; Hargadon, 2003; Keijl et al., 2016).
- Tellis et al. (2006) also proposed that the benefits of acquiring distant knowledge are numerous, especially, increasing the probability of technological breakthroughs considered as the engine of economic growth by providing more distant knowledge resources.

2. Knowledge recombination: Social network analysis

- The research on innovative regions cites social networks as the crux of innovation (Piore and Sabel, 1984; Almeida and Kogut, 1999; Singh, 2005).
- Silicon Valley's is the typical example, where, there are formal and informal networks of knowledge collaboration (Saxenian, 1994).
- More recently, Fleming, found, by using model of small world of knowledge networking , "a simple measure of the degree of connectedness between regional inventors demonstrates a stronger correlation in significance and magnitude with subsequent patenting than any small world structure"(Fleming et al; OS, 2007, p.939).

2. Embeddedness in other regions

- **Embeddedness into the external knowledge pool and regional growth**
- **An observation of Chinese economist Li that: Chendu is connected more with Shenzhen than other cities with is good for its catching up.**
- Where does new idea come from?
- Sebestyén and Varga (2013) found the quality of interregional knowledge networks to be related to the knowledge potential of collaborative partners and the extent of connectivity among regions, which can directly determine regional knowledge outcomes. Based on this assumption, In our study, the high level of external embeddedness can be characterized as close knowledge collaboration with a long-distance external high-value knowledge pool.

2. Knowledge recombination: Research gap

- Research on knowledge recombination has gradually developed from simple theoretical combination mode to complex knowledge networks linked by socially networked relationships at the empirical level, realizing the refined exploration of knowledge recombination (Zhang et al., 2019).
- Although the characteristics of knowledge networks have obvious influence on the probability of knowledge recombination and regional economic growth, quantitative research based on the perspective of complex networking structure remains scarce.
- Mewes and Broekel (2020, p.1) contend that "the relation between complexity of knowledge recombination and economic growth is still unexplored".

3. Research Questions

- If the complexity of knowledge recombination in a region is good for economic growth, what kind of complexity of knowledge recombination is appropriate for such growth?
- How does external embeddedness moderate the relationship between the complexity of regional knowledge recombination and economic growth?
- Are there any differences in the impact of knowledge recombination on the economy given the regional and developmental heterogeneity? Will a low-complexity region gain more from the embeddedness of the external high-value knowledge pool compared with high-complexity regions?

