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Impact of Urbanization on Total Factor Carbon Productivity in Central Asia

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Abstract: Research on the impact of urbanization on total factor carbon productivity is of great significance to promote carbon emission reductions and achieve sustainable development. Based on the panel data of Central Asian countries from 1991 to 2019, the SBM–Malmquist index model and entropy method were used to measure total factor carbon productivity and urbanization, respectively. The nonlinear regression, Tobit, and quantile regression models were used to empirically analyze the impact of urbanization on total factor carbon productivity in Central Asia. The results show that urbanization drives total factor carbon productivity in Central Asia. Urbanization has a nonlinear inverted U-shaped impact on total factor carbon productivity in Central Asia, and it is in the first half of the inverted U-shaped correlation. Urbanization has driving and evolutionary effects on total factor carbon productivity in Central Asia. Urbanization not only directly drives total factor carbon productivity, but also indirectly drives total factor carbon productivity through technical efficiency improvement and technological progress.

Keywords: urbanization; total factor carbon productivity; Central Asia

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1. Introduction

Central Asia, where Kazakhstan, Kyrgyzstan, Tajikistan, Uzbekistan, and Turkmenistan are located, lies in the heart of the Eurasian continent. Since ancient times, it has been the main route of land transportation between the East and West, and its strategic location is very important. Central Asia is not only an energy resource-rich area, but also an ecologically fragile area. Central Asian countries are faced with the dual tasks of economic development and environmental protection. Total factor carbon productivity refers to the total factor productivity achieved by increasing energy consumption and carbon emission factors in the total factor productivity accounting system [1]; it is the source and key to the high-quality, sustainable development of a country or region. Central Asian countries pursued the strategy of rejuvenating the country with energy. In 2019, the energy consumption in Central Asia was 44.17 million tons of oil equivalent, and the carbon dioxide emissions were 405.54 million tons (World Bank Database, 2022). It is imminent for Central Asia to improve its total factor carbon productivity. It is worth mentioning that Central Asian countries have realized the importance of energy conservation, emission reduction, and improving total factor carbon productivity. To implement the Paris Agreement of the United Nations, Kazakhstan has set the goal of reducing greenhouse gas emissions by 15% by 2030, put forward a new national independent emission-reduction-contribution (NDC) target, and formulated the road map for 2022–2025; to reduce carbon emissions, Kazakhstan formulated the Vision of Low-carbon Economy Development by 2050 and the Vision of Achieving Carbon Neutrality by 2060 in 2020. Kyrgyzstan is the main advocate of the Shanghai Cooperation Organization's green energy production and consumption. In 2018, Kyrgyzstan issued the National Development Strategy to 2040, announcing that the proportion of renewable energy will increase to 50%; the 2026 National Development

Program released in 2021 set the goal of reducing greenhouse gas emissions by 17%. In 2016, the National Development Strategy of Tajikistan until 2030 issued by the government discussed energy conservation and emission reduction. In 2019, Uzbekistan's Transition Strategy to Green Economy from 2019 to 2030, based on 2010, set the goal of reducing greenhouse gas emissions per unit GDP by 10%. Since 2019, Turkmenistan has successively formulated the National Climate Change Strategy, the National Strategy for Renewable Energy Development to 2030, and the new Renewable Energy Law in accordance with the contents of the United Nations 2030 Agenda and the Paris Agreement. Urbanization is not only a process in which population, factors, and industries are constantly gathering, but also a process in which energy is consumed in high amounts and carbon emissions are highly concentrated. Urban areas are also the leaders of economic and social, green, low-carbon transformations and green low-carbon technology innovations, which play a vital role in promoting carbon emission reduction and improving total factor carbon productivity [2]. In 2021, the average level of urbanization in Central Asia was 45.22% (World Bank Database, 2022), which is far lower than the average level of world urbanization, and the driving effect of urbanization on total factor carbon productivity was insufficient. According to Northam's "S-shaped" curve theory of urbanization, the urbanization rate of 30~70% is the rapid development period of urbanization [3], and the urbanization in Central Asia has great development potential. Therefore, it is very important to address the following issues: can urbanization affect total factor carbon productivity? If so, what impact does urbanization have on total factor carbon productivity in Central Asia? Research on these issues is conducive to improving the understanding of the relationship between urbanization and total factor carbon productivity, contributes to the green, low-carbon and sustainable development of the Central Asian economy, and is of great significance to the lasting prosperity of the region.

The main contributions of this study are as follows: (1) in terms of the research perspective, this paper explores total factor carbon productivity in Central Asia from the perspective of urbanization. Urbanization not only directly drives total factor carbon productivity, but also indirectly drives total factor carbon productivity through technical efficiency improvements and technological progress; urbanization has both positive and negative effects on total factor carbon productivity, and the former is the key issue. (2) In terms of the research content, this paper studies total factor carbon productivity rather than the single-index carbon productivity; this paper establishes a comprehensive evaluation index system to evaluate urbanization in Central Asia rather than the urbanization rate. Based on the panel data of Central Asian countries from 1991 to 2019, the SBM–Malmquist index model and entropy method are used to measure total factor carbon productivity and urbanization, respectively. We hold that urbanization has a nonlinear impact and evolutionary effect on total factor carbon productivity. The nonlinear regression, Tobit, and quantile regression models were used to empirically analyze the impact of urbanization on total factor carbon productivity in Central Asia. (3) In terms of the research area, this paper selects Central Asia as the research object, rather than other large countries with global influence. The research on urbanization and total factor carbon productivity in Central Asia provides a useful reference for other countries and regions, especially developing countries and regions.

The rest of this paper is arranged as follows: Section 2 reviews the relevant literature and proposes research hypotheses; Section 3 introduces the research methods, variable selection, and data sources of this paper in detail; Section 4 empirically analyzes the impact of urbanization on total factor carbon productivity, including the Tobit and quantile models' results; and, finally, Section 5 presents the conclusions, policy implications, and limitations of the paper.

