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Can New Quality Productive Forces Promote Green and Low-Carbon Agricultural Development? Evidence from China

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Abstract

Green and low-carbon agricultural development is an important pathway for achieving the "dual carbon" targets and sustainable development. New Quality Productive Forces (NQP) play a key role in promoting green and low-carbon agricultural development. Based on provincial panel data for China from 2014 to 2023, this study constructs comprehensive evaluation index systems for NQP and green and low-carbon agricultural development (GLCA) and employs fixed-effects and mediation-effect models to systematically examine the mechanisms through which NQP affects GLCA. The results show that: (1) NQP has a significant positive impact on GLCA; (2) NQP can further promote GLCA by enhancing the educational attainment of the labour force; and (3) the effects of NQP on GLCA vary across regions. Accordingly, this study recommends promoting the deep integration of NQP with agriculture, enhancing the educational level of the agricultural labour force, and advancing regionally differentiated development to establish a multi-stakeholder governance system for green and low-carbon agriculture.

Keywords

New Quality Productive Forces; Green and Low-Carbon Agricultural Development; Fixed Effects; Mediating Effects.

1. Introduction

On 22 September 2020, President Xi Jinping delivered a formal declaration at the 75th Session of the United Nations General Assembly, stating that "China will strive to peak carbon dioxide emissions before 2030 and achieve carbon neutrality before 2060." However, due to the high energy consumption, intensive resource use, and severe environmental pollution associated with traditional agricultural production modes, carbon emissions from agriculture and land-use change already account for 21%–37% of total global carbon emissions [1]. Against this backdrop, green and low-carbon agricultural development (GLCA) has become one of the key pathways for China to achieve its "dual carbon" goals. GLCA not only requires a thorough transformation of agricultural production modes but also emphasises the synergistic interaction between agricultural development and ecological and environmental protection [2]. Thus, accelerating the practice and exploration of green, low-carbon, and efficient agricultural production models has become a pressing issue that must be urgently addressed.

The emergence of New Quality Productive Forces (NQP) provides an unprecedented opportunity for GLCA. In September 2023, General Secretary Xi Jinping first proposed the concept of "new quality productive forces" during an inspection tour in Heilongjiang and subsequently stressed in a series of meetings the need to vigorously develop NQP. As a new form of productive forces that integrates scientific and technological innovation, industrial transformation, new service formats, and green sustainable development, NQP represents a new stage in the evolution of productive forces [3]. This concept not only encompasses advanced production technologies and management models but also places strong emphasis

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on the optimal utilisation of natural resources and comprehensive environmental protection. In the agricultural sector, this is reflected in the application of advanced technologies such as bioengineering, intelligent technologies, and new materials, which enhance crop yield and quality while simultaneously reducing negative impacts on the ecological environment.

Existing research on the relationship between NQP and GLCA mainly focuses on two aspects. The first concerns GLCA itself and its influencing factors. GLCA aims to ensure both the yield and quality of agricultural products while, through technological innovation, optimisation of agricultural production methods, and improvements in resource utilisation efficiency, achieving energy conservation and emissions reduction in the agricultural production process, thereby reducing carbon emissions and promoting sustainable agricultural development [4]. In terms of influencing factors, innovation, policy, and economic conditions all shape the progress of GLCA. From the perspective of innovation, technological progress [5], innovation capacity [6], and green agricultural technology innovation [7] can all promote GLCA. From the policy perspective, policy orientation [8], policies targeting major grain-producing areas [9], and high-standard farmland construction policies [10] help advance GLCA. From the economic perspective, digital inclusive finance [10], the digital economy [11], and agricultural fiscal expenditure [12] exert important impacts on GLCA.