4. Research Design: Theoretical model

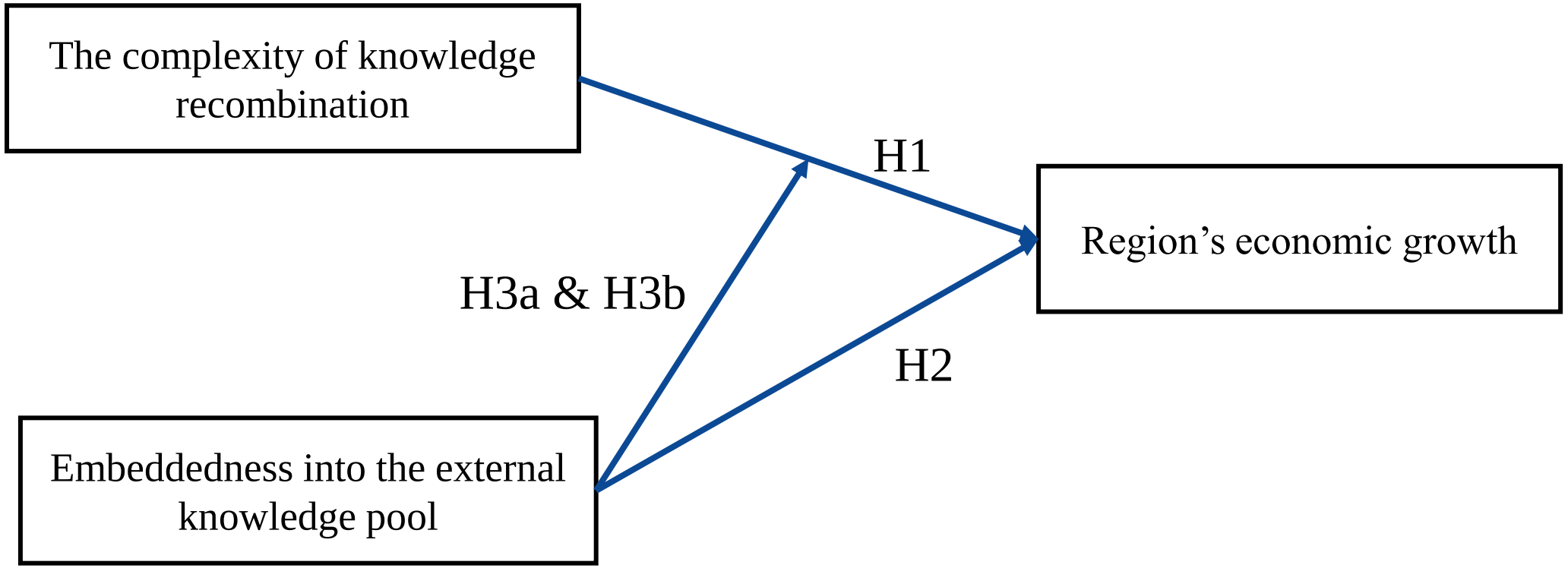

Figure 2. Theoretical model

4. Research Design: Hypotheses

- **(1) The complexity of regional knowledge recombination and economic growth**
- In our study, we examine the actor level, proposing that the complexity of regional knowledge recombination is primarily reflected in the collaborative intensity between actors and the diversity of industries involved in patent coauthorship among actors (Rosiello and Maleki, 2021).
- Through frequent and close knowledge interaction and cooperative activities, heterogeneous actors establish timely communication channels and receive more expedient feedback, which improves the high level of recognizability and "cognitive legitimacy" (Keijl et al., 2016). Subsequently, economic actors can easily transform new knowledge emerging from recombination into novel products and processes to accelerate local economic development (Bergé, 2017).
- Yayavaram and Chen (2015) argued that various recombinations of knowledge domains open more possibilities to move to parts of the search space that have not yet been explored, which can serve as a steppingstone to new technology entry or even radically disruptive innovation.
- **Hypothesis 1: The complexity of knowledge recombination is positively related to a region's economic growth.**

4. Research Design: Hypotheses

- **(2) Embeddedness into the external knowledge pool and regional growth**
- Ejermo and Karlsson (2006, p.414) proposed that "modern knowledge economies are typically characterized by incomplete and scattered knowledge". When knowledge actors can frequently access external knowledge, innovative combinations that bring together original knowledge and external knowledge will emerge (Yayavaram and Ahuja, 2008).
- In our study, the high level of external embeddedness can be characterized as close knowledge collaboration with a long-distance external high-value knowledge pool.
- Through embedding into the external knowledge pool, local actors can identify collaborative partners in a wider space without considering the limitation of geographical boundaries. With the continuous replacement of old and new collaborative relationships, more advanced knowledge from the external source can be absorbed by economic actors, and eventually transformed into a driving force to maintain the long-term growth of the regional economy (Järvi et al., 2017; Zhang et al., 2019).
- **Hypothesis 2: Embeddedness into the external knowledge pool is positively related to the economic growth.**