2. Literature Review and Hypotheses

Urbanization is the inevitable trend of economic and social development, and its connotations can be divided into narrow and broad senses. The narrow sense mainly

refers to the process of the continuous transformation of the rural population into an urban population, that is, population urbanization. Urbanization in a broad sense is also called comprehensive urbanization [4], which not only includes population urbanization, but also economic, social, and cultural urbanization. From a broad perspective, we believe that urbanization is a process in which the rural population continuously transfers to urban areas, the economic elements continuously gather in urban areas, and the rural lifestyle continuously changes into an urban lifestyle, thus increasing the number and scale of cities and towns, and it can be divided into three parts: population urbanization, economic urbanization, and social urbanization. Economic urbanization is a process in which resources, capital, technology, enterprises, and industries gather in urban areas, and the economic scale of urban areas continues to expand [5]. Social urbanization is a process of continuous transformation from rural to urban lifestyles, including the optimization of public services, the improvement of the consumption capacity, and the quality of life [6]. Many classical theories, including the Lewis–Ranis–Jinghan Fei model, Todaro model, Jorgenson model, "push–pull" population migration theory, and new economic migration theory, have analyzed urbanization and its driving mechanisms. Urbanization is characterized by stages and needs to be steadily promoted [7]. According to the World Bank statistics, in 2021, the urbanization rates of Kazakhstan, Kyrgyzstan, Tajikistan, Uzbekistan, and Turkmenistan were 57.82%, 37.15%, 27.73%, 50.43%, and 53.00%, respectively. Affected by the political and economic situation, the urbanization of Central Asian countries presents the stage characteristics from stagnant to rapid developments [8]. The urbanization of the five Central Asian countries is not balanced [9], and the urbanization potential is great.

As one of the core concepts of neoclassical economic theory, total factor productivity (TFP) is considered to be the only source of sustained economic growth and is also known as the "Solow residual" [10]. Total factor carbon productivity (TFCP) is the total factor productivity under the constraints of energy conservation and emission reduction [11] and is a comprehensive indicator that considers economic growth, energy consumption, and carbon emissions, and its power source is technical efficiency and technological progress [12]. Total factor carbon productivity takes into account several input and output factors, which is comprehensive and accurate. Improving total factor carbon productivity reduces carbon emissions as much as possible while reducing factor input and increasing the expected output [13]. Scholars have conducted in-depth research on total factor carbon productivity at the meso- and macrolevels, including research on total factor carbon productivity in manufacturing [14,15], industry [16,17], the service industry [18], countries, and regions [19–21].

Scholars have three main views on the impact of urbanization on carbon emissions. The first is that urbanization increases carbon emissions [22]; the second is that urbanization reduces carbon emissions [23]; and the third is that there is a nonlinear U-shaped correlation between urbanization and carbon emissions [24]. Based on the existing research, we believe that the impact of urbanization on total factor carbon productivity is complex. Urbanization can not only directly affect total factor carbon productivity, but also indirectly affects total factor carbon productivity through technical efficiency and technological progress. Urbanization has both positive and negative effects on total factor carbon productivity.

First, urbanization directly affects total factor carbon productivity. The population, factor, and industrial agglomerations brought by urbanization can drive the changes in production mode and lifestyle and improve total factor carbon productivity. With the improvement of marginal productivity and labor remuneration in urban areas, urbanization absorbs rural surplus labor [25], improves rural factor allocation efficiency and land-intensive management efficiency, accelerates rural capital accumulation [26], and promotes the mechanization intensification of agriculture, which increases the per capita output of farmers and improves total factor carbon productivity. Urbanization has a selection effect [27]; it alleviates the shortage of urban labor, promotes the optimization and upgrading of industrial structures through industrial agglomeration and the professional division of labor [28], reduces the cost of industry and service industry, saves economic resources and energy [29], promotes low-carbon production and low-carbon services, and

improves total factor carbon productivity. Due to the large population, the driving effect of urban areas on consumption is much greater than that of rural areas, and it is easier to produce "demonstration effects" of consumption, expand the scale of the consumer market [30], and promote low-carbon lifestyle changes. Reasonable and orderly urban spatial structures drive innovation element agglomeration, the professional division of labor and technology diffusion through the siphon, scale-interaction, and diffusion effects [31]; promotes technological innovations and technological spillovers; reduces the innovation cost [32]; and achieves energy conservation and emission reduction through technical means, which improves total factor carbon productivity.

Second, urbanization affects total factor carbon productivity through technical efficiency improvement and technological progress. The demographic and structural dividends brought by urbanization improve technical efficiency [33]. The demographic dividend brought by urbanization refers to the economic benefits obtained in the process of population scale and human capital advancement brought by the flow and agglomeration of rural population to cities and towns, and it can be divided into quantitative and qualitative demographic dividends. Classical theories, such as the Lewis, Fei Jinghan–Lanes, and Todaro models have all conducted in-depth discussions on the positive impact of rural-surplus labor transfer on economic development [34–36]. Schultz's human capital theory posits that economic development mainly depends on human capital improvement. The complex labor performed by skilled, technical, academic, and engineering talent creates more value than ordinary labor, improves the utilization efficiency of resources, provides guarantees for the improvement of environmental quality, and improves ecological efficiency [37] and total factor productivity [38]. The structural dividend created by urbanization refers to the optimization of the industrial structure and the structure of supply and demand created by the flow of factors from the low-productivity agricultural sector to the high-productivity nonagricultural sector, which can improve technical efficiency, technological progress, and total factor carbon productivity. The structural dividend hypothesis posits that structural optimization improves total factor productivity [39]. In the process of urbanization, factors of production continue to flow from rural to urban areas, from agriculture with relatively low productivity rates to industry and services with higher productivity rates, which promotes the rationalization and advancement of the industrial structure and improves technical efficiency [40]. The technological dividend created by urbanization drives technological progress. Neoclassical growth theory holds that technological progress is the fundamental source of economic growth. Urbanization has a technological innovation effect [41], and the population agglomeration created by it stimulates learning, competition, and division effects [42]; enterprise and industrial agglomerations created by urbanization promote labor division and specialization [43], and drive innovation resource agglomeration and technological progress. Urbanization provides demand guarantees and market conditions for low-carbon technology spillover, transfer, diffusion, and sharing, and forms an agglomeration–diffusion mechanism of innovation resources, which improves technological progress and low-carbon economic efficiency [44].

Third, urbanization has both positive and negative effects on total factor carbon productivity. The positive impact is that urbanization can not only directly drive total factor carbon productivity, but also indirectly drive total factor carbon productivity through technical efficiency and technological progress, as mentioned in the above analysis; the negative impact is mainly reflected in the crowding effect caused by very rapid or excessive urbanization, which reduces total factor carbon productivity. The crowding effect refers to the excessive agglomeration and competition created by urbanization [45], resulting in "urban diseases", such as space squeeze, traffic congestion, resource shortage, and environmental pollution, which lead to a reduction in the total factor carbon productivity. The IPAT model proposed by Ehrlich and Holdren (1971) posits that the environmental pressure of an economy is affected by the size of the population [46], and the formula of the IPAT model is:

$$I = P \times A \times T \quad (1)$$

where I represents the environmental pressure, P is the population size, A is the affluence of the economy, and T is the technological progress. Excessive population growth and agglomeration values cause a series of problems, such as urban population expansion, environmental pollution, ecological damage, resource shortages, energy shortages, rising costs, excessive competition, and semi-urbanization, resulting in traffic congestion, parking difficulties, facility shortages, housing shortages, garbage siege, air pollution, frequent occurrence of smog, noise pollution, water pollution, employment difficulties, medical difficulties, poor security, widening gap between rich and poor, extensive management, slow emergency response, increased hidden dangers, and social fragmentation, which create considerable challenges to the production of enterprises, people's lives, and government management, as well as pressure on ecology, environment, resources, and energy, resulting in the decline of urban vitality and sustained economic growth, and a reduction in the total factor carbon productivity.

