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Building a knowledge economy: The interplay of higher education attainment, public finance, and law and order

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Abstract

This study explores the influence of disaggregated fiscal outlays on education, science and technology (S&T), and research and development (R&D) concerning provincial economic advancement in China. Additionally, it assesses the moderating influence of higher educational attainment and the facilitating impact of law and order in cultivating a knowledge-driven economy. Utilizing panel time series data spanning from 2004 to 2023 across 31 provinces in China, the research engages sophisticated econometric methodologies alongside machine learning techniques, which encompass artificial neural networks. Such methodologies facilitate a rigorous estimation of both the long-term and short-term impacts of public expenditure and institutional quality on gross provincial product per capita (GRPC). The analysis indicates that the attainment of higher education exerts an inconsequential influence on GRPC in both the short and medium terms; however, it demonstrates a significant contribution in the long term. Fiscal allocations directed toward education, S&T, and R&D consistently exhibit positive impacts on GRPC over an extended period, underscoring their importance in fostering economic efficiency and competitiveness. Furthermore, the enforcement of law and order is recognized as an essential facilitator, enhancing the efficacy of public expenditure on economic performance. The results exhibit robustness across a range of advanced econometric techniques and machine learning approaches.

Keywords: Knowledge economy; Higher education attainment; Public finance; Machine learning; China

JEL Classification: H40, H41, H52, H55

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1. INTRODUCTION

The rapid economic transformation in the People's Republic of China over recent decades highlights the crucial role of local government fiscal allocations in promoting regional development (Wu et al., 2010). Public expenditure, allocations towards education, science and technology (S&T), and research and development (R&D) are vital for provincial economic growth. Investment in education enhances human capital, while funding for S&T and R&D stimulate innovation, technological progress, and industrial competitiveness (Cevik & Correa-Caro, 2020; Song et al., 2019). These investments help to mitigate regional economic disparities, as they empower provinces to harness local resources. In the context of Chinese provinces, where provincial administrations are instrumental in the execution of national strategies, understanding the effects of government spending in these sectors is essential for optimizing fiscal policies for sustainable economic growth. Therefore, this research investigates the impact of local government spending on education, S&T, and R&D on provincial economic growth.

The motivation of this study to explores the crucial role of local government expenditure in fostering provincial economic advancement within China is motivated by a few aspects. Firstly, as the country prioritizes sustainable development and technological autonomy, allocations toward education, S&T as well as R&D are essential for innovation and bolstering provincial competitiveness (Lai et al., 2024; Liu et al., 2023). These expenditures are crucial for cultivating a proficient labour force, establishing an environment for technological innovation, and encouraging industrial growth, thereby fortifying provincial economies. Notwithstanding the increasing focus on these areas, there exists a notable deficiency of comprehensive assessment regarding the impact of local government fiscal allocations on provincial economic growth. This coherence will help in more precise investment allocation and ensure that provincial strategies contribute to national economic enhancement and social welfare.

Secondly, understanding the relationship between national development goals and the economic configurations and resource allocations of individual provinces is crucial for China. This study investigates the economic impacts of investments in education, S&T, and R&D to provide empirical evidence for how provincial administrations can allocate resources to enhance productivity, stimulate innovation, and accelerate economic transformation. Moreover, in light of fiscal constraints and the need for optimization of public expenditures, this inquiry provides

insights into the most efficacious use of public resources to attain sustainable provincial advancement.

Thirdly, despite extensive literature on China's economic transformation and the role of public expenditure in regional development, several critical gaps persist, limiting a comprehensive understanding of how fiscal investments shape long-term economic competitiveness at the provincial level. For instance, while prior studies underscore the importance of education, S&T, and R&D in fostering economic growth (Cevik & Correa-Caro, 2020; Song et al., 2019), most analyses remain fragmented, often examining these expenditures in isolation. The synergistic effects of these investments—particularly how their combined implementation influences regional economic performance—remain underexplored. Given the shift toward a knowledge-driven economy, a more integrated analytical approach is needed to assess the interplay between these fundamental components of innovation and competitiveness. Besides, although education spending is widely associated with human capital development, empirical evidence on the interaction between higher education attainment and fiscal allocations remains scarce, particularly at the provincial level in China. Most existing research focuses on aggregate national trends, overlooking regional disparities in how education expenditures translate into economic productivity. Furthermore, the long-term economic effects of higher education enrolment, particularly when moderated by government investments in R&D and S&T, lack sufficient empirical validation. Addressing this gap is crucial, as global evidence suggests that nations excelling in higher education-linked innovation ecosystems—such as Germany and South Korea—demonstrate enhanced economic competitiveness and industrial resilience. Furthermore, the role of institutional quality—proxied by law and order—remains underexamined in the Chinese context. Prior research often considers governance indicators at a macroeconomic level, failing to account for how variations in institutional stability and enforcement mechanisms influence the effectiveness of public expenditures at a regional scale. Given the significance of regulatory efficiency and institutional trust in fostering investment, innovation, and business competitiveness, further investigation into these microeconomic interactions is warranted. Lastly, while traditional econometric approaches dominate research in this field, they often struggle to capture complex, non-linear relationships between government spending, education, and institutional quality. Studies utilizing advanced empirical techniques, such as machine learning and high-dimensional econometrics, remain scarce in this domain. Incorporating machine learning

methodologies, as seen in recent studies on fiscal policy effectiveness in Germany and South Korea (Lee & Kim, 2022; Balsmeier et al., 2019), offers greater predictive accuracy and deeper insights into the dynamic interdependencies shaping economic outcomes.