4. Research Design: Hypotheses

- **(3) Moderation effect of external embeddedness**
- Actors with high level of external embeddedness gain access to more distant and diversified knowledge, delaying the homogenization of the regional knowledge base (De Noni et al., 2017). Accordingly, the number of knowledge recombinations exponentially grows, which may trigger path breaking events in related and unrelated technological fields, ultimately enhancing the positive effect of the diversity of knowledge recombination on economic growth (Guan and Liu, 2016).
- Additionally, to fully understand and acquire more valuable and complex knowledge flowing from the high-value knowledge pool and achieve the best matching (Bergé, 2017), local actors must strengthen collaborative ties with others in the same or different organizations and industries based on the advantage of proximity, which will facilitate interactive learning and strengthen collaborative intensity (Sun and Liu, 2016). Hence, the positive effect of intraregional intensity in cooperation on economic growth will also be strengthened.
- Overall, external embeddedness into the high-value knowledge pool could not only bring more diversified resources, but also further strengthen ties between local actors, which is eventually reflected in knowledge recombination and regional economic growth.
- **Hypothesis 3a: The relationship between the complexity of regional knowledge recombination and economic growth is positively moderated by the embeddedness into the external knowledge pool.**

4. Research Design: Hypotheses

- When economic actors frequently interact with external inventors in the high-value knowledge pool, they will become sensitive to truly valuable dependencies in the form of old ties between local actors that are not productive(Quatraro, 2010). Consequently, ties between local actors may vary in intensity, from strong to weak to non-exist, and the positive effect of the intensity of intraregional cooperation on economic growth could be weakened accordingly.
- Also, external collaborations are especially efficient when regions establish specific knowledge base (Whittle et al., 2020). Ning et al. (2016) proposed that regions with highly specialized knowledge bases have more advantages in assimilating fresh external knowledge. That is to say, regions with a low convergence of specialized industries cannot readily understand knowledge acquired from external resources, which may lead to misinterpretation or misunderstanding (Hansen, 2002). Therefore, inflow of knowledge through embeddedness into external knowledge pool could cause redundancy, as it cannot be accurately or fully absorbed (Demirkan et al., 2013), thereby weakening the positive effect of the diversity of regional knowledge recombination on economic growth.
- **Hypothesis 3b: The relationship between the complexity of regional knowledge recombination and economic growth is negatively moderated by the embeddedness into the external knowledge pool.**

5. Empirical Study: Data and Methodology

- Many studies used patent data to trace the recombination of knowledge components (Gruber et al., 2013; Fleming, 2001). Patent coauthorship networks constitute channels and conduits for knowledge transfer across organizations and geographical borders, providing a range of opportunities to foster knowledge recombination (Tsouri et al., 2022). Thus, we define and measure knowledge recombination via patent coauthorship.
- Our main variables are computed based on patent data. We extract invention patents applied by all sample cities between 2005 and 2019 from the widely used State Intellectual Property Office (SIPO).
- Other data are obtained from the China City Statistical Yearbook and the China Regional Economic Statistical Yearbook published by the National Bureau of Statistics. Our database includes 275 prefecture-level regions in China over a 15-year window, from 2005 to 2019.

5. Empirical Study: The measurement of variables

- **① The complexity of regional knowledge recombination (CRKR)**
  - Both the intensity and the diversity of patent coauthorship shape the characteristic of the complexity of knowledge recombination in a region.

$$CRKR_{i,t} = Intensity_{i,t} \times Diversity_{i,t}$$

- **② The degree of embeddedness into external knowledge sources (ED)**
  - The higher degree of embeddedness, the more high-value knowledge elements can be allocated.

$$ED_{i,t} = \sum_{j=1}^{N} \frac{1}{d_{i,j}} \times S_{ijt} \times innovation\ capability_{j,t}$$