Based on the above analysis, we hold that urbanization not only directly drives total factor carbon productivity, but also indirectly drives total factor carbon productivity through technical efficiency improvement and technological progress. Urbanization has both positive and negative effects on total factor carbon productivity, and the former is the key issue. There may be a nonlinear correlation between urbanization and total factor carbon productivity. Therefore, this paper proposes the following hypotheses:

Hypothesis 1. *Urbanization drives total factor carbon productivity.*

Hypothesis 2. *Urbanization has a nonlinear impact on total factor carbon productivity. Urbanization has an evolutionary effect on total factor carbon productivity.*

Hypothesis 3. *Urbanization not only directly drives total factor carbon productivity, but also indirectly drives total factor carbon productivity through technical efficiency improvement and technological progress.*

3. Methodology and Data

3.1. Models

3.1.1. Tobit Model

The Tobit model is commonly used to analyze truncated variables in the literature [47]. Total factor carbon productivity in Central Asia is truncated datum with nonnegative values. Therefore, the panel Tobit model is used to empirically analyze the impact of urbanization on total factor carbon productivity in Central Asia. In 1958, Tobin proposed the Tobit model, which adopts the maximum likelihood method (ML) for regression, solves the problem of parameter estimation bias when the explained variables are limited in value [48], and effectively avoids the estimation bias caused by the least-squares (OLS) regression. Based on the above theoretical analysis, urbanization may have a nonlinear effect on total factor carbon productivity; therefore, the square term of urbanization is put into the model to reveal this nonlinear influence. Technical efficiency and technological progress are important power sources of total factor carbon productivity. To explore the influence of urbanization on technical efficiency and technological progress, they are also put into the model. Based on the work by Gong et al. [49], the nonlinear regression models are set as follows:

$$TFCP_{it} = \alpha_0 + \alpha_1 URB_{it} + \alpha_2 URB_{it}^2 + \varphi D_{it} + \varepsilon_{it} \quad (2)$$

$$EC_{it} = \beta_0 + \beta_1 URB_{it} + \beta_2 URB_{it}^2 + \upsilon D_{it} + \varepsilon_{it} \quad (3)$$

$$TC_{it} = \gamma_0 + \gamma_1 URB_{it} + \gamma_2 URB_{it}^2 + \lambda D_{it} + \varepsilon_{it} \quad (4)$$

where $TFCP$, EC, and TC represent total factor carbon productivity, technical efficiency, and technological progress in Central Asia, respectively; URB is urbanization; URB^2 is the square term of urbanization; D is the control variable; I is the country; t is the year; α_0, β_0

and γ_0 are the constant terms; α_1, β_1, γ_1, α_2, β_2, γ_2, φ, υ, and λ are the parameters to be estimated; and ε is a random error.

3.1.2. Quantile Regression Model

Considering that the impact of urbanization on total factor carbon productivity is not uniform, this paper used panel quantile models to study the different impacts of urbanization on total factor carbon productivity under different quantiles to study its evolutionary effects. In 1978, Koenker and Basett proposed the quantile regression model [50], which can reflect the heterogeneity of the influence of explanatory variables on the explained variables through the difference in significance levels and regression coefficients at different quantiles. It can analyze the marginal impact of explanatory variables on the explained variables more comprehensively, without being disturbed by outliers, and has the characteristics of flexibility, comprehensiveness, robustness, and precision. Based on the work by Li and Wang [51], the quantile regression models are set as follows:

$$Quant_\theta(TFCP_{it}|URB_{it}) = \alpha'_0 + \alpha'_\theta URB_{it} + \alpha''_\theta URB_{it}^2 + \varphi D \quad (5)$$

$$Quant_\theta(EC_{it}|URB_{it}) = \beta'_0 + \beta'_\theta URB_{it} + \beta''_\theta URB_{it}^2 + \upsilon D \quad (6)$$

$$Quant_\theta(TC_{it}|URB_{it}) = \gamma'_0 + \gamma'_\theta URB_{it} + \gamma''_\theta URB_{it}^2 + \lambda D \quad (7)$$

where $Quant_\theta(TFCP_{it}|URB_{it})$, $Quant_\theta(EC_{it}|URB_{it})$, and $Quant_\theta(TC_{it}|URB_{it})$ represent the value of the explained variable total factor carbon productivity, technical efficiency, and technological progress, respectively, at the θ quantile under the given explanatory variable urbanization conditions, and D is the control variable. α'_0, β'_0, γ'_0, α', β', γ', φ, υ, and λ are the parameters to be estimated. We selected quintiles of 0.10, 0.25, 0.5, 0.75, and 0.90 for the regression analysis.

3.2. Variables and Data

The explained variable in this paper is total factor carbon productivity in Central Asia, which is represented by *TFCP*. In recent years, many scholars have evaluated total factor carbon productivity using different DEA models [52]. The SBM–Malmquist index model is a commonly used method for measuring total factor productivity, such as Zheng et al. [53] and Zheng [54]. This paper used the SBM–Malmquist index model to measure total factor carbon productivity in Central Asia. The SBM–Malmquist index model is a kind of nonparametric efficiency analysis method that combines the SBM model and the Malmquist index method. It has the advantages of there being no need to set the specific form of the production function, no need to consider price factors, and the dynamic evaluation and decomposition of total factor carbon productivity [55]. Based on the work by Li et al. [56], the measurement steps of total factor carbon productivity are as follows:

First, an evaluation index system of total factor carbon productivity was established. We selected labor, capital, and energy as input indicators and measured them with labor quantity, physical capital stock, and total energy consumption, respectively. We selected the expected and undesired outputs as the output indicators, which were measured by GDP and carbon dioxide emissions, respectively. In this paper, the evaluation index system of total factor carbon productivity in Central Asia is constructed as shown in Table 1.

The physical capital stock is accounted for using the perpetual inventory method, and the formulas are as follows:

$$K_t = IN_t + (1-\delta)K_{t-1} \quad (8)$$

$$K_0 = IN_0/(g+\delta) \quad (9)$$

where K_t stands for the physical capital stock in period t; IN_t stands for fixed assets in period t; g is the average growth rate of fixed-asset investment in Central Asian countries from 1991 to 2019; δ is the depreciation rate, based on the work by Shan [57], set at 10.96%; and the base period is 1991.