This study provides several substantial contributions to the academic discourse concerning public finance, human capital, and regional economic development, focusing on the Chinese provinces. First, in contrast to previous research that has concentrated on aggregate fiscal outlays, our theoretical framework elucidates the specific functions of targeted government investments. We apply a dynamic analysis approach, evaluating the short, intermediate, and long-run effect of local government spending on building a knowledge-based economy on provincial economic growth. Second, this study also investigates the interactive influences between higher education enrolment and various categories of government expenditure, thereby illuminating the synergistic relationship between human capital and fiscal outlays in education, S&T, and R&D. Third, this study incorporates local government expenditure on law and order as a control variable, acknowledging the critical role of institutional stability and governance in optimizing the efficacy of public financial resources. Fourth, we utilize a variety of sophisticated econometric techniques and machine learning frameworks, including LASSO-CV, gradient boosting and random forest to scrutinize panel data spanning from 2004 to 2023, thereby guaranteeing the robustness and precision of our conclusions. Fifth, the study identifies the temporal dimensions and sectors of public expenditure that yield maximal returns, providing a strategic framework for resource allocation. Finally, our findings indicate that the attainment of higher education, although not significantly influencing GRPC in the short and medium terms, plays a facilitative role in promoting long-term economic growth. Furthermore, local government investments in education, S&T and R&D substantially enhance GRPC in the long run. The study also emphasizes the essential role that law-and-order plays in economic advancement. Our empirical results underscore the necessity of implementing targeted policies at the local level to cultivate a knowledge economy and suggest that sustained investments in these domains are imperative for long-term economic prosperity.

The rest of the paper is presented as follows. Section 2 provides a review of academic literature on the knowledge-based economy. Section 3 provides a description of the data and methods used and represents the research objectives and established hypothesis. Section 4 shows the results of the impact of government spending on economic growth in China’s provinces.

Section 5 concludes the study by providing a summary of the findings and presenting valuable policy implications.

2. THEORITICAL BACKGROUND

The concept of a knowledge-based economy has gained significant attention in contemporary economic discourse, emphasizing the critical role of education, science, technology, and research and development (R&D) in driving economic growth. A growing body of literature explores how government expenditure in these sectors contributes to improving higher education outcomes and, ultimately, economic performance (De Meulemeester & Rochat, 1995). As nations invest in education and innovation, they create a skilled workforce that can adapt to the demands of the rapidly changing global market, thereby fostering an environment conducive to sustainable economic development (Khan et al., 2024; Ullah et al., 2021; Zhang, 2023). Such investments not only improve individual earning potential but also promote social mobility and create a more equitable society, where opportunities are accessible to all citizens (Byaro & Ngowi, 2024). These advancements can also encourage entrepreneurship and attract foreign investment, further bolstering a nation's economic resilience and competitiveness on the global stage. However, Popescu and Diaconu (2021) argue that government spending has a positive effect on economic development indicators only in the short term.

The role of education spending in economic well-being has been extensively examined in the academic literature under the concept of the knowledge-based economy. A number of prior studies indicate that higher levels of education can lead to increased productivity and innovation, which are crucial components for fostering a robust knowledge economy. Gyimah-Brempong et al. (2006) empirically find that higher education enhances economic growth in African countries. Mekdad, Dahmani, and Louaj (2014) explore the impact of public education spending on economic growth in Algeria, finding a positive causal relationship. This positive relationship was also confirmed by Ziberi et al. (2022) in the case of North Macedonia, while Suwandaru et al. (2021) observe insignificant linkage in the case of Indonesia. Analysing the impact of education in terms of student achievement, Hanushek (2016) notes that both broad basic skills and high achievement have a significant positive impact on long-term economic growth.

These prior findings emphasizes that investment in education fosters human capital development, which in turn drives economic growth. Similarly, Amaghionyeodiwe (2019)

examines West African countries and concludes that government spending on education significantly enhances economic performance, especially when it is targeted at improving access and quality. In a broader context, Dissou et al. (2016) model the dynamics of education spending and human capital accumulation, demonstrating that strategic investments in education lead to long-term economic benefits by increasing labour productivity and innovation. However, another part of the literature emphasises the heterogeneity of the impact of education spending on economic growth. For instance, Deskins et al. (2010) and Maneejuk and Yamaka (2021) added nuance to this discourse by investigating the impact of state-level education spending, revealing that the effectiveness of spending varies based on allocation priorities, such as higher education versus primary and secondary education. Gupta et al. (2002) assessed education spending in developing and transition economies, highlighting its dual role in enhancing labour force capabilities and reducing income inequality. Their findings suggest that, while education spending is generally effective, its impact is maximized when complemented by institutional reforms and governance improvements.

Another part of the literature emphasises the critical role of public investment in research and development in generating long-term economic growth. For instance, Inekwe (2015) reveals the high contribution of R&D expenditure to economic growth in developing economies, highlighting that R&D investments stimulate innovation, which is critical for sustaining economic growth in technology-driven sectors. Celli et al. (2024) provide further evidence on the example of lagging regions, demonstrating that R&D expenditures promote growth by enhancing regional competitiveness and attracting high-value industries. Goel et al. (2008) adopt a disaggregated approach to examine the role of R&D expenditures in the United States, identifying sector-specific growth impacts. Their study highlights that R&D investments yield the highest returns in industries with high innovation potential, underscoring the importance of strategic resource allocation. Kim et al. (2021) find evidence for the positive contribution of public investment in R&D in driving China’s economic development.

However, the efficacy of public spending on education, science and technology, and research and development for sustainable economic growth is contingent on both the prevailing political regime and the quality of institutions. Specifically, Barra et al. (2020) explore the short and long-term dynamics between economic development and government spending, emphasizing the critical role of institutional quality. Their findings suggest that, while government spending

can stimulate economic growth in the short term, its long-term effectiveness is contingent on robust institutional frameworks that ensure efficiency and transparency in resource allocation. Similarly, Facchini and Seghezza (2018) extend this discussion to historical contexts by analyzing the public spending structure in France from 1870 to 2010. Their findings suggest that shifts towards a minimal state structure, characterized by less government intervention, can often lead to higher economic growth. They emphasize the importance of targeted spending on essential public goods and services, such as education and infrastructure, in sustaining growth. Meanwhile, the positive effect of public spending can be even more pronounced due to the high quality of institutions (Ali et al., 2022). Besides, Plümper and Martin (2003) offer a political-economic perspective on the relationship between democracy, government spending, and economic growth. Their analysis introduces the "Barro-effect," which suggests that democracies tend to allocate resources more equitably, potentially leading to better growth outcomes. However, excessive government spending under democratic regimes can crowd out private investment, thereby dampening growth. Similarly, Barra et al. (2020) emphasize the pivotal role of governance and institutional quality, arguing that weak institutions can undermine the growth-enhancing potential of government spending by fostering inefficiencies and corruption.