S_{ijt} : a proxy of the strength of ties between regions

$innovation\ capability_{j,t}$: a proxy of regional innovation performance

$d_{i,j}$: a proxy of spatial distance

5. Empirical Study: The measurement of variables

- ③ Control variables

Variable	Definition and measurement
Economic growth	Total gross domestic product (purchasing power standards) divided by total population (in log).
CRKR	The complexity of regional knowledge recombination (in log), which is measured by the amount of the intraregional applicant coauthorship patents from different organizations.
ED	The embeddedness into external knowledge pool (in log). A high level of external embeddedness can be characterized as close knowledge collaboration with a long-distance external high-value knowledge pool.
Population density	Total population (10,000 persons) divided by land area in square kilometers.
Science expenditure	The public science and technology budget (10,000 yuan) divided by the total population (10,000 persons).
Higher education level	Full-time teachers in higher education (10,000 persons) divided by employees in the education industry (10,000 persons).
Unemployment rate	The proportion of unemployed employees (10,000 persons) in the total population (10,000 persons).
Finance	Financial institutions' deposits (10,000 yuan) divided by financial institutions' loans (10,000 yuan).
Patent applications	The amount of invention patent applications in the region divided by the total population (10,000 persons) (in log).
Capital stock	The capital stock is estimated by using a fixed capital investment in the base year of 2003 (in log).

5. Empirical Study: Model establishment

- We try to capture the effect of unobserved macro-environmental factors on annual economic growth by including time-specific dummy variables. Furthermore, given the panel structure of our dataset, the unobserved regional effects also need to be controlled by introducing the region-specific dummy variables. Thus, the two-way fixed-effect model is utilized in regressions (Li et al., 2017; Ge and Liu, 2022).

$$\log\left(Economic\ growth_{i,t}\right) = \alpha_1 \times \log\left(CRKR_{i,t}\right) + \alpha_2 \times \log\left(ED_{i,t}\right) + \alpha_3 \times \log\left(CRKR_{i,t}\right) \times \log\left(ED_{i,t}\right) + \beta X_{i,t} + \partial + \emptyset_i + \gamma_t + \mu_{i,t}$$

where the dependent variable, $Economic\ growth_{i,t}$, is the regional GDP of regions i in year t, X is a matrix of control variables, and the β contains the control variables' parameters. Regional fixed effect $\emptyset_i$, year fixed effect γ_t, constant term ∂, and error term $\mu_{i,t}$ are also included.

5. Empirical Study: Regression results

① According to the regression results of Model (2), the coefficient in Model 2 shows statistical significance (α_1=0.018, p<0.05), suggesting that **the complexity of the regional knowledge recombination has a positive effect on economic growth,** which is consistent with hypothesis 1.

② Hypothesis 2 is supported in Model (3), the embeddedness into the external knowledge pool has a significant and positive influence on economic growth (α_2=0.005,p<0.05).

③ According to the regression results of Model (4), we find that the coefficient of the interaction is significantly positive (α_3=0.004,p<0.1), which shows that the embeddedness into the external knowledge pool has a positive moderating effect on the relationship between the complexity of regional knowledge recombination and economic growth. This result supports hypothesis 3a.

Independent variable	(1)	(2)	(3)	(4)
$Economic\ growth_{i,t+1}(log)$	Model (1)	Model (2)	Model (3)	Model (4)
$CRKR_{i,t}(log)$		0.018**		-0.021
		(0.009)		(0.023)
$ED_{i,t}(log)$			0.005**	0.005**
			(0.002)	(0.002)
$CRKR_{i,t}(log) * ED_{i,t}(log)$				0.004*
				(0.002)
Constant	3.212***	3.188***	3.235***	3.144***
	(0.528)	(0.527)	(0.524)	(0.521)
Control variables	Included	Included	Included	Included
Number of regions	275	275	275	275
Number of observations	3850	3850	3850	3850
Year dummy	Yes	Yes	Yes	Yes
Region dummy	Yes	Yes	Yes	Yes
R^2	0.976	0.976	0.976	0.976
$Adjusted\ R^2$	0.974	0.974	0.974	0.974
F-Value	309.63	294.71	297.29	274.00
P-Value	0.000	0.000	0.000	0.000

Note: Standard errors clustered by region are shown in parentheses.
*p < 0.1, **p < 0.05, ***p < 0.01.