Table 1. Evaluation index system of total factor carbon productivity in Central Asia.

First-Level Indicators	Second-Level Indicators	Third-Level Indicators	Measurement Indicators
Total factor carbon productivity	Input indicators	Labor input	Labor force (10,000 people)
		Capital investment	Physical capital stock (USD billion)
		Energy input	Total energy consumption (10,000 tons of petroleum equivalent)
	Output indicators	Expected output	GDP (USD billion)
		Undesired output	Carbon dioxide emissions (10,000 tons)

Second, a nonradial and nonangular SBM model was constructed. In 2001, Tone proposed the slack-based measure (SBM) model, which is a nonradial DEA model based on slack variable measures [58]. The model puts the slack variables of input and output factors into the objective function, which overcomes the problem that the traditional DEA model does not consider slack variables. Assuming that there are n decision-making units (DMUs), each DMU has m input elements, s_1 expected outputs, and s_2 undesired outputs; the fractional planning of the SBM model is:

$$\rho = \min \frac{1 - \frac{1}{m}\sum_{i=1}^{m}\frac{s_i^-}{x_{i0}}}{1 + \frac{1}{s_1+s_2}\left(\sum_{r=1}^{s_1}\frac{s_r^d}{y_{r0}^d} + \sum_{l=1}^{s_2}\frac{s_l^u}{y_{l0}^u}\right)} \tag{10}$$

$$\text{Subject to} \begin{cases} x_0 = X\lambda + s^- \\ y_0^d = Y^d\lambda - s^d \\ y_0^u = Y^u\lambda + s^u \\ \lambda \geq 0 \\ s^- \geq 0 \\ s^d \geq 0 \\ s^u \geq 0 \\ i = 1, 2, \ldots, m \\ r = 1, 2, \ldots, s_1 \\ l = 1, 2, \ldots, s_2 \end{cases}$$

where ρ is the efficiency value; x, y^d, and y^u are the input, expected output, and undesired output, respectively; s^-, s^d, and s^u are the slack variables; and λ is the weight.

Third, the SBM–Malmquist index model was constructed. Based on the work by Fare et al. [59], the total factor carbon productivity index *tfcpch* is set as:

$$M(x_t, y_t, x_{t+1}, y_{t+1}) = \frac{D^{t+1}(x_{t+1}, y_{t+1})}{D^t(x_t, y_t)} \times \sqrt{\frac{D^t(x_{t+1}, y_{t+1})}{D^{t+1}(x_{t+1}, y_{t+1})} \times \frac{D^t(x_t, y_t)}{D^{t+1}(x_t, y_t)}} \tag{11}$$

where M is the total factor carbon productivity index *tfcpch* in Central Asia, $D(x, y)$ is the output distance function, and t stands for period. M measures the changes in total factor carbon productivity in Central Asia; when $M > 1$, it means that total factor carbon productivity is increasing; when $M = 1$ or $M < 1$, it means that total factor carbon productivity remains unchanged or declines, and its decomposition formula is:

$$tfcpch = effch \times techch \tag{12}$$

where *effch* is the technical efficiency index, which measures the changes in technical efficiency, and *techch* is the technological progress index, which measures the changes in technological progress.

Fourth, the index is converted into a fixed-base index. Considering that $tfcpch$ is a chain index, it is necessary to convert the total factor carbon productivity index into a

fixed-base index, and we set the base period value as 1. The total factor carbon productivity of Kazakhstan, Kyrgyzstan, Tajikistan, Uzbekistan, and Turkmenistan is calculated for 1991–2019, and the fixed-base index method was also used to measure technical efficiency and technological progress.

The explanatory variable is urbanization, denoted by *URB*. The measurement methods of urbanization include the single- and comprehensive–index methods. The single-index method uses the urbanization rate, which is the proportion of the urban population in the total population to measure; the comprehensive-index method measures urbanization by constructing a comprehensive evaluation index system [60]. Based on the broad concept of urbanization and the availability of relevant data in Central Asian countries, this paper constructed an evaluation index system of urbanization in Central Asia from three aspects: population urbanization, economic urbanization, and social urbanization, as shown in Table 2.

Table 2. Evaluation index system of urbanization in Central Asia.

First-Level Indicators	Second-Level Indicators	Measurement Indicators
Urbanization	Population urbanization	Urban population (% of total population) Urban population growth (annual %) Proportion of nonagricultural employment (%)
	Economic urbanization	GDP per capita (USD at present) Proportion of nonagricultural output value (%) Per capita household-consumption expenditure (USD at present)
	Social urbanization	Life expectancy at birth (years) Mobile cellular subscriptions (per 100 people) Government expenditure on education, total (% of GDP)

The entropy method was used to measure the urbanization level of Central Asia. Based on the work by Wang and Lu [61], the calculation formulas of the entropy method are as follows:

$$X'_{ij} = \left[X_{ij} - \min(X_{ij})\right] / \left[\max(X_{ij}) - \min(X_{ij})\right] \quad (13)$$

$$P_{ij} = X'_{ij} / \sum_{i=1}^{n} X'_{ij} \quad (14)$$

$$e_j = -\frac{1}{\ln n} \sum_{i=1}^{n} P \ln(P) \quad (15)$$

$$\mathrm{d_j} = 1 - e_j \quad (16)$$

$$W_\mathrm{j} = d_j / \sum_{j=1}^{m} d_j \quad (17)$$

$$Z_\mathrm{i} = \sum_{j=1}^{m} W_j \times X_\mathrm{ij} \quad (18)$$

where X_{ij} represents the observation value of the ith evaluation object on the jth index, $0 \le i \le n$ and $0 \le j \le m$. $\min(X_{ij})$ and $\max(X_{ij})$ are the minimum and maximum values within the group, respectively. Since all indicators are positive indicators, the positive extreme value method is used to standardize all data. X'_{ij}, P_{ij}, e_j, $\mathrm{d_j}$, W_j, and Z_i represent the standardized index value, efficacy function, entropy value, difference coefficient, index weight, and comprehensive evaluation value, respectively. The greater the value of Z_i, the more important the ith index is, and vice versa; the less important the ith index is, $0 \le Z_i \le 1$.