Wahab (2004) examines the relationship between economic growth and government expenditure using a novel test specification, providing evidence of a nonlinear relationship, where moderate levels of government spending support growth, but excessive expenditure may hinder it due to inefficiencies and fiscal imbalances. Artige and Cavenaile (2023) also reveal that level of economic growth depends on the level of public education expenditures and on the shape of the human capital distribution. Facchini and Seghezza (2018) also highlight the significance of the composition of government spending, suggesting that productive expenditures, such as those on infrastructure and human capital, exert a more pronounced positive effect on economic growth compared to unproductive expenditures.

3. DATA, RESEARCH OBJECTIVE AND METHODOLOGY

3.1 Data

This study utilizes annual data for 31 provincial-level regions of People's Republic of China, including statistics of 22 provinces, 5 autonomous regions, and 4 municipalities for the period from 2004 to 2023. Table 1 provides a description of the data used, which have been obtained from

the National Bureau of Statistics of China. Particularly, to represent economic growth, we use gross regional product as the dependent variable. Other independent variables and their descriptions are presented in Table 1. We also use the interaction variable of human capital with three types of government expenditure to account for the joint impact of these factors on economic growth in Chinese provinces.

Tab. 1 – Data description. Source: National Bureau of Statistics of China

Variable	Definition
LGRPC	Logarithmic form of gross regional products per capita in RMB.
HC	Human capital is proxied by the higher education enrolment per 1000 people.
EXP_EDU	Logarithmic form of local government expenditure on education in 100 m RMB.
EXP_ST	Logarithmic form of local government expenditure on science and technology in 100 m RMB.
EXP_RND	Logarithmic form of local government expenditure on Research & Development in 100 m RMB.
LNO	Law and order is proxied by logarithmic form of government expenditure on safety and security of the people in 100 m RMB.
INVS	Gross investment in province as share of GRP.

3.2 Research objective and hypothesis

This study comprehensively investigates the crucial role of China's government spendings in establishing a knowledge-based economy in fostering economic development across Chinese provinces. To this end, we formulate the following research objectives, which our study aims to fulfil. A comprehensive review of the prior literature in the context of building a knowledge-based economy has enabled the formulation of several research hypothesis.

Firstly, this study investigates the role of higher education enrolment in promoting regional economic development. It was established in the literature section that higher levels of education attainment can lead to increased productivity, foster a robust knowledge economy and improve regional development. We also analyse the joint impact of higher education attainment as a proxy for human capital and three categories of government expenditures, thereby studying the

synergistic relationship between human capital and expenditure on building a knowledge-based economy. This allows us to form the following hypothesis:

H1: Human capital plays a pivotal role in fostering regional economic growth, while the combined effect of human capital and government spending on education, S&T and R&D enhances economic development across China's provinces in a more extant way.

Secondly, our study sheds light on the impact of public expenditure on education, science and technology and research and development in driving short, medium and long-run economic growth. Since the prior literature consistently underscores the divergent impacts of government spending on economic growth over short and long run horizons, we suppose that this impact in case of Chinese provinces may vary over time horizons. Thus, we formulate the following research hypothesis:

H2: While fiscal stimulus can boost aggregate demand and spur economic activity in the short-run, the long-term effect of such spending can depend on factors such as institutional quality, fiscal discipline, and the productivity of expenditures and technology (S&T), and research and development (R&D) on provincial economic growth.

Thirdly, we utilise other control variables, including fixed capital formation and local government expenditure on law and order, considering the critical role of regional investments as well as institutional stability and governance in optimizing the efficacy of public financial resources. Based on the literature review and our own presumptions, we formulate the following hypothesis:

H3: Government spending on safety and security and gross investment in provinces increase regional economic growth. However, this effect is less in comparison with government spending on establishing a knowledge-based economy.

3.3 Methodology

3.3.1 Advanced Econometric Techniques in Economic Analysis

A multilevel fixed-effects model is a statistical technique used to analyse data that contains multiple sources of variation. This type of model is particularly useful when dealing with hierarchical data, such as that collected from different groups within a population. The model accounts for multiple high-dimensional factors that can control for unobserved differences between groups.

The general form of the multilevel fixed effects model is as follows (Guimarães & Portugal, 2009):

$$Y = \beta X + \alpha D_1 + \gamma D_2 + \varepsilon \text{ (1)}$$

where Y is the dependent variable; X is the matrix of explanatory variables; β is the coefficients for X; D_1 and D_2 are the matrices of dummy variables representing the first and second high-dimensional fixed effects, respectively; while α and γ are the vectors of coefficients for these high-dimensional fixed effects, respectively; ε is the error terms.

In our study, the model can be represented as follows:

$$\Delta LGPPC_{i,t} = \beta X_{i,t-1} + \delta_i + \mu_t + \varepsilon_{i,t} \text{ (2)}$$

where δ_i is a cross-section dummy to consider companies fixed effects in the regression; μ_t represents time-specific dummy to consider year fixed effects.

Additionally, a long-difference econometric framework has been applied to investigate the impact of various variables over extended periods. This method allows us to analyse how one variable responds to long-term, short-term, and transitional changes in another variable, rather than merely capturing the immediate response. This technique is especially useful for handling clustered data and enabling the estimation of both individual and group-level effects over time. The long-difference model can be represented as follows:

$$\Delta LGPPC_{it} = \alpha \Delta X_{i,t} + \beta X_{i,t-1} \Delta X_{i,t} + \gamma X_{i,t-1} + \delta_i + \varepsilon_{i,t} \text{ (3)}$$

where α, β and γ indicate the coefficients of the short-run, transition and long-run effects. Therefore, this regression can be considered a special case of the long-difference approach proposed by Burke and Emerick (2016).