5. Empirical Study: Robustness checks

We conduct several tests to confirm the robustness of our empirical results.

- In addition to testing the significance of the model with time lags (the two-year lag and three-year lag of all explanatory variables), we also used the other two methods to check the robustness of empirical results.
- Firstly, we rerun regressions using total GDP (purchasing power standards) as an alternative measurement of regional economic growth. The reported results are consistent with our previous findings.
- Secondly, we change the method of measuring intraregional applicant coauthorship patents, defining that at least two applicants of a patent should be located in the same region. The measurement of CRKR is adjusted accordingly, and the estimated results align with our previous findings.

5. Empirical Study: Additional analysis

(1) Regional heterogeneity

Sample cities are grouped into three clusters according to China's regional development geography.

Empirical results of three clusters (2005-2019).

Independent variable $Economic\ growth_{i,t+1}(log)$	(1) Eastern China			(2) Central China			(3) Western China		
	Model (1)	Model (2)	Model (3)	Model (4)	Model (5)	Model (6)	Model (7)	Model (8)	Model (9)
$CRKR_{i,t}(log)$	0.021*		-0.007	0.016		-0.074	0.013		-0.094**
	(0.011)		(0.030)	(0.016)		(0.050)	(0.017)		(0.038)
$ED_{i,t}(log)$		0.004	0.004		0.007**	0.008***		0.005*	0.005*
		(0.004)	(0.004)		(0.003)	(0.003)		(0.003)	(0.003)
$CRKR_{i,t}(log) * ED_{i,t}(log)$			0.003			0.010*			0.012**
			(0.003)			(0.006)			(0.005)
Constant	3.294***	3.297***	3.273***	5.214***	5.362***	5.064***	4.192***	4.225***	4.187***
	(0.727)	(0.721)	(0.723)	(1.536)	(1.521)	(1.518)	(1.005)	(0.993)	(0.980)
Control variables	Included	Included	Included	Included	Included	Included	Included	Included	Included
Number of regions	115	115	115	80	80	80	80	80	80
Number of observations	1610	1610	1610	1120	1120	1120	1120	1120	1120
Year dummy	YES	YES	YES	YES	YES	YES	YES	YES	YES
Region dummy	YES	YES	YES	YES	YES	YES	YES	YES	YES
R^2	0.978	0.978	0.978	0.970	0.971	0.971	0.977	0.977	0.977
$Adjusted\ R^2$	0.976	0.976	0.976	0.967	0.968	0.968	0.975	0.975	0.975
F-Value	182.53	181.56	176.23	185.34	179.56	164.19	181.35	180.19	170.85
P-Value	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000

Note: Standard errors clustered by regions are shown in parentheses.
*p < 0.1, **p < 0.05, ***p < 0.01.

5. Empirical Study: Additional analysis

(1) Regional heterogeneity

For eastern regions, the complexity of regional knowledge recombination can effectively promote economic growth, but for regions of central China and western China, the effect does not exist. In particular, regions with a high complexity of knowledge recombination have the ability to produce valuable knowledge elements to meet the requirements of sustained economic growth (Wang and Zhang, 2019), which lead to less desire to embed into the external knowledge pool (Roesler and Broekel, 2017).

For central China and western China, embedding into an external high-value knowledge pool is an effective strategy to promote economic growth. To access valuable resources that cannot be generated internally, some regions may prefer to cut corners, namely, open geographical boundaries and intentionally establish collaborative relationships with advanced areas (Qiu et al., 2017). By embedding into the external knowledge pool, undeveloped regions have the opportunity to grow at the same rate as the frontier region by taking the advantage of latecomers. Even if the knowledge spillover is not necessarily the most cutting-edge core technology, advanced business models, valuable technical information and management experience from the external high-value knowledge pool will also help less developed regions gradually eliminate "path locking" or "low-value locking" by moving up the industrial chain (Bergé, 2017).