The control variables in this paper were selected as follows: the first was economic development. Economic development not only increases the expected output, but also

provides material support for reducing energy consumption and carbon emissions, and a higher level of economic development usually leads to higher energy utilization efficiency [62], which helps to improve total factor carbon productivity. The second was economic agglomeration. Economic agglomeration promotes economic efficiency [63] and total factor productivity [64]; it not only promotes economic growth and technological progress, but also promotes energy conservation, emission reduction, and environmental governance through scale and cost effects and reduces undesired outputs. The third was government macro-control. Government macro-control has an important impact on economic development [65], and the improvement of the government's macro-control is conducive to reducing the negative externalities created by urbanization, enhancing environmental regulation, reducing carbon emissions, improving the governance capacity of cities, and providing a good institutional environment for urbanization to drive the improvement of total factor productivity [66]. The fourth was industrialization. On the one hand, industrialization can bring about the improvement of production technology and production capacity, increase economic output, and improve economic efficiency; on the other hand, industrialization creates more resource and energy consumption and pollutant emissions, reducing green total factor productivity [67]; however, the positive impact of industrialization on total factor carbon productivity was the main aspect. The fifth was informatization. Informatization improves scale, technical, and allocation efficiencies and promotes technological progress [68]; informatization also reduces production, transaction, and circulation costs through network, scale, and long-tail effects, reduces information asymmetry, and improves total factor carbon productivity [69]. The sixth was opening up to the outside world. Opening up to the outside world is an important channel to optimize the allocation of economic resources and improve green total factor productivity [70]. Opening up to the outside world promotes international trade and provides a good external environment for the improvement of total factor carbon productivity.

The selection of variables in this paper is shown in Table 3.

Table 3. Variable selection.

Variable Types	Variable Names	Measurement Indicators	Symbols	Data Sources
Explained variable	Total factor carbon productivity	Total factor carbon productivity	*TFCP*	Measurement results
	Technical efficiency	Technical efficiency	*EC*	Measurement results
	Technological progress	Technological progress	*TC*	Measurement results
Explanatory variables	Urbanization	Urbanization	*URB*	Measurement results
	Square term of urbanization	Square term of urbanization	URB^2	Calculation results
Control variables	Economic development	GDP per capita (USD 100)	*PGDP*	World Bank database
	Economic agglomeration	GDP/land area (10,000 USD/square kilometers)	*ECON*	World Bank database
	Government macro-control	Government general consumption expenditure/GDP	*GOV*	World Bank database and the Statistical Yearbook of Central Asian Countries
	Industrialization	Industrial added value/GDP	*INDU*	Asian Development Bank database
	Informatization	Mobile cellular subscriptions (per 100 people)	*INFOR*	World Bank database and the Statistical Yearbook of Central Asian Countries
	Opening up to the outside world	Trade volume/GDP	*OPEN*	World Bank database and the Statistical Yearbook of Central Asian Countries

As shown in Table 3, both explained and explanatory variables are derived from measurement values, and the rest of the data are obtained from the World Bank database, the Asian Development Bank database, and the Statistical Yearbook of Central Asian Countries. Individual missing data are filled with mean interpolations. The descriptive statistics of the variables are shown in Table 4.

Table 4. Descriptive statistics.

Variables	Mean	SD	Max	Min
TFCP	1.827	1.214	5.435	0.426
EC	1.196	0.466	2.760	0.617
TC	1.699	1.294	5.563	0.333
URB	0.311	0.210	0.974	0.050
URB^2	0.141	0.195	0.949	0.003
PGDP	22.068	29.902	138.906	1.384
ECON	3.765	3.743	18.232	0.487
GOV	15.329	6.529	49.247	5.941
INDU	31.943	11.406	66.580	5.782
INFOR	47.569	57.106	185.706	0.000
OPEN	84.604	35.604	181.590	10.103

To overcome the bias caused by different dimensions, all the variables were standardized by the extreme-value method. All the variables were positive indicators; the higher they were, the better. Therefore, the positive extreme-value method was adopted, and the formula is:

$$x'_{ij} = \left[x_{ij} - \min(x_{ij})\right] / \left[\max(x_{ij}) - \min(x_{ij})\right] \quad (19)$$

where x_{ij} is the original value of the j indicator in country i, x'_{ij} is the normalized value, the value range is [0, 1], $\max(x_{ij})$ is the maximum value, and $\min(x_{ij})$ is the minimum value.

4. Results

Based on the relevant data of the five Central Asian countries from 1991 to 2019, a scatterplot of urbanization and total factor carbon productivity was drawn, as shown in Figure 1.

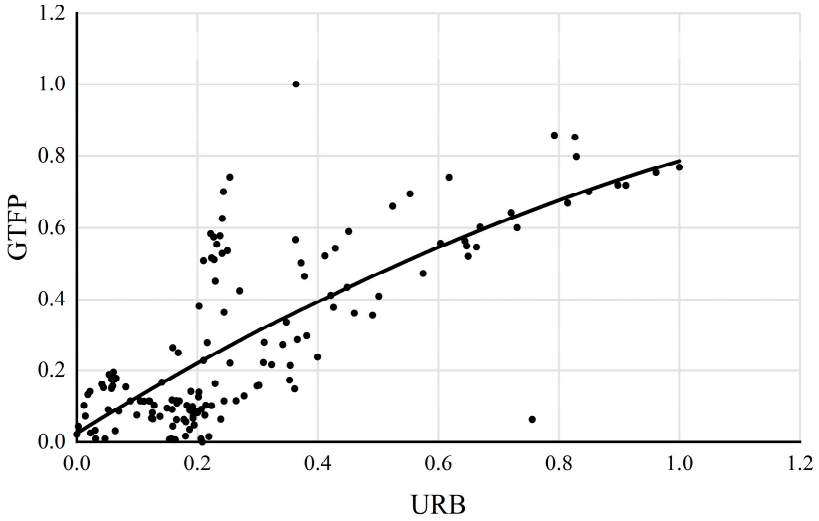

Figure 1. Scatter plots.

As shown in Figure 1, the nonlinear correlation between urbanization and total factor carbon productivity in Central Asia is obvious. From the fitting line trend, there is an obvious inverted U-shaped correlation between urbanization and total factor carbon productivity in Central Asia. The value of urbanization is much smaller than the inflection point value, and urbanization is still in the first half of the inverted U shape, which indicates that there is a monotonically increasing positive correlation between urbanization and total factor carbon productivity in Central Asia; that is, urbanization can drive the improvement of total factor carbon productivity in Central Asia.

4.1. Tobit Regression Results

Based on the panel data of the five Central Asian countries from 1991 to 2019, the LLC and IPS tests were used for the unit root test, and the Kao and Pedroni tests were used for the cointegration test. The results show that all the variables refute the null hypothesis of the existence of a unit root and no co-integration relationship, and the regression analysis of the panel data can be conducted. The Tobit model was used to empirically analyze the impact of urbanization on total factor carbon productivity, technical efficiency, and technological progress in Central Asia, and the regression results are shown in columns (1) to (3) of Table 5. The robustness test was performed using the variable-substitution method; that is, the urbanization rate was used to replace the explanatory variable urbanization (*URB*). The results of the robustness test are shown in columns (4) to (6) of Table 5.