The second aspect concerns the mechanisms through which NQP drives GLCA. Developing NQP is an inherent requirement for realising the green and low-carbon transformation of agriculture [13]. In terms of technological breakthroughs, the introduction and application of advanced biotechnologies, information technologies, and new material technologies not only increase crop yield and quality but also enhance the resilience of agricultural systems, thus providing a solid guarantee for GLCA [14]. In terms of factor allocation, NQP facilitates the integration of new factors, such as data, with traditional production factors, realising precise monitoring and intelligent management of agricultural production processes, improving resource utilisation efficiency, and reducing resource waste [15]. In terms of industrial development, NQP promotes the transformation and upgrading of traditional agriculture and the construction of a modern agricultural system. Through intensive and standardised production, they reduce the use of chemical inputs and energy in agricultural production, thereby advancing GLCA [16].

In summary, the existing literature predominantly examines the theoretical relationship between NQP and GLCA, whereas empirical analyses of the impact of NQP on GLCA remain relatively limited and need to be further strengthened. Based on data on the levels of NQP and GLCA for 30 Chinese provinces from 2014 to 2023, this paper empirically investigates the role of NQP in GLCA and its underlying mechanisms. The marginal contributions of this study are as follows: (1) It incorporates NQP and GLCA into a unified analytical framework and, from the sub-dimensions of innovation drive, technological renewal, and business format optimisation, explores in depth the enabling mechanisms of NQP for GLCA and empirically tests their effects. (2) It introduces the educational attainment of the labour force into the research framework of NQP empowerment for GLCA, examines its transmission mechanism, and conducts empirical tests, thereby enriching research findings in related fields.

2. Mechanism Analysis and Research Hypotheses

2.1. Direct Impacts of NQP on GLCA

Agriculture is fundamental to human survival, providing the basis for food, clothing, and all productive activities. Since the founding of the People’s Republic of China, the government has consistently prioritised agricultural development, emphasising the acceleration of green and low-carbon transitions in agriculture and rural areas. The inherent characteristics of NQP closely align with the objectives of GLCA, shifting the agricultural paradigm from solely pursuing production output and economic benefits towards ecological preservation and

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sustainable resource utilisation. Therefore, NQP offers a scientifically viable pathway to achieving agricultural sustainability goals. Their impact on GLCA is primarily evident in three aspects:

Firstly, NQP stimulates technological advancement in green agricultural production. Emphasising technological innovation, they represent a transformative shift from traditional agricultural practices toward adopting cutting-edge scientific achievements and refined management strategies. Such transformation significantly enhances agricultural productivity and considerably reduces agriculture’s negative environmental impacts, facilitating a comprehensive transition toward greener, low-carbon, and modern agriculture. Agricultural production processes are markedly optimised by leveraging advanced technologies such as biotechnology, intelligent systems, and innovative materials. Breakthroughs in bioengineering, such as developing crop varieties with traits including saline-alkali resistance, drought tolerance, and disease resilience, substantially reduce dependence on chemical pesticides and significantly elevate green productivity and environmental performance. These innovations enhance agricultural efficiency while fostering sustainability and deepening agricultural greening.

Secondly, NQP can enhance the efficiency of the circular utilisation of agricultural resources. The theory underscores innovative recombination of production factors, significantly supporting GLCA. The Internet of Things, a critical manifestation of NQP, integrates digital technologies—such as Artificial Intelligence, Cloud Computing, Big Data analytics, and Blockchain—with traditional agriculture. This integration optimises resource allocation for land, water, and labour, reducing resource wastage and elevating ecological circularity. Concurrently, deploying precision agriculture technologies and renewable energy sources contributes to reduced greenhouse gas emissions and improved energy efficiency, thus providing robust support for agriculture’s transition towards low-carbon practices.

Thirdly, NQP bolsters agricultural industrial resilience. Concerning structural resilience, compared to traditional productivity theories, NQP emphasises adjustments in agricultural industrial structures and extensions in value chains, promoting diversification and higher-value agricultural products. This focus strengthens the capacity of agriculture to cope with challenges such as climate change and market fluctuations, facilitating stable and sustainable development. Regarding production resilience, agricultural systems become more risk-resilient and market-accepted by fostering agriculture sectors tailored to regional characteristics, leveraging local natural resources and cultural advantages, and developing competitive green agricultural products. Furthermore, NQP encourage scientific adjustments in crop cultivation and livestock breeding structures, facilitating the rational selection of appropriate species and optimising resource allocation to enhance ecological recycling. By promoting coordination and collaboration within agricultural sectors, these productive forces enable closely integrated industrial chains that foster resource sharing and complementary advantages, elevating agricultural systems' overall efficiency and sustainable development capabilities.