5. Empirical Study: Additional analysis

(1) Regional heterogeneity

In addition, for central and western regions, the interactive term shows a significantly positive relationship with regional economic growth, which means embedding into the external knowledge pool can benefit innovation in undeveloped regions, and improving the complexity of regional knowledge recombination can further strengthen the economic efficiency of external embeddedness. The two effects are mutually synergistic, which is consistent with the research on the “absorptive capacity”.

5. Empirical Study: Additional analysis

(2) Heterogeneity in time phases

In 2014, China proposed the concept of the "New Normal" to address the challenges of its slowing economic growth, the need for structural adjustments, and the emergence of new economic development challenges. The "New Normal" represents a new phase of the Chinese economy characterized by a shift from high-speed growth to medium-high-speed growth, and from scale expansion to quality improvement and innovation-driven development. All this means that the macro environment for China's economic growth changed dramatically around 2014.

In line with this, our study divided the time window into two phases, one is from 2005 to 2014, and the other is from 2015 to 2019.

5. Empirical Study: Additional analysis

(2) Heterogeneity in time phases

The regression results of the first stage (from 2005 to 2014) are shown in Models (1) – (3), **the direction and significance of coefficients of two main exploratory variables and the interaction term, are similar to the main results.**

However, in the second phase (from 2015 to 2019), the significance of all the variables that we mainly focus on does not reach the lowest significance level, which is inconsistent with our previous findings.

Empirical results of two time phases.

Independent variable: $Economic\ growth_{i,t+1}(log$	(1) From 2005 to 2014			(2) From 2015 to 2019		
	Model (1)	Model (2)	Model (3)	Model (4)	Model (5)	Model (6)
$CRKR_{i,t}(log)$	0.018**		-0.017	0.004		-0.004
	(0.008)		(0.021)	(0.007)		(0.029)
$ED_{i,t}(log)$		0.004**	0.004**		0.002	0.002
		(0.002)	(0.002)		(0.003)	(0.003)
$CRKR_{i,t}(log) * ED_{i,t}(log)$			0.004*			0.001
			(0.002)			(0.003)
Constant	5.382***	5.364***	5.282***	5.594***	5.644***	5.631***
	(0.509)	(0.507)	(0.511)	(1.077)	(1.075)	(1.079)
Control variables	Included	Included	Included	Included	Included	Included
Number of regions	275	275	275	275	275	275
Number of observations	2750	2750	2750	1100	1100	1100
Year dummy	YES	YES	YES	YES	YES	YES
Region dummy	YES	YES	YES	YES	YES	YES
R^2	0.988	0.988	0.988	0.984	0.984	0.984
$Adjusted\ R^2$	0.987	0.987	0.987	0.978	0.978	0.978
F-Value	374.82	381.77	345.43	17.75	17.92	15.82
P-value	0.000	0.000	0.000	0.000	0.000	0.000

Note: Standard errors clustered by regions are shown in parentheses.
*p < 0.1, **p < 0.05, ***p < 0.01.

5. Empirical Study: Additional analysis

(2) Heterogeneity in time phases

From 2005 to 2014, the proportion of China's R&D investment achieved rapid growth. Under the guidance of the central government, local governments also began to increase R&D investment and focus on technological development, which tends to increase the complexity of knowledge recombination within the regions.

It seems that in the second period (from 2015 to 2019), the economic growth is more relied on other factors rather than knowledge recombination and networking. In terms of the reason behind this, we propose that it lies in more new credit has been allocated to state-owned firms with low productivity than to private firms with high productivity during these years (Cong et al., 2019). **This phenomenon, as highlighted by Brandt et al. (2020), has led to a lack of resource allocation to more productive firms, consequently contributing to the slowing growth of China's economy in recent years.** Moreover, to control air pollution, governments have put more emphasis on green development, which will slow down the economic growth in the short run (Xia and Xu, 2020).