3.3.2 Machine Learning Analysis techniques

This study also employs machine learning analysis (MLA) techniques to estimate the role of government spending in promoting economic growth in China. Particularly, LASSO-CV (least absolute shrinkage and selection operator with cross-validation), random forest, and gradient boosting (e.g., gradient boosted trees) are machine learning techniques used for regression and classification tasks. However, these methods work differently and serve distinct purposes.

LASSO-CV is a linear regression technique that incorporates L1 regularization to shrink coefficients of less important features to zero, effectively performing feature selection. The use of cross-validation ensures the regularization parameter is optimized for better generalization. It

assumes linear relationships between variables and is particularly suited for high-dimensional data with many irrelevant features.

Random forest is a tree-based ensemble learning method that builds multiple decision trees and aggregates their predictions. It introduces randomness by using bootstrap sampling (bagging) and selecting a random subset of features for each tree split, making it robust to overfitting and capable of handling non-linear relationships.

Gradient boosting**,** on the other hand, builds decision trees sequentially, where each tree attempts to correct the errors of the previous one. It optimizes a loss function and is highly effective for capturing complex non-linear patterns in data. The main differences lie in their approach and application: LASSO-CV is a linear, interpretable method focused on feature selection; random forest is a robust, non-linear model resistant to overfitting; and gradient boosting is a powerful, non-linear technique that often achieves superior performance but may require careful tuning to prevent overfitting.

4. Results and Discussion

4.1 Preliminary Findings

Tab. 2 presents the results of descriptive statistics for dependent and independent variables related to economic and innovation dynamics across provinces. Descriptive statistics indicate moderate variability across regions in terms of their gross regional product per capita (log-transformed). We also observe a relatively high variability in human capital (HC), suggesting significant differences in educational attainment across provinces. Moreover, the statistics for government expenditures into different areas shows variability in values, indicating that investments in some provinces are substantially high in comparison with others. We also exhibit significant heterogeneity in the combined impact of human capital and various expenditures across provinces, with some regions displaying negative or low interactions, highlighting potential disparities.

Tab. 2 – Descriptive Statistics. Source: own research

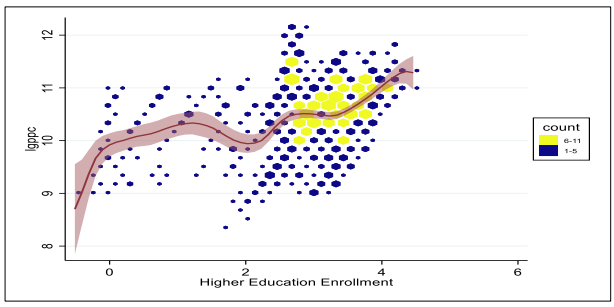
Variable	Obs	Mean	Std. dev.	Min	Max
LGRPC	620	10.51	0.73	8.35	12.21
HC	589	2.82	0.98	-0.51	4.46

LNO	496	5.26	0.79	2.69	7.26
EXP_EDU	480	6.27	0.85	3.51	8.26
EXP_ST	496	4.01	1.24	0.66	7.06
EXP_RND	465	13.91	1.85	2.30	17.29
INVS	620	13.63	11.81	-56.60	41.80
HC*EXP_EDU	480	18.29	6.83	-1.05	30.83
HC*EXP_ST	496	12.44	6.21	-0.19	30.62
HC*EXP_RND	465	41.58	16.37	-1.37	75.99

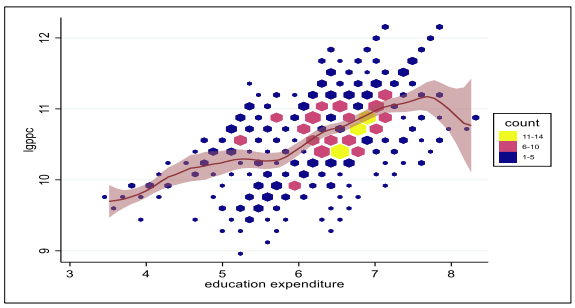
Fig. 1 depicts the relationship between the logarithm of GDP per capita (on the vertical axis) and higher education enrolment, and government expenditure on education, science and technology, and research and development (on the horizontal axis) for Chinese provinces (Panel A-G). The data points are visualized using a hexagon plot, where the density of data points is represented by hexagonal bins coloured according to their count. Yellow hexagons indicate a higher density of data points (6-11 observations), while blue hexagons represent a lower density (1-5 observations). The trend line with a shaded confidence interval shows a nonlinear relationship between higher education enrolment and provincial GDP per capita.

Initially, we observe a modest increase in GRP per capita as higher education enrolment increases. However, at a certain enrolment threshold (approximately 2-3 on the horizontal scale), the growth accelerates more significantly. This suggests that growing level of enrolment in higher education is positively associated with higher gross regional product per capita, particularly beyond moderate levels of enrolment. The shaded area around the trend line reflects the confidence interval, indicating the variability in the observed relationship among regions. Therefore, results presented in Fig. 1 highlights the critical role of higher education in promoting economic development, with higher enrolment levels contributing to improved gross provincial product per capita in China.