Hypothesis 1. Developing NQP positively promotes GLCA.

2.2. NQP Promote GLCA Through the Education Attainment of the Labour Force

NQP reshapes modern education models from the dimensions of intensiveness and inclusiveness, effectively improving the educational attainment of the labour force. First, NQP increases the intensity of education. Relying on generative artificial intelligence and digital technologies, NQP facilitates the systematic integration and efficient multiplication of educational resources, propelling the traditional educational ecosystem toward a more effective, structured model. This technology-driven transformation enables workers to acquire more targeted, higher-quality educational resources quickly. Second, NQP promotes

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educational inclusiveness. In the era of digital intelligence, establishing a concept of lifelong learning has become critical to addressing existential crises [17]. By leveraging technology to transcend spatial and temporal boundaries, NQP enables workers in remote areas and vulnerable groups to access high-quality educational resources, thus raising their educational standards.

A high level of education in the labour force is an important support for the achievement of GLCA. From the perspective of mindset shifts, the higher the household educational level, the more substantial farmers' willingness to adopt sustainable agricultural practices [18]. From the standpoint of industrial structure, an increase in educational level aligns with the demands of transitioning from traditional agriculture to sustainable agriculture, as high-quality human capital can effectively guide and utilise advanced material capital to maximise resource value. From an economic benefit perspective, the input of high-quality human capital enhances cost-control capabilities, optimises management practices, improves production efficiency, and ultimately leads to significant growth in agricultural economic returns. Therefore, raising the labour force’s educational level can effectively facilitate mindset shifts, industrial structure optimisation, and economic gains supporting GLCA, thereby promoting green and low-carbon agricultural development.

Hypothesis 2. Developing NQP promotes GLCA by enhancing Education Attainment of the labour force.