Table 5. Tobit regression results.

Variables	(1) Tobit Regression *TFCP*	(2) Tobit Regression *EC*	(3) Tobit Regression *TC*	(4) Robustness Test *TFCP*	(5) Robustness Test *EC*	(6) Robustness Test *TC*
URB	0.977 ***	−0.316	1.197 ***	1.843 ***	0.203	1.421 ***
	(0.210)	(0.299)	(0.219)	(0.319)	(1.504)	(0.315)
URB^2	−1.182 ***	0.400	−1.611 ***	−1.768 ***	−0.648 ***	−1.401 ***
	(0.257)	(0.356)	(0.257)	(0.329)	(1.487)	(0.325)
PGDP	0.685 ***	−0.112	1.147 ***	0.384 ***	0.062	0.569 ***
	(0.155)	(0.200)	(0.146)	(0.091)	(0.103)	(0.090)
ECON	−0.020	0.963 ***	−0.363 ***	0.036	1.052 ***	−0.249 ***
	(0.077)	(0.103)	(0.075)	(0.069)	(0.110)	(0.068)
GOV	−0.113	0.123	−0.208 ***	−0.256 ***	0.110	−0.284 ***
	(0.073)	(0.093)	(0.067)	(0.077)	(0.100)	(0.076)
INDU	0.026	−0.063 **	0.072	0.007	−0.082	0.269 ***
	(0.066)	(0.082)	(0.060)	(0.057)	(0.082)	(0.057)
INFOR	0.371 ***	−0.411 ***	0.322 ***	0.488 ***	−0.454 ***	0.416 ***
	(0.056)	(0.071)	(0.052)	(0.057)	(0.070)	(0.057)
OPEN	0.117 **	−0.059	0.023	0.190 ***	−0.056 **	0.049
	(0.051)	(0.064)	(0.047)	(0.054)	(0.066)	(0.053)
_cons	−0.056	0.271 ***	−0.025	−0.056	0.422 ***	−0.042
	(0.049)	(0.093)	(0.051)	(0.041)	(0.150)	(0.041)
Prob	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000

Note: Standard errors are in parenthesis. *** $p < 0.01$, ** $p < 0.05$.

As shown in column (1) of Table 5, urbanization (*URB*) drives the improvement of total factor carbon productivity (*TFCP*) in Central Asia. Both urbanization and its square term (URB^2) passed the significance test at the 1% confidence level, indicating that there is a significant nonlinear correlation between urbanization and total factor carbon productivity. The coefficients of urbanization and its squared term are positive and negative, respectively, indicating that there is a significant inverted U-shaped correlation between urbanization and total factor carbon productivity in Central Asia; that is, with the improvement of urbanization, total factor carbon productivity presents an inverted U-shaped characteristic of first rising and then falling. The inflection point and denormalization formulas were used to calculate the inflection point value, which was 0.413; that is, when the urbanization level was lower than 0.413, urbanization had a positive correlation with total factor carbon productivity. The average value of urbanization in Central Asia was 0.282, which was far lower than the inflection point value of 0.413, which indicates that urbanization in Central Asia should be in the first half of the inverted U shape; that is, there is a monotonically increasing positive correlation between urbanization and total factor carbon productivity in Central Asia, and urbanization has a significant driving effect on total factor carbon productivity. Pan et al. [71] and Guo and Sun [72] also found that urbanization drives the improvement of total factor carbon productivity. Among the control variables, economic

development (*PGDP*), informatization (*INFOR*), and opening up to the outside world (*OPEN*) passed the significance test, and the coefficients were positive, indicating that these factors drive the improvement of total factor carbon productivity in Central Asia.

As shown in column (2) of Table 5, the impact of urbanization on technical efficiency (*EC*) is not significant. Urbanization and its squared term did not pass the significance test, indicating that the driving effect of urbanization on technical efficiency was not significant during the study period, which may be related to the inefficient management of urbanization in Central Asian countries. Among the control variables, economic agglomeration (*ECON*) passes the significance test, and the coefficients are positive, indicating that economic agglomeration drives technical efficiency.

As shown in column (3) of Table 5, urbanization drives the improvement of technological progress (*TC*) in Central Asia. Both urbanization (*URB*) and its square term (URB^2) passed the significance test at the 1% confidence level, indicating that there is a significant nonlinear correlation between urbanization and technological progress. The coefficient of urbanization is positive, and the coefficient of urbanization's square term is negative, which indicates that there is a significant inverted U-shaped correlation between urbanization and technological progress in Central Asia; that is, with the improvement of urbanization, technological progress presents an inverted U-shaped characteristic of first rising and then falling. When the urbanization level is lower than the inflection point value of 0.370, urbanization has a positive correlation with technological progress. The average value of urbanization in Central Asia is 0.282, which is far lower than 0.370, indicating that urbanization should be in the first half of the inverted U shape; that is, there is a monotonically increasing positive correlation between urbanization and technological progress in Central Asia, indicating that urbanization can not only directly improve total factor carbon productivity, but also improve total factor carbon productivity by promoting technological progress. Among the control variables, economic development (*PGDP*) and informatization (*INFOR*) passed the significance test, and the coefficients were positive, indicating that they promote technological progress in Central Asia.

From the robustness test results of columns (4) to (6) in Table 5, urbanization has a significant driving effect on total factor carbon productivity and technological progress; that is, the conclusion that urbanization can drive total factor carbon productivity and technological progress is robust.

4.2. Quantile Regression Results

Based on the panel data of five Central Asian countries from 1991 to 2019, quantile regression models were used to empirically analyze the marginal impact of urbanization on total factor carbon productivity in Central Asia. The regression results are shown in Table 6.

From columns (1) to (5) in Table 6, (1) urbanization has an evolutionary effect on total factor carbon productivity in Central Asia. In terms of significance, at the 0.1, 0.5, 0.75, and 0.9 quantiles, both urbanization (*URB*) and its square term (URB^2) passed the significance test, indicating that there is a nonlinear correlation between urbanization and total factor carbon productivity (*TFCP*). At the 0.25 quantile, urbanization passed the significance test at the 1% level, indicating that urbanization has a significant linear impact on total factor carbon productivity. In terms of the coefficient, at the 0.1, 0.5, 0.75, and 0.9 quantiles, the coefficient of urbanization shows an increasing trend, indicating that with the improvement of the quantile of total factor carbon productivity, the marginal impact of urbanization on total factor carbon productivity continues to increase. At the 0.1, 0.5, 0.75, and 0.9 quantiles, the absolute value of the coefficient of urbanization's square term has an increasing trend, and the nonlinear impact of urbanization on total factor carbon productivity is increasing. (2) Among the control variables, the significance and coefficients of the control variables are different at different quantiles, suggesting that they have evolutionary effects on total factor carbon productivity.