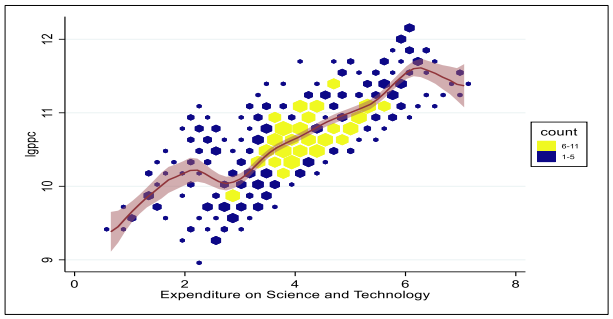
Panel A



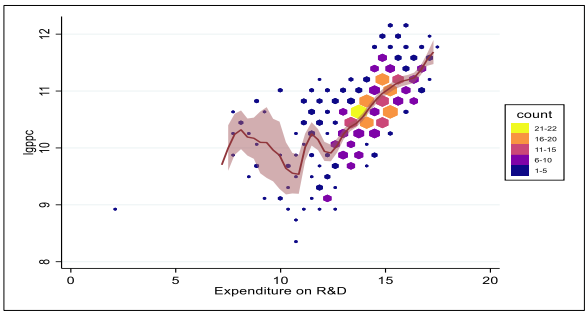
Panel B



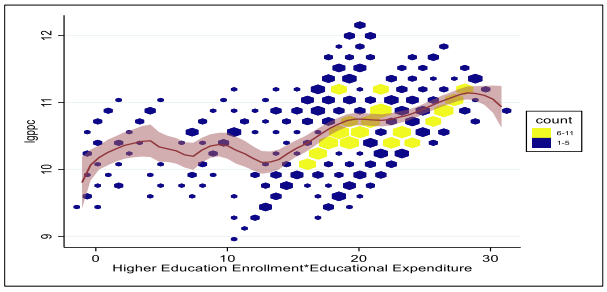
Panel C



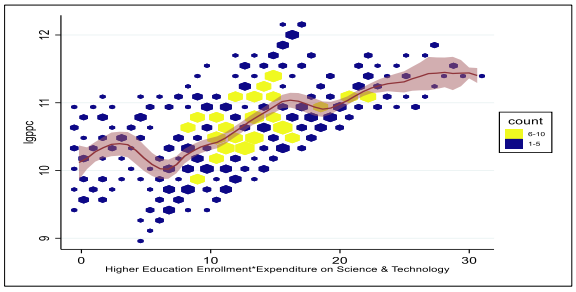
Panel D



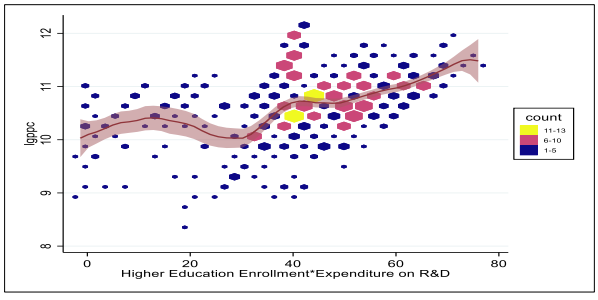
Panel E



Panel F



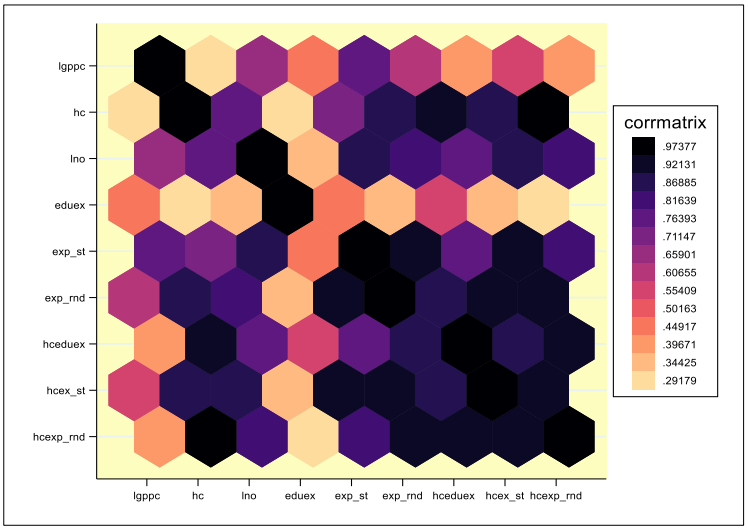
Panel G



Notes: Yellow to blue hexagons indicate higher or lower density of data points, respectively, which is also reflected in the legend. The trend line with a shaded confidence interval shows a nonlinear relationship.

Fig. 1 – Hexagon Analysis. Source: own research

Fig. 2 illustrates the correlation matrix between the variables used in this study. We observe a strong positive correlation between GRP per capita and HC (0.92), suggesting that human capital, as measured by higher education enrolment per 1000 people, is closely linked to economic performance. Similarly, GRP is strongly correlated with LNO (0.87), highlighting the importance of law and order in driving economic growth. Education expenditure **(**EXP_EDU**)** demonstrates a substantial positive correlation with both human capital (0.82) and expenditures on science and technology (0.71), suggesting that regions allocating greater resources to education also tend to allocate resources to innovation-supporting sectors. We also observe the combined impact of human capital and targeted expenditures on economic outcomes as indicated by interaction terms of human capital and types of public spending.



Notes: The hexagons reflect the level of correlation between variables, where darker hexagons indicate a stronger correlation, while lighter hexagons indicate a weaker correlation.

Fig. 2 – Heatmap of correlation. Source: own research

4.2 Main Findings under econometrics analysis

This section provides the results of the econometric evaluation by using fixed effects and long difference analysis approaches. Tab. 3 presents the results of the fixed effects technique for three models, each of them corresponding to one type of public expenditure. Other variables including human capital, law and order and level of investment are the same for all three models. We also include interaction terms between human capital and type of expenditure to estimate the joint

effects. Our empirical results demonstrate a consistent positive impact of higher education attainment on GRP per capita. Similarly, the growth in government spending on safety and security is ensuring stable economic growth across Chinese provinces. Meanwhile, the size of investments has practically no impact on the economic development of regions. Conversely, the higher expenditures on education and science and technology as well as research and development stimulate economic growth.