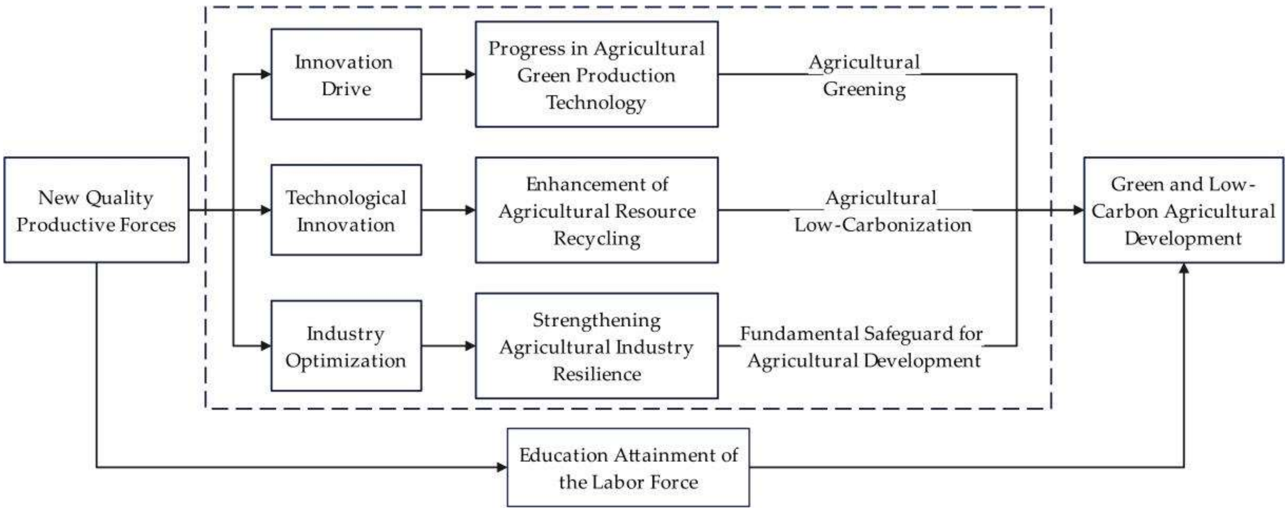

Figure 1. Analysis of the mechanism of NQP and GLCA

3. Variable Descriptions and Model Specification

3.1. Variable Definitions

1) Independent Variable: Green and Low-Carbon Agricultural Development (GLCA). GLCA refers to promoting sustainable agricultural development and ecological environmental protection by adopting low-carbon and environmentally friendly technologies and management practices throughout the agricultural production process. Drawing on the exploratory research of Liu and Yang [19, 20] and considering data availability, this paper constructs an evaluation index system for GLCA from four dimensions: agricultural carbon reduction, agricultural pollution reduction, agricultural green expansion, and agricultural growth, as shown in Table 1.

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Table 1. Evaluation index system for the development level of GLCA

Primary Indicator	Secondary Indicator	Indicator Explanation	Attribute
Agricultural carbon reduction	Agricultural carbon sequestration	-	+
	Agricultural carbon emissions	-	-
	Agricultural water-saving coefficient	Sown area / total agricultural water consumption	+
	Agricultural ammonia nitrogen emissions	-	-
Agricultural pollution reduction	Agricultural COD emission intensity	Total agricultural COD emissions / cultivated area	-
	Fertilizer usage level	Pure fertilizer usage / sown area of crops	-
	Pesticide usage level	Pesticide usage / sown area of crops	-
	Agricultural film usage level	Agricultural plastic film usage / sown area of crops	-
Agricultural green expansion	Soil and water loss control area	-	+
	Green food products	Number of products with valid green food labels	+
	Green food enterprises	Number of enterprises with valid green food labels	+
	Cropland replanting index	Sown area of crops / arable land area	-
Agricultural growth	Level of agricultural development	Gross agricultural production / GDP	+
	Output per agricultural worker	Gross agricultural production / agricultural employment	+
	Grain yield per unit area	Total grain output / sown area of crops	+
	Level of agricultural mechanization	Total power of agricultural machinery / sown area of crops	+

2) Independent Variable: New Quality Productive Forces (NQP). NQP, as the core driving force in the new era, lead the dual processes of economic transformation and sustainable development. The term “new” emphasises the distinction between NQP and traditional productive forces, with innovation as the main feature and expression in new production factors, new industries, new driving forces, and new production relations. The term “quality” reflects their inherent requirements and assessment standards, focusing on improving quality, boosting the integration of production factors, and significantly increasing total factor productivity. Based on the connotations and characteristics of NQP, this paper develops a measurement system for the development level of NQP from three aspects: innovation drive, technological improvement, and industry optimisation, as shown in Table 2.

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Table 2. Evaluation index system for the development level of new quality productive forces.

Primary indicator	Secondary indicator	Tertiary indicator	Quaternary indicator	Attribute
Innovation drive	Innovation foundation	Basic investment	Proportion of basic research expenditure to internal R&D expenditure	+
		Basic support	Number of Regular undergraduate institutions	+
			Number of science and technology business incubators	+
	Innovation talent	Talent reserve	Number of Full-time Teachers in Regular Higher Educational Institutions	+
			Number of doctoral students enrolled in higher education institutions	+
		Core talent	Number of R&D personnel	+
	Innovation Environment	Research manpowe r	Full-time equivalent of R&D personnel	+
		Research financial resources	Proportion of R&D expenditure to GDP	+
		Research vitality	The ratio of enterprises with R&D activitie s to total enterprises in large-scale industrial enterprises	+
Technologi cal improveme nt	High-tech	Scale of high-tech industries	Number of high-tech industry enterprises	+
		High-tech output	Number of scientific papers issued by ordinary colleges and universities	+
			Number of valid invention patents in high-tech industry enterprises	+
			Number of registered scientific and technological achievements	+
		High-tech transfor mation vitality	Transaction value of technology markets	+
	High efficiency	Production efficiency per capit a output	Labor productivity	+
			Capital productivity	+
			Per capita GDP	+
	High quality	Economic high quality	Engel's coefficient for residents	-
			Per capita disposable income of residents	+
		Living high quality	Resident population density	-
			Minimum living security rate for residents	-
Industry optimizatio n	New elements	Internet penetration rate	Number of broadband subscribers port of internet	+
		Optical fiber netwo rk coverage rate	Length of fiber optic cables	+
		Digital service revenue	Total income from information technology services	+
	New cross combinations	Degree of digital development	E-commerce Sales Revenue	+
			Digital finance index	+
			Number of computers used per hundred employees in enterprises	+
	High allocative efficiency	Industrial structure upgrade	Advancement of industrial structure	+
			Rationalization of industrial structure	-