Table 6. Quantile regression results (*TFCP*).

Variables	(1) $\theta = 0.1$	(2) $\theta = 0.25$	(3) $\theta = 0.5$	(4) $\theta = 0.75$	(5) $\theta = 0.9$
URB	0.614 ***	0.595 ***	0.933 ***	0.922 ***	1.440 ***
	(0.109)	(0.179)	(0.246)	(0.338)	(0.501)
URB^2	−0.748 **	−0.566	−1.029 ***	−1.098 ***	−1.778 ***
	(0.312)	(0.347)	(0.201)	(0.386)	(0.660)
PGDP	0.661 **	0.501	0.401 *	0.403	0.668
	(0.333)	(0.324)	(0.237)	(0.263)	(0.415)
ECON	−0.068	0.036	−0.066	−0.040	−0.007
	(0.093)	(0.109)	(0.097)	(0.063)	(0.104)
GOV	−0.171 **	−0.165 *	−0.057	−0.003	0.005
	(0.077)	(0.084)	(0.063)	(0.085)	(0.105)
INDU	−0.098 **	−0.023	−0.009	−0.023	−0.085
	(0.048)	(0.059)	(0.088)	(0.142)	(0.324)
INFOR	0.274 ***	0.246 **	0.539 ***	0.606 ***	0.501 ***
	(0.085)	(0.115)	(0.135)	(0.145)	(0.119)
OPEN	0.047	0.045	0.084	0.067	0.141
	(0.037)	(0.069)	(0.127)	(0.124)	(0.122)
_cons	0.012	−0.002	−0.042	0.002	0.014
	(0.027)	(0.047)	(0.077)	(0.064)	(0.207)

Note: Standard errors are in parenthesis. *** $p < 0.01$, ** $p < 0.05$, * $p < 0.1$.

The changes in the quantile regression coefficients at different quantiles are shown in Figure 2.

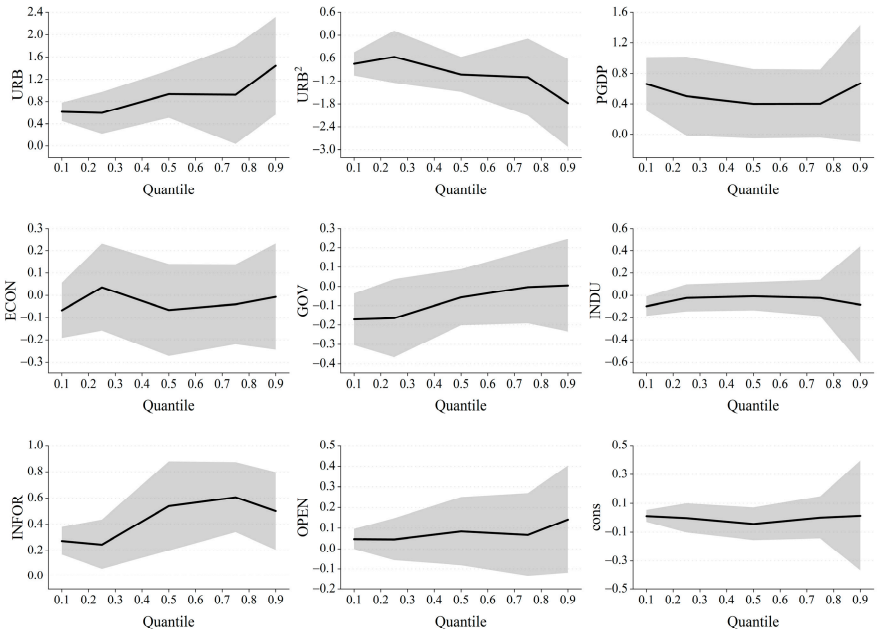

Figure 2. Coefficient changes in quantile regression.

As shown in Figure 2, (1) the marginal impact of urbanization on total factor carbon productivity is increasing. There is a nonlinear correlation between urbanization (*URB*) and total factor carbon productivity (*TFCP*). The urbanization coefficient generally shows an increasing trend, indicating that the marginal impact of urbanization on total factor carbon productivity is increasing, and at high quantiles, the impact of urbanization on total factor carbon productivity is stronger. The coefficient of the square term of urbanization (URB^2) is negative and shows a decreasing trend, and its absolute value shows an increasing trend, which indicates that with the increase in quantiles, the inverted U-shaped characteristic of urbanization on total factor carbon productivity is more significant. (2) Among the control

variables, economic development (*PGDP*), economic agglomeration (*ECON*), government macro-control (*GOV*), industrialization (*INDU*), informatization (*INFOR*), and opening up to the outside world (*OPEN*) have different impact strengths on total factor carbon productivity with different quantiles.

Quantile regression models were used to empirically analyze the marginal impact of urbanization on technical efficiency and technological progress in Central Asia. The regression results are shown in Table 7.

Table 7. Quantile regression results (*EC* and *TC*).