Tab. 3 – Provincial Fixed Effect Analysis. Source: own research

Dependent variable: LGRPC	Model 1	Model 2	Model 3
HC_{t-1}	0.187*** (0.0659)	0.382***(0.0415)	0.227***(0.0821)
EXP_EDU_{t-1}	0.113***(0.0402)		
$HC_{t-1} * EXP\_EDU_{t-1}$	0.035***(0.0083)		
EXP_ST_{t-1}		0.187***(0.0279)	
$HC_{t-1} * EXP\_ST_{t-1}$		-0.00773 (0.00592)	
EXP_RND_{t-1}			0.193***(0.0219)
$HC_{t-1} * EXP\_RND_{t-1}$			0.0042(0.0052)
LNO_{t-1}	0.490*** (0.0341)	0.530*** (0.0234)	0.526*** (0.0220)
$INVS_{t-1}$	-0.0009* (0.0005)	-0.00079(0.0005)	1.71e-05(0.000513)
Observations	480	496	434
R-squared	0.976	0.977	0.978

To test the results of the fixed effects analysis, we also perform a long difference fixed effects analysis. Tab. 4 presents the regression results of long-difference econometric framework, which provides insight into the impact of education spending on GRP per capita over time. The negative and statistically significant coefficient on lagged GRP per capita indicates a convergence effect. Provinces with higher initial levels of GDP per capita tend to experience slower subsequent growth, suggesting that poorer regions are catching up to the richer ones. Human capital (HC) and education expenditures (EXP_EDU) exhibit more time-dependent relationships. Higher education

enrolment positively and significantly influences economic growth among Chinese provinces in the long run, implying that having a stronger base of human capital supports future economic growth. However, in the short-run and transition periods, we do not observe a significant response of economic growth to human capital development, suggesting that although the level of human capital matters, higher education attainment does not stimulate economic growth development in the short-run; rather, it follows a long-term trend. Higher spending on education can stimulate economic development in the short run, which is confirmed by a significant positive coefficient at the ΔEXP_EDU. Meanwhile, although growth in education expenditures may boost economic development in the short run, the impact of additional expenditures may weaken after reaching a certain level of investment in education, which explains the negative effect when we consider the effects in the long run and in the transition period. Model 2 shows the results with the inclusion of an interaction variable reflecting the joint impact of human capital and education expenditure. However, we do not observe the significance of these indicators.

Tab. 4 – Long Difference Fixed Effects (EXP_EDU). Source: own research

Dependent variable: $\Delta.LGPPC$	Model 1	Model 2
$LGPPC_{t-1}$	-0.160***	-0.164***
	(0.0232)	(0.0242)
$\Delta.HC$	0.145	-0.0558
	(0.0993)	(0.373)
HC_{t-1}	0.0562***	0.0305
	(0.0208)	(0.0515)
$\Delta.HC * HC_{t-1}$	-0.0361	-0.0107
	(0.0310)	(0.0809)
$\Delta.EXP\_EDU$	0.468***	0.368
	(0.161)	(0.235)
EXP_EDU_{t-1}	-0.0479***	-0.0577**
	(0.0164)	(0.0257)
$\Delta.EXP\_EDU * EXP\_EDU_{t-1}$	-0.0804***	-0.0729**
	(0.0269)	(0.0323)

$\Delta.HCI * EXP\_EDU$		0.0319
		(0.0572)
$HCI * EXP\_EDU_{t-1}$		0.00414
		(0.0075)
$\Delta.HCI * EXP\_EDU*HCI * EXP\_EDU_{t-1}$		-0.0006
		(0.0018)
LNO_{t-1}	0.103***	0.104***
	(0.019)	(0.020)
$INVS_{t-1}$	0.00026	0.00025
	(0.00024)	(0.00024)
Constant	1.390***	1.492***
	(0.139)	(0.225)
Observations	390	390
R-squared	0.511	0.512

Notes: The symbols *, ** and *** denote significance at the 10%, 5% and 1% levels, respectively. Standard errors are presented in parentheses. The symbol Δ or delta indicates the first difference value of the corresponding indicator, representing the result of the short-run estimates, whilst t-1 represents the lag of the variable, reflecting the results of the long-run estimates. The multiplication of the delta with the lag reflects the results of the transition period.

Finally, government expenditure on safety and security (LNO) has a significant positive impact in all models. It is evident that provinces which allocate a greater level of government expenditure to safety and law and order demonstrate a higher degree of sustainable economic development. Consequently, the response to fluctuations in government spending exhibits temporal variability. While both education and public investment have the capacity to promote growth, their impact depends on prior dynamics and changing policy conditions.

Tab. 5 presents the results of the long-term fixed effects model, examining government spending on science and technology (EXP_ST) and research and development (EXP_RND). The results of long-difference regression demonstrate the comprehensive dynamic relationship between human capital, expenditures on S&T, R&D and economic growth. We also confirm a negative effect of the GRP per capita lag, suggesting a convergence effect where provinces starting at higher income levels grow more slowly, suggesting that poorer regions may catch up over time.

Tab. 5 – Long Difference Fixed Effects (EXP_ST & EXP_RND). Source: own research

Dependent variable: $\Delta.LGPPC$	Model 3	Model 4
$LGPPC_{t-1}$	-0.154***	-0.141***
	(0.0227)	(0.0240)
$\Delta.HC$	0.0477	-0.487
	(0.106)	(0.342)
HC_{t-1}	0.0243	0.00162
	(0.0228)	(0.0421)
$\Delta.HC * HC_{t-1}$	-0.0566	-0.0821
	(0.0395)	(0.0665)
$\Delta.EXP\_ST$	0.0104	
	(0.0441)	
EXP_ST_{t-1}	-0.0106	
	(0.0153)	
$\Delta.EXP_{ST} * EXP\_ST_{t-1}$	-0.0163	
	(0.0162)	
$\Delta.HC * EXP\_ST$	0.0542**	
	(0.0215)	
$HC * EXP\_ST_{t-1}$	0.00288	
	(0.00315)	
$\Delta.HC * EXP\_ST * HCI * EXP\_ST_{t-1}$	-0.00115	
	(0.00078)	
$\Delta.EXP\_RND$		0.0121
		(0.102)
EXP_RND_{t-1}		0.0250**
		(0.0120)
$\Delta.EXP\_RND * EXP\_RND_{t-1}$		0.000748
		(0.0119)
		0.0526*