5. Empirical Study: Multiple Discussions

Empirical results of multiple discussions

Independent variable $Economic\ growth_{i,t+1}(log)$	(1) More applicants[2]			(2) Company[3]			(3) IUR[4]			(4) Code C[5]		
	Model (1)	Model (2)	Model (3)	Model (4)	Model (5)	Model (6)	Model (7)	Model (8)	Model (9)	Model (10)	Model (11)	Model (12)
$CRKR_{i,t}(log)$	0.013*		-0.053***	0.013*		-0.016	0.031***		-0.064***	-0.001		-0.020***
	(0.007)		(0.017)	(0.007)		(0.019)	(0.008)		(0.017)	(0.004)		(0.006)
$ED_{i,t}(log)$		0.002	0.001		0.001	0.0006		0.004**	0.004**		0.004**	0.003*
		(0.002)	(0.002)		(0.002)	(0.002)		(0.002)	(0.002)		(0.002)	(0.002)
$CRKR_{i,t}(log) * ED_{i,t}(log)$			0.007***			0.003			0.011***			0.002***
			(0.002)			(0.002)			(0.002)			(0.001)
Constant	3.148***	3.192***	3.076***	3.146***	3.206***	3.105***	3.173***	3.224***	3.071***	3.236***	3.231***	3.039***
	(0.528)	(0.523)	(0.523)	(0.528)	(0.528)	(0.527)	(0.526)	(0.524)	(0.521)	(0.542)	(0.525)	(0.542)
Control variables	Included	Included	Included	Included	Included	Included	Included	Included	Included	Included	Included	Included
Number of regions	275	275	275	275	275	275	275	275	275	275	275	275
Number of observations	3850	3850	3850	3850	3850	3850	3850	3850	3850	3850	3850	3850
Year dummy	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Region dummy	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
R^2	0.976	0.976	0.976	0.976	0.976	0.976	0.976	0.976	0.976	0.976	0.976	0.976
$Adjusted\ R^2$	0.974	0.974	0.974	0.974	0.974	0.974	0.974	0.974	0.974	0.974	0.974	0.974
F-Value	294.65	295.40	275.11	294.12	295.05	270.85	299.19	298.54	285.19	309.13	296.11	280.09
P-Value	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000

[2] Invention patent applications involving three or more applicants.
[3] The patent is invented through cooperation within the company.
[4] The applicants of these patents involve both industries and one or two types of research institutions and universities.
[5] Patent cooperation belongs to the same industry (classified to the national economic code C).

5. Empirical Study: Multiple Discussions

The empirical results demonstrate that with regard to the knowledge recombination involving more applicants, inter-enterprise collaboration, and IUR cooperation, the higher the complexity of knowledge recombination within cities (CRKR), the greater the contribution to regional economic. What's more, the embeddedness of the external knowledge pool (ED) related to IUR cooperation or intra-industry cooperation can effectively promote economic growth.

It is worth noting that IUR cooperation has a positive effect on economic development. Specifically, both the complexity of regional knowledge recombination and the embedding of external knowledge pools achieved through IUR cooperation have a positive impact on local economic development, and the interaction between them also has a significant and positive impact on regional economic growth.

In fact, IUR cooperation has been considered to be an internal driving force of economic growth as it achieves the commercialization of new knowledge (De Wit-de Vries et al., 2019). In addition, IUR can also accelerate regional economic growth by achieving more knowledge recombination associated with new inventions. Academic research provides insightful ideas for tracing the technological frontier, exposing more novelties and unexplored combinations which may disrupt existing cognitive frameworks to innovative entities, thereby exploring possible complementarities between knowledge elements, and ultimately transforming them into patentable inventions or commercial applications (Yayavaram and Ahuja, 2008; Soh and Subramanian, 2014).