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3) Control Variables: To avoid interference from other factors in the empirical results, this paper controls for variables that may affect GLCA from the perspectives of policy support, external investment, natural conditions, market demand, and resource allocation. The control variables include government support (GOV), measured by the natural logarithm of fiscal expenditures related to agriculture; foreign direct investment (FDI), measured as the ratio of total foreign direct investment inflows to GDP; the proportion of disaster-affected area (Dis_ar), which reflects the extent to which natural disasters affect agricultural production and is measured by the ratio of disaster-affected cultivated land area to total cultivated land area; the social consumption level (Consum), which captures the structure and scale of market demand and is measured as the ratio of total retail sales of consumer goods to GDP; and land scale management (Scale), which reflects the concentration and utilization efficiency of land resources and is measured by cultivated land area per capita.

4) Mediating Variable： The mediating variable is the educational attainment of the labour force (EALF). The educational attainment of the labour force reflects the stock of high-quality human resources and serves as a key catalyst for technological innovation and technology adoption. It also constitutes an important foundation for regional economic development and the sustained progress of various industries. Following the method proposed by Thomas et al. [21], EALF is calculated by weighting the proportion of the population at each education level by the corresponding years of schooling, including primary, junior secondary, senior secondary, and higher education.

3.2. Data Sources

This study uses data from 30 Chinese provinces (excluding Tibet, Hong Kong, Macao, and Taiwan) for the period 2014–2023. The data are mainly obtained from the *China Statistical Yearbook*, *China High-tech Industry Statistical Yearbook*, *China Statistical Yearbook on Science and Technology*, *China Rural Statistical Yearbook*, various regional statistical yearbooks, the official website of the National Bureau of Statistics, the EDGAR database [22], the Peking University Digital Financial Inclusion Index, and the *Annual Reports on Green Product Statistics*. A small amount of missing data is supplemented using linear interpolation, and the descriptive statistics of the relevant variables are reported in Table 3.

Table 3. Results of descriptive statistics.

Variables	N	Mean	SD	Min	Max
GLCA	300	0.295	0.085	0.149	0.566
NQP	300	0.179	0.117	0.046	0.691
GOV	300	6.364	0.540	4.703	7.283
Dis_ar	300	0.113	0.102	0.000	0.619
Scale	300	0.738	0.578	0.231	3.637
Consum	300	0.390	0.067	0.180	0.610
FDI	300	0.018	0.019	0.000	0.121
EALF	300	9.467	0.909	7.301	12.681

3.3. Model Methods

To examine the impacts of NQP on GLCA, this study constructs the following econometric models:

Fixed-effect model:

$$GLCA_{it} = \alpha_0 + \alpha_1 NQP_{it} + \alpha_2 Control_{it} + \mu_i + \varepsilon_{it} \tag{1}$$

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Where: i is province, t is year; $GLCA$ is the level of green and low-carbon agricultural development; NQP is the level of New Quality Productive Forces; $Control_{it}$ represents a series of time-varying control variables; μ_i captures individual fixed effects; ε is the random error term.