$\Delta.HC * EXP\_RND$		(0.0292)
$HC * EXP\_RND_{t-1}$		-0.00201
		(0.00261)
$\Delta.HC * EXP\_RND{*}HC * EXP\_RND_{t-1}$		-9.76e-05
		(0.00028)
LNO_{t-1}	0.0800***	0.112***
	(0.0160)	(0.0158)
$INVS_{t-1}$	0.00027	0.00042*
	(0.0002)	(0.0002)
Constant	1.234***	0.701***
	(0.148)	(0.165)
Observations	465	372
R-squared	0.476	0.341

Notes: The symbols *, ** and *** denote significance at the 10%, 5% and 1% levels, respectively. Standard errors are presented in parentheses. The symbol Δ or delta indicates the first difference value of the corresponding indicator, representing the result of the short-run estimates, whilst t-1 represents the lag of the variable, reflecting the results of the long-run estimates. The multiplication of the delta with the lag reflects the results of the transition period.

We observe a positive and statistically significant coefficient on the interaction term of changes in human capital and science and technology expenditures (ΔHC * EXP_ST) and human capital and research and development expenditures (ΔHC * EXP_RND), suggesting that improvements in human capital becomes a more significant driver of economic growth when S&T and R&D spending increases. Thus, higher education enrolment has greater economic benefits if it is supported by significant investments in science and technology and research and development.

We observe that an increase in R&D expenditure does not ensure immediate growth, as indicated by the insignificant coefficient in the short run, but in the long run, R&D expenditure has a positive impact on economic development in Chinese provinces. Moreover, such interaction terms as the combination in human capital and R&D spending (ΔHC * EXP_RND), show that a higher level of education enrolment is more beneficial when a favourable environment for R&D already exists. Hence, the growth of a skilled labour force combined with a significant investment in R&D can lead to amplified positive effects.

Therefore, the findings indicate that public policy, which encourages the development of human capital, when combined with strategic investments in science, technology, and research and development (R&D), has the potential to generate powerful synergies. An integrated approach to capacity-building, as opposed to a focus on any single factor in isolation, is more likely to yield robust and enduring growth in provincial economies.

4.3 Machine learning analysis

This section presents the simulation results of machine learning analysis (MLA), a modern effective tool for modelling and forecasting economic processes. Specifically, we compare how three different advanced modelling techniques, namely Lasso CV, random forest, and gradient boosting are capable of identifying the importance of variables in predicting provincial economic growth. Tabs. 6-8 show the results obtained by applying machine learning algorithms. Since this study incorporates multiple measures of government spendings on building knowledge-based economy, we form 3 separate models. Specifically, models 1-3 include expenditure on education, S&T, and R&D, respectively.

Tab. 6 represents MLA to capture the impact of government spending on education, however the models yield somewhat differing views. Under the lasso CV approach, government spendings on safety and security (LNO) stands out with a notable positive impact, while higher education enrolment (HC) is effectively deemed irrelevant in the linear framework. Education expenditure alone and in combination with human capital measure (HC * EDUEX) shows more nuanced, weaker effects, and fixed capital formation (INVS) appears to exert a mild negative influence. In contrast, the random forest model substantially elevates the importance of both law and order and fixed capital formation, suggesting that these factors play a more critical role in driving regional economic performance across Chinese provinces when allowing for complex interactions. Similarly, gradient boosting confirms the influence of LNO and INVS, while also granting moderate significance to educational factors.

Tab. 6 – Deep and Machine Learning Analysis: Importance of Parameters (Model 1). Source: own research

Dependent variable: GRP per capita	Lasso CV	Random forest	Gradient boosting
HC	0.000000	0.10933	0.11359
EXP_EDU	0.22324	0.08870	0.08220
HC * EXP_EDU	-0.27983	0.05843	0.04257
INVS	-0.10512	0.33913	0.32375
LNO	0.48430	0.40439	0.43787
Weight	0.000	0.809	0.083
Sample	0.333	0.098	0.173
CV	0.339	0.278	0.295

Tab. 7 shows the results of machine learning modelling for science and technology expenditure (EXP_ST) (Model 2). The results of all three MLA techniques indicate that S&T expenditures play a key role in driving the economic growth of Chinese provinces, while the human capital indicator (HC) and its combination with EXP_ST also have weak significance, similarly to Model 1 (Tab. 6). We also observe significant importance of the "weight" variable, indicating that certain weighting or contextual adjustments strongly shape predictions.

Tab. 7 – Deep and Machine Learning Analysis: Importance of Parameters (Model 2). Source: own research

Dependent variable: GRP per capita	Lasso CV	Random forest	Gradient boosting
HC	-0.2102	0.0850	0.0890
EXP_ST	0.7083	0.6107	0.5812
HC*EXP_ST	-0.2986	0.0366	0.0270
INVS	-0.1021	0.1895	0.1827
LNO	0.1571	0.0779	0.1198
Weight	0.2675	0.2355	0.4599
Sample	0.256	0.090	0.156
CV	0.258	0.249	0.243

Applying MLA to assess the importance of parameters by EXP_RND, we find that a growing level of government expenditures on R&D contributes significantly to driving regional economic performance (Tab. 8). Moreover, government spending on law and order and fixed capital formation play an important role in ensuring stable economic growth in China's provinces.

Tab. 8 – Deep and Machine Learning Analysis: Importance of Parameters (Model 3). Source: own research

Dependent variable: GDP per capita	Lasso CV	Random forest	Gradient boosting
HC	-0.5124	0.0985	0.1414
EXP_RND	0.6056	0.4293	0.3916
HC*EXP_RND	-0.1082	0.0645	0.0226
INVS	-0.0893	0.2634	0.2541
LNO	0.3069	0.1440	0.1900
Weight	0.000	0.440	0.342
Sample	0.247	0.070	0.110
CV	0.251	0.207	0.205

Therefore, these findings suggest that, while linear methods minimize the direct role of schooling, more flexible machine learning techniques highlight law and order and capital formation as key drivers of GDP per capita and underscore the potential importance of other factors contributing to a knowledge-based economy, including government expenditures on education, S&T and R&D within more complex, non-linear frameworks.