Variables	(1) *EC* *θ = 0.1*	(2) *EC* *θ = 0.25*	(3) *EC* *θ = 0.5*	(4) *EC* *θ = 0.75*	(5) *EC* *θ = 0.9*	(6) *TC* *θ = 0.1*	(7) *TC* *θ = 0.25*	(8) *TC* *θ = 0.5*	(9) *TC* *θ = 0.75*	(10) *TC* *θ = 0.9*
URB	−0.492	0.336 *	0.481 ***	0.304	1.027 *	0.207	0.451 **	0.778 ***	1.251 ***	1.411 ***
	(0.352)	(0.199)	(0.128)	(0.246)	(0.570)	(0.168)	(0.222)	(0.143)	(0.196)	(0.311)
URB^2	0.771 *	−0.171	−0.327	−0.410	−1.571 **	−0.638 **	−0.558	−1.308 **	−1.749 ***	−1.800 ***
	(0.439)	(0.365)	(0.204)	(0.299)	(0.756)	(0.256)	(0.658)	(0.595)	(0.400)	(0.645)
PGDP	−0.352 *	−0.120	−0.144	−0.042	0.445	0.940 ***	0.556	1.145 *	1.189 ***	1.086 *
	(0.183)	(0.250)	(0.193)	(0.380)	(0.672)	(0.241)	(0.544)	(0.600)	(0.381)	(0.629)
ECON	0.553 ***	0.375 **	0.599 ***	0.804 ***	0.734 ***	−0.201 *	−0.257 ***	−0.150	−0.153	−0.176
	(0.190)	(0.167)	(0.207)	(0.084)	(0.230)	(0.107)	(0.075)	(0.144)	(0.154)	(0.229)
GOV	−0.012	0.034	0.163 *	0.276	0.998 *	−0.143 **	−0.200 *	−0.122	−0.030	−0.031
	(0.090)	(0.094)	(0.091)	(0.258)	(0.563)	(0.070)	(0.103)	(0.128)	(0.124)	(0.153)
INDU	−0.068	−0.352 ***	−0.457 ***	−0.586 ***	−1.091 ***	0.112(0.074)	0.095	0.058	0.121	0.215
	(0.135)	(0.119)	(0.108)	(0.196)	(0.267)		(0.082)	(0.091)	(0.094)	(0.131)
INFOR	−0.096	−0.097	−0.192 ***	−0.220	−0.298 *	0.261 ***	0.371 ***	0.354 ***	0.291 ***	0.233 ***
	(0.096)	(0.106)	(0.067)	(0.176)	(0.177)	(0.069)	(0.043)	(0.064)	(0.068)	(0.071)
OPEN	0.138 ***	0.143 **	0.131 **	0.029	0.159	−0.019	0.027	0.093 **	0.170 *	0.135
	(0.049)	(0.057)	(0.065)	(0.073)	(0.156)	(0.028)	(0.042)	(0.043)	(0.087)	(0.124)
_cons	0.075	0.159 ***	0.214 ***	0.403 ***	0.521 ***	0.011	0.001	−0.052	−0.113	−0.097
	(0.046)	(0.034)	(0.065)	(0.095)	(0.092)	(0.023)	(0.041)	(0.055)	(0.075)	(0.118)
Prob	−0.492	0.336 *	0.481 ***	0.304	1.027 *	0.207	0.451 **	0.778 ***	1.251 ***	1.411 ***
	(0.352)	(0.199)	(0.128)	(0.246)	(0.570)	(0.168)	(0.222)	(0.143)	(0.196)	(0.311)

Note: Standard errors are in parenthesis. *** $p < 0.01$, ** $p < 0.05$, * $p < 0.1$.

From columns (1) to (5) in Table 7, urbanization has an evolutionary effect on the technical efficiency in Central Asia. In terms of significance, at the 0.1 quantile, there is a U-shaped correlation between urbanization (*URB*) and technical efficiency (*EC*); at the 0.25 and 0.5 quantiles, there is a linear correlation; at the 0.75 quantile, the impact of urbanization on technical efficiency is not significant; and at the 0.9 quantile, there is an inverted U-shaped correlation between urbanization and technical efficiency, which shows that urbanization has different effects on technical efficiency at different quantiles; that is, urbanization has an evolutionary effect on technical efficiency in Central Asia, indicating that urbanization can not only directly affect total factor carbon productivity, but can also affect total factor carbon productivity through technical efficiency.

From columns (6) to (10) in Table 7, urbanization has an evolutionary effect on technological progress in Central Asia. At the 0.25 quantile, urbanization (*URB*) has a significant linear impact on technological progress (*TC*); at the 0.1, 0.5, 0.75, and 0.9 quantiles, urbanization has a significant nonlinear impact on technological progress. Urbanization and its square term (URB^2) coefficients are positive and negative, respectively, indicating that at these four quantiles, urbanization and technological progress have an inverted U-shaped correlation. At the 0.1, 0.5, 0.75, and 0.9 quantiles, the absolute value of urbanization and its square term keep increasing, indicating that the inverted U-shaped impact of urbanization on technological progress is increasing as the quantile increases, which shows that urbanization can not only directly drive total factor carbon productivity, but can also drive total factor carbon productivity through technological progress.

Among the control variables, economic development (*PGDP*), economic agglomeration (*ECON*), government macro-control (*GOV*), industrialization (*INDU*), informatization (*INFOR*), and opening up to the outside world (*OPEN*) have evolutionary effects on techni-

cal efficiency and technological progress. These factors have different impact strengths on technical efficiency and technological progress with different quantiles.

5. Conclusions

Urbanization is not only the process of population, factor, and industry gathering, but also the process of energy consumption and carbon emissions. Driving total factor carbon productivity with urbanization is not only an important measure for the development of Central Asia, but also an important part of the sustainable development in other countries and regions around the world, especially in developing countries and regions. This paper focused on the impact of urbanization on total factor carbon productivity. Based on the panel data of Central Asian countries from 1991 to 2019, the SBM–Malmquist index model and entropy method were used to measure total factor carbon productivity and urbanization in Central Asia, respectively. The nonlinear regression, Tobit, and quantile regression models were used to empirically analyze the impact of urbanization on total factor carbon productivity in Central Asia. The results show the following: (1) urbanization drives total factor carbon productivity in Central Asia. Urbanization has a nonlinear inverted U-shaped impact on total factor carbon productivity in Central Asia, and it is in the first half of the inverted U-shaped correlation. (2) Urbanization has a driving effect and evolutionary effect on total factor carbon productivity in Central Asia. (3) Urbanization not only directly drives total factor carbon productivity, but also indirectly drives total factor carbon productivity through technical efficiency improvement and technological progress.

Based on the above conclusions, this paper has the following policy implications. Central Asian countries should promote the construction of urbanization. First, the process of population urbanization should be accelerated. Central Asian countries should guide the orderly flow of population, coordinate population distribution, and spatial distribution; improve the resource allocation system; avoid a very rapid and excessive population agglomeration; form an awareness and actions of energy conservation and emission reduction; promote the professional division of labor and information sharing; and improve the education and training mechanism. Second, the process of economic urbanization should be accelerated. According to the goal of peak carbon dioxide emissions and carbon neutrality, the process of economic urbanization should be accelerated under the constraint of total factor carbon productivity in Central Asia. Insufficient industrial support has seriously hindered the urbanization process of Central Asian countries, and improving the industrial support capacity is the key to urbanization development. Therefore, Central Asian countries should actively combine industrialization, informatization, and low carbonization, and take advantage of the "One Belt, One Road" construction opportunities to improve the modernization level and opening-up level of agriculture, industry, and service industries. Third, the process of social urbanization should be accelerated. The comprehensive governance and public service capabilities of cities should be improved; social security systems, such as transportation, medical care, employment, and education, should be improved; a low-carbon lifestyle needs to be promoted; and the connotative development of cities should be guided to promote low-carbon, green, and sustainable economic transformations, and improve total factor carbon productivity.

This study had the following limitations. Due to the limitation of the data, this paper did not include other variables of environmental pollution in the evaluation index system when measuring total factor carbon productivity. This paper only analyzed the impact of urbanization on total factor carbon productivity in the five Central Asian countries. The research on the impact of urbanization on total factor carbon productivity needs to be expanded in both time and space, and the comparative study of regional and country differences in the impact of urbanization on total factor carbon productivity also needs to be expanded in the future.

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