Mediating-Effect Model:

In addition to the total effects represented by the above equation, NQP may indirectly affect GLCA through certain mediating mechanisms. Given the widely recognised limitations and deficiencies of the traditional three-step mediation testing method in current literature, this study follows the approach recommended by Jiang[23], emphasising the necessity of selecting mediating variables that are explicitly justified by economic theory and clearly represent the transmission channels. The mediating-effect models are specified as follows:

$$Labor\_edu_{it} = \beta_0 + \beta_1 NQP_{it} + \beta_2 Control_{it} + \mu_i + \varepsilon_{it} \quad (2)$$

where: $Labor\_edu_{it}$ is the mediating variable; Other parameters and variables are defined as previously specified.

4. Empirical Analysis

4.1. Benchmark Regression Results

Table 4. Benchmark Regression Results.

Variables	(1)	(2)
	GLCA	GLCA
NQP	0.534*** (4.058)	0.379*** (3.889)
Dis_ar		-0.005 (-0.495)
FDI		-0.542* (-1.946)
GOV		0.043*** (3.466)
Consum		0.058 (1.329)
Scale		0.076*** (9.319)
Constant	0.199*** (8.458)	-0.113 (-1.460)
Province FE	yes	yes
R^2	0.522	0.723
N	300	300

Note: Standard errors in parentheses; * p < 0.1, ** p < 0.05, and *** p < 0.01.

This study selected the fixed-effect (FE) model as the benchmark regression model following the F-test and Hausman test procedures. Table 4. summarises the regression results. Column (1) demonstrates that, without incorporating control variables, the coefficient for NQP is positive and statistically significant at the 1% confidence level, suggesting that NQP significantly promotes GLCA. Column (2) further shows that, although the coefficient for NQP slightly decreases after adding control variables, it remains significantly positive, providing preliminary empirical support for Hypothesis H1. Additionally, coefficients for government support and land-scale management are both significantly positive. The positive effect of

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government support suggests that governmental roles extend beyond direct financial investment in agricultural environmental protection projects, encompassing continuous support for ecological technological innovations, low-carbon agricultural infrastructure, and relevant subsidy policies. These measures effectively lower barriers to agricultural green transformation, facilitating the widespread adoption of green production practices. Moreover, land-scale management contributes positively by optimising resource allocation and reducing unit production costs, thus promoting agricultural mechanisation and intelligence, ultimately mitigating resource waste and environmental pollution. Although the social consumption level coefficient lacks statistical significance, its positive direction indicates a potential facilitating role in green and low-carbon transformation. Conversely, foreign direct investment presents a significantly negative coefficient, reflecting foreign investors' preference for short-term economic returns over long-term environmental sustainability. Finally, while statistically insignificant, the proportion of disaster-affected areas shows a negative relationship, implying that higher disaster risks might partially hinder the transition towards green and low-carbon agriculture.

4.2. Robustness Tests

To verify the robustness of the econometric results, this study conducts several robustness tests, including alternative measurement approaches, lagging the core explanatory variable by one period, removing municipalities directly under the central government, and applying winsorization. The results are presented in Table 5.

Table 5. Robustness test.

Variable	(1)	(2)	(3)	(4)	(5)	(6)
	Alternative Measurement Approaches			Lagged One Period	Excluding Municipalities	5% Winsorizing
NQP	0.098*** (4.312)	1.541*** (3.464)	0.398*** (3.814)	0.431*** (3.492)	0.439*** (4.067)	0.453*** (5.507)
Control variable	yes	yes	yes	yes	yes	yes
Province FE	yes	yes	yes	yes	yes	yes
R^2	0.731	0.431	0.434	0.703	0.755	0.733
N	300	300	300	270	260	300

(1) Alternative Measurement Approaches. Previously, the entropy method was applied to measure NQP and GLCA. In this robustness check, factor analysis was employed to recalculate composite indices for both variables, which were then substituted into the regression models. As shown in columns (1), (2), and (3) of Table 8, where the explanatory variable, dependent variable, and both variables were replaced, respectively, the coefficients of NQP remained significantly positive at the 1% level.