4.3 Discussion

Our findings emphasise the complex relationship between fiscal allocations towards education, science and technology (S&T), as well as research and development (R&D) and economic development across the provinces of China. The results identify both temporary and persistent effects, and clarify the complex interactions between financial expenditure, higher education attainment and the quality of institutions. This observation is consistent with extant literature that

emphasises the necessity of such governmental investments for the establishment of a knowledge-based economy and the enhancement of regional competitiveness (Cevik & Correa-Caro, 2020; Song et al., 2019; Badur & Sohag, 2024).

We observe that fiscal allocations towards education, S&T, and R&D have a sustained positive impact on gross provincial product per capita (GRPC) over an extended temporal framework. This corroborates previous studies, which established that deliberate investments in human capital and innovation catalyse economic productivity and technological progress (Erum et al., 2024; Mekdad et al., 2014; Inekwe, 2015). Notably, our findings also indicate the presence of diminishing marginal returns for particular categories of expenditures, notably in education, thereby underscoring the necessity for optimized allocation methodologies.

The level of higher education enrolment shows substantial long-term repercussions on economic growth. However, in the short to medium term, its effects are comparatively less pronounced, indicating a delayed manifestation of benefits. This confirms that the cultivation of human capital through higher education contributes to sustainable economic transformation rather than immediate growth (De Meulemeester & Rochat, 1995). Moreover, the interaction between higher education and fiscal expenditures elucidates that investments in education yield maximal efficacy when augmented by robust institutional frameworks and innovation ecosystems.

The institutional quality measure, represented by government expenditures on safety and security, is pronounced in enhancing the efficacy of public spending on economic outcomes, which is in line with Barra et al. (2020), who underscored the important role of governance in ensuring the efficacy and efficiency of fiscal policies. Stable and secure environments cultivate trust and incentivize investments, thereby creating a conducive milieu for economic activities and innovation. The utilization of sophisticated econometric and machine learning methodologies significantly enhances the robustness of our conclusions. Machine learning frameworks, including random forest and gradient boosting, underscore the importance of expenditures related to innovation and the interactions between human capital and fiscal investments. These revelations illuminate the intricacy of the dynamics of economic growth, suggesting that linear models may inadequately capture the interdependencies inherent among the variables.

These findings echo global trends observed in Germany and South Korea, where public-private partnerships in R&D have played a significant role in fostering economic resilience and global competitiveness. In Germany, collaborations between universities, research institutes (e.g.,

Max Planck and Fraunhofer Institutes), and industries have accelerated knowledge diffusion, improving industrial efficiency (Balsmeier et al., 2019). South Korea's focus on high-tech clusters and innovation hubs has driven its rapid economic ascent, with companies like Samsung and Hyundai leveraging government support for technology and R&D. For Chinese provinces, fostering innovation ecosystems—modelled on Germany's industrial clusters or South Korea's tech-driven economic zones—could enhance regional competitiveness and long-term economic sustainability.

5. CONCLUSION AND POLICY IMPLICATIONS

This study examines the complex interrelations between higher educational attainment, governmental spendings on education, science and technology, and research and development, alongside the facilitative role of institutional quality, as indicated by law and order, in propelling economic advancement in the context of Chinese provinces. Employing sophisticated econometric methodologies and machine learning techniques on panel data spanning from 2004 to 2023, the results highlight several pivotal findings.

Initially, higher education enrolment is found to significantly influence long-term economic growth, although its effects in the short and medium-term appear to be constrained. This underlines the need for sustained investment in human capital to facilitate sustainable economic transformation. Subsequently, strategic fiscal allocations directed towards education, S&T, and R&D exhibit consistently favourable impacts on gross provincial product per capita (GRPC), with the most pronounced effects manifesting over long-term. Moreover, the importance of institutional quality in enhancing the effectiveness of fiscal policy is evident, reinforcing the notion that stable and secure governance structures are essential prerequisites for fostering innovation and economic progress.

The results provide a compelling empirical case for the strategic alignment of fiscal policy with overarching development objectives, highlighting the intricate interdependence between education, innovation and institutional quality as fundamental elements of a knowledge-based economy. These findings not only deepen the understanding of provincial economic dynamics within China but also enrich the broader dialogue on sustainable economic progress in emerging markets.

In light of these findings, the following policy implications are advocated. First, policymakers should prioritise higher education as a critical area for investment. While the immediate economic impact may be limited, the long-term advantage of a well-educated workforce is substantial, fostering innovation, technology adoption and productivity growth. Second, to optimise the economic returns from fiscal expenditure, governments should focus on an equitable distribution between education, S&T and R&D. While these areas contribute independently to economic progress, their collective and synergistic effects offer greater potential for fostering innovation and regional competitiveness. Third, effective governance and institutional stability, as evinced by investments in law and order, are essential facilitators of fiscal policy effectiveness. Policymakers should ensure transparency, mitigate inefficiencies and foster confidence, all of which are essential for sustaining economic growth. Fourth, investments in R&D and S&T should be supplemented with policies that advocate for the adoption of emergent technologies, such as artificial intelligence and digital infrastructure. These initiatives will aid in the transition towards a knowledge-based economy and bolster the global competitiveness of provinces. Fifth, fostering private sector engagement in education and innovation can enhance the efficacy of public investments. Collaborative frameworks, exemplified by public-private partnerships, can mobilize supplementary resources and stimulate innovation-driven growth. The establishment of robust mechanisms for evaluating the impacts of fiscal expenditures is crucial for ensuring accountability and guiding adjustments to enhance resource allocation efficiency. These systems should incorporate advanced data analytics and machine learning methodologies to ensure precision and adaptability.

Further research could explore the interplay between public and private investments in education and innovation across different economic contexts. Additionally, comparative studies involving other countries could provide broader insights into the global applicability of these findings. By addressing these avenues, policymakers and researchers can continue refining strategies for building sustainable, knowledge-driven economies.

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