6. Discussions and Conclusions: Main findings

① We found that the complexity of regional knowledge recombination has a positive effect on regional economic growth.

when seeking opportunities for knowledge recombination, actors should not only search locally around its core technology fields but also search distantly in broader fields. Regional policies should encourage heterogeneous entities, such as universities, scientific research institutes, and enterprises to conduct cooperative research in different industries, and actively promote cross-industry knowledge exchanges and cooperation.

② Regarding the embeddedness into the external knowledge pool, we found external embeddedness is positively associated with regional economic growth.

By embedding into the external knowledge pool, a region can become an incubator of knowledge recombination by acquiring heterogeneous external knowledge components (Sebestyén and Varga, 2013; Aghion and Jaravel, 2015). Such knowledge innovation can be transformed into comparative advantages for regional economic growth.

6. Discussions and Conclusions: Main findings

③ It is worth noting that although both the complexity and embeddedness of knowledge recombination can enhance economic growth, heterogeneity in different regions and time phases cannot be ignored.

For underdeveloped areas, which are far from the technological frontier and have limited access to high-quality innovation resources, establishing collaborative relationships with advanced regions is an effective strategy to further leverage the knowledge spillover effect to promote regional development.

- Developing regions are more likely to obtain the transfer of innovation concepts and business models rather than high-value cutting-edge knowledge spillover from developed regions, resulting in more incremental innovation rather than radical innovation.
- Regional coordinated development is one of the major strategies in the new era of China, and the central government has issued multiple policies to address this imperative, such as, “the Western Region Development” strategy and "the Rise of Central China" strategy.

6. Discussions and Conclusions: Main findings

- Especially in recent years, the digital industry has experienced significant growth, leading to closer collaboration between the eastern and western regions. For example, with the support of the central government's "East data, West computing" project, Guizhou, a less developed city in western China, leverages its advantages in big data storage to provide companies in Shenzhen with cloud computing and data management services. Cross-regional cooperation between Guizhou and Shenzhen enables Guizhou to tap into the technological and market advantages of developed regions and even establish a comprehensive digital ecosystem that can support its sustainable economic growth.

In terms of the heterogeneity analysis based on time phases, we find that in the early stage (from 2005 to 2014), the complexity and embeddedness of knowledge recombination can effectively promote regional economic growth. However, the effect does not exist in the second stage (2015–2019). This is more a reflection of redirecting China’s development strategy since 2014.

6. Discussions and Conclusions: Contributions

① Most previous research considered the concept of knowledge recombination at a micro level of technological components.

- In this study, we focus on the actor level in various organizations within or beyond the region, extending the research on knowledge recombination to the regional level.

② Previous studies have specifically emphasized the role of knowledge recombination on innovation.

- In our study, we proposed an extended concept—regional knowledge recombination from two dimensions of the complexity of regional knowledge recombination as well as the heterogeneous knowledge inflow through embeddedness into the external high-end knowledge pool, connecting them with regional economic growth.

③ Our study also contributes to the theory on regional heterogeneity development strategy, indicating that regions can have different innovation strategies at different stages of innovation development. Though our work was based on China; however, the findings can extend to other regions with similar contexts in emerging countries.

6. Discussions and Conclusions: Limitations and future research

This study has some limitations that could be explored in future research.

① First, a more comprehensive evaluation of regional knowledge recombination should not just depend on cooperative patent measurements, but also the cooperative development of new products and processes as well as collaborative papers. The availability of more comprehensive datasets would allow future research results to be extended and improved.

② Second, a more realistic representation is also required for embeddedness in the external knowledge pool. In our studies, geographical distance is one of key factors affecting interregional collaboration. Future research could take administrative protection or cultural distance into consideration to obtain more precise measures.

③ Third, we only distinguished collaborations within a region and those across regions, and did not consider interregional collaborations across countries. Particularly developed regions may not attach importance to cooperation with other regions in the country, but rely heavily on relationships with other regions abroad; thus, future research could expand to a global scope.

THANKS

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