(2) Lagged Core Explanatory Variable. Considering the potential bidirectional causality between NQP and GLCA, and the possible time-lagged empowerment effects of NQP, a lagged NQP by one period was introduced into the regression analysis. As displayed in column (4) of Table 8, the coefficient of lagged NQP was positive and statistically significant at the 1% level.

(3) Exclusion of Municipalities Directly under the Central Government. Given that municipalities directly under central government administration (Beijing, Tianjin, Shanghai, and Chongqing) possess unique political, technological, and infrastructural advantages and typically benefit from preferential pilot policies, these municipalities were excluded from the

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sample to test the sensitivity of the results. Column (5) in Table 8 shows that the coefficient of NQP remained positively significant at the 1% level after removing these municipalities.

(4) Winsorization Treatment. To further enhance the reliability of conclusions, main variables were winsorized at the 5% level, and the regression analysis was re-estimated. Column (6) in Table 8 indicates that the estimated coefficient of NQP remained positively significant at the 1% level, consistent with the previous findings.

4.3. Mechanism Tests

Further analysis of the mediation mechanism by which NQP promote GLCA through the educational attainment of the labour force is shown in Table 6. The results indicate that NQP have an impact coefficient of 2.596 on the EALF, significant at the 1% level, demonstrating their effective enhancement of labor education levels. Existing research shows that rural education positively impacts agricultural production, and enhancing human capital helps improve production conditions, increase production levels, and reduce pollution [24], promoting GLCA. Consistent with the expectations stated earlier, NQP effectively drive GLCA by enhancing the EALF, confirming research Hypothesis H2.

Table 6. Results of Testing the Impact Mechanism

Variable	(1)
	EALF
NQP	2.596*** (5.608)
EALF	
Control variable	yes
Province FE	yes
R^2	0.618

Note: Standard errors in parentheses; * p < 0.1, ** p < 0.05, and *** p < 0.01.

4.4. Heterogeneity Analysis

Given the considerable variations among Chinese provinces in terms of technological capabilities, economic development levels, R&D investments, and natural resource endowments, notable regional differences in the development of NQP are observed. Consequently, it is essential to examine regional heterogeneity by categorising provinces into eastern, central, western, and northeastern regions. Moreover, significant disparities exist in agricultural development levels across China. For instance, in 2024, the major grain-producing areas accounted for 77.7% of the nation's total grain output. Therefore, the analysis is further conducted by subdividing the overall sample into major and non-grain-producing regions.

The results presented in Table 7, models (1)– (4), demonstrate that the regression coefficient for the western region is 0.790, notably higher than other regions. This finding may be attributed to constraints the western provinces face, including limited economic development, geographic disadvantages, and scarcity of human capital. These constraints result in a higher reliance on labour-intensive traditional agriculture, enabling improvements in NQP to exert more pronounced effects on talent cultivation, technological advancement, and management innovation, consequently yielding a more significant impact on green and low-carbon agricultural development. In contrast, eastern regions, benefiting from robust economic foundations, abundant technological investments, and strong R&D capabilities, typically achieve green and low-carbon agricultural development through industrial structure optimisation and competitive market advantages, rendering the marginal effect of NQP relatively weaker.

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Furthermore, the results from Table 7, models (5) and (6), reveal a more pronounced empowering effect of NQP in major grain-producing regions. The likely explanation is that these regions possess well-developed agricultural infrastructure, including efficient irrigation systems, high-quality soil resources, and extensive agricultural technological accumulation, all of which create favourable conditions for fully realising NQP.

Table 7. Heterogeneity analysis.

Variable	(1)	(2)	(3)	(4)	(5)	(6)
	East	**Central**	**West**	**Northeast**	**Major Grain-Producing Areas**	**Non-Grain Producing Areas**
NQP	0.371*** (2.889)	0.631** (2.101)	0.790*** (7.226)	0.766** (2.279)	0.232** (2.399)	0.586*** (4.850)
Control variable	yes	yes	yes	yes	yes	yes
Province FE	yes	yes	yes	yes	yes	yes
R^2	0.655	0.806	0.82	0.935	0.589	0.857
Control variable	100	60	110	30	170	130

Note: Standard errors in parentheses; * p < 0.1, ** p < 0.05, and *** p < 0.01.

5. Conclusion and Policy Recommendations

5.1. Conclusion

Drawing on the theoretical framework of NQP, this study systematically analyses the direct and indirect mechanisms through which NQP empower GLCA from the perspectives of innovation drive, technological improvement, and industry optimisation. Using panel data from 30 Chinese provinces for the period 2014–2023, comprehensive evaluation index systems for NQP and GLCA are constructed, their respective composite development indices are calculated, and fixed-effects models are employed to empirically test the theoretical mechanisms. The main conclusions are as follows. First, enhancing NQP helps to promote GLCA. This conclusion remains robust after a series of robustness checks, including alternative measurement approaches, lagging the core explanatory variable by one period, excluding municipalities directly under the central government, and applying winsorization to the main variables. Second, the educational attainment of the labour force plays an important transmission role in the process through which NQP foster GLCA. By strengthening workers' awareness of sustainable development, higher education levels encourage more active adoption of green and low-carbon practices, thereby promoting GLCA. Third, the driving effects of NQP on GLCA exhibit pronounced regional heterogeneity: compared with the central and eastern regions, NQP exert stronger promoting effects on GLCA in the western and northeastern regions. In addition, while NQP positively influence GLCA in both major grain-producing and non-grain-producing areas, its empowering effect is more substantial in major grain-producing regions.

5.2. Policy Recommendations

Based on the above conclusions, this study proposes the following policy recommendations.

First, promote the deep integration of NQP with agriculture. In terms of technological innovation, it is advisable to increase investment in disruptive research and development, focusing on breakthroughs in key technologies such as biological carbon sequestration and intelligent agricultural machinery. An agricultural carbon neutrality science and technology fund should be established, and the collaborative innovation mechanism among enterprises, research institutes, and demonstration bases should be improved to accelerate technology transfer and application. In major grain-producing regions, the deployment of 5G base stations and agricultural Internet of Things nodes should be expedited, an integrated “sky–space–earth” monitoring network should be established, and green and low-carbon technologies should be widely promoted to optimise cultivated land management and carbon emission monitoring.

Second, enhance the educational level of the agricultural labour force. Universities and research institutes should be encouraged to establish targeted training programs to cultivate urgently needed professionals such as green agriculture technicians and carbon sink accounting specialists, thereby providing intellectual support for the green transformation of agriculture. At the same time, grassroots agricultural technology extension stations and farmer cooperatives should be leveraged to carry out demonstration and promotion activities in areas such as water-saving irrigation and organic composting, accompanied by the development of micro-courses in local dialects to make training more targeted and practical. In addition, policies supporting talent flows to rural areas should be further improved, treating human capital development as an important safeguard for agricultural green and low-carbon transformation, to effectively enhance the professional competencies and practical skills of the agricultural workforce.

Third, promote coordinated regional development. Each region should advance GLCA and the development of NQP in a manner suited to its own economic conditions and development foundation. The eastern region can leverage its advantages in research, finance, and management to take the lead in building zero-carbon agricultural science and technology parks, thereby exerting a radiating and driving effect on other regions. The central region should build on its manufacturing base to foster industrial clusters in intelligent agricultural machinery and equipment. The western region should focus on establishing circular development models such as “photovoltaics + eco-pastoralism,” with a view to expanding and strengthening its characteristic industries.

Fourth, build a governance system led by the government and involving multiple stakeholders. A multi-level governance structure should be established that fully harnesses the demonstrative and leading role of state-owned enterprises, stimulates the innovation vitality of private enterprises, mobilises social capital, and enhances the participation of social organisations. By improving information disclosure and social supervision mechanisms and making use of international cooperation platforms, global collaboration in key technologies, financial support, and talent training can be strengthened, thereby jointly advancing green, low-carbon, and sustainable agricultural development.

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