Temporal and spatial evolution and influencing factors of urban ecological total factor productivity in the Yellow River basin under strong sustainable development

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Abstract

A growing consensus worldwide has indicated the need to protect the ecological environment and achieve sustainable development. Ensuring ecological protection and high-quality development of the Yellow River basin have become China's major national strategy. We reviewed extant literature, summarised government reports and guidance documents on the Yellow River basin, and proposed introducing a strong sustainable development theory into the study of total factor productivity (TFP). The spatial–temporal evolution and influencing factors of urban ecological TFP in the Yellow River basin are of great practical significance. We proposed a new ecological TFP indicator: the modified input-oriented Luenberger productivity indicator (MIL). Using panel data from

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78 cities in the Yellow River basin during 2003–2019, we measured the urban ecological TFP. We adopted the geographic information system tool and kernel density estimation to analyse the temporal and spatial evolution of the indicator, as well as its spatial effects and influencing factors, using the global Moran's I index and dynamic spatial Durbin model (SDM). Our results show that, during the sample period, our indicator increased in cities in the region with an average annual growth rate of 0.627%, driven by technological progress. The average annual growth rate in urban areas showed a decreasing distribution of 'downstream-midstream-upstream'. Fiscal decentralisation (FD), industrial structure (IND), financial development (FIN), urbanisation level (URB) and research and development (RD) investment improved growth rates in this and the adjacent regions through direct and indirect effects. However, environmental regulation (ER), opening level (OPEN) of cities and population density (POP) were obstacles to TFP growth.

Introduction

The Yellow River was formed approximately 1.5 million years ago, after a long geological period of development and erosion; approximately 100,000 years ago, it became a marine water system flowing eastward into the sea. As the fifth largest river worldwide, it is 5464 km long. The average annual natural runoff is 53.5 billion m^3 (1/17 times more than that of the Yangtze River). Its average annual sediment discharge and sediment concentration are 1.6 billion tons and 35 kg/m^3, respectively, which are the highest worldwide. (Data source: http://www.yrcc.gov.cn/hhyl/hhgk/, Zhengzhou, China).

The Yellow River is essential to China's ecological construction. Grasslands, lakes and swamps dominate its upper reaches to form the primary runoff and water source conservation area, directly affecting the river's changing water resource trends. In the middle reaches, the Loess Plateau's ecological community characteristics are the root causes of soil erosion and riverbed siltation. The downstream estuary delta ecosystem, where over 1500 kinds of animals thrive, is among the most important wetland ecosystems located in China's warm temperate zone. Furthermore, the Yellow River is an important ecological corridor that not only provides water resources for arid basin areas, but also forms a belt ecosystem with the river course, ecological forests along the river, wetland parks and vast beach areas; this positively affects biodiversity maintenance and local climate regulation.[1] Environmental 'ecology' plays a critical role in the Yellow River basin's sustainable development and 'ecosystem' quality and stability determine the sustainable development ability and potential of cities located in the region.

The sustainable development theory is widely used to study economic development,[2] climate change,[3–5] carbon emissions,[6–8] carbon neutralisation,[9–11] renewable energy[12,13] and water environment.[14,15] The weak sustainable development theory claims that natural and human-made capital can be substituted without considering ecological limits, which can cause serious ecological degradation.[16] The strong sustainable development theory posits that natural and human-made capital are not interchangeable, especially in the

ecological environment.[17] In 2003, based on the strong sustainable development theory, the European Commission constructed a theoretical framework to identify key sources of natural capital, aiming to create a strong sustainability standard to protect key natural capital stock. At the United Nations' 2012 'Rio + 20' Global Sustainable Development Conference, the strong sustainability theory was officially identified as a new green development paradigm, requiring human social and economic development to respect the earth's boundaries and ecological constraints.[18]

The traditional total factor productivity (TFP) index does not consider energy and environmental factors in the measurement process, which creates biased results.[19] Accordingly, scholars are gradually incorporating energy and environmental factors into the TFP research framework and promoting the evolution of traditional TFP to green TFP.[20,21] Data envelopment analysis (DEA) is widely used to measure TFP. Energy is typically regarded as an input variable; pollution is regarded as a negative output variable.[22] The radial method requires reducing or expanding all inputs or outputs in equal proportion,[23] while, the non-radial method (slacks-based measure (SBM)) puts the relaxation variable directly into the objective function. While this eliminates the assumption that factor input is reduced and expanded in the same proportion,[24] it loses the proportion information between the input or output target value and actual value. In view of this, Tone and Tsutsui proposed a hybrid distance model epsilon-based measure compatible with radial and non-radial characteristics.[25] However, their method ignored the abnormal phenomenon that may occur in large-scale technological retrogression.[20,26]

Recently, with the development of spatial econometrics, some scholars have used Moran's I index to research on the spatial correlation.[27] Other scholars have referenced an SBM-DEA model and quantitatively evaluated environmental governance from various perspectives. Using an SBM-DEA model, Vlontzos et al.[28] evaluated EU member states' environmental governance efficiency. However, the setting of the SBM model's direction vector is subjective and cannot overcome the deviation from using the same decision-making unit under different direction vector settings.[29] Mancini et al.[30] used a three-dimensional ecological footprint model to evaluate the dynamic evolution of natural capital while Wu et al.[31] applied Moran's I to calculate the spatial correlation effect of the Yellow River basin's total nitrogen pollution.

The Yellow River basin's environment is fragile and its economic development lags behind. These two factors restrict and influence each other. Some scholars posit that the environment will experience greater damage when economic development is low,[3] and some argue further that, with a certain extent of economic development, the damage will decrease.[32] Some scholars have found that improving the environment can promote regional economic growth.[33] In China, the ecological protection of the Yellow River basin is regulated by the government, which comprehensively supervises the region through relevant laws, system documents and policies. Table 1 shows that central local authorities have issued several government reports and policy documents on the Yellow River basin. In our review of earlier literature, government reports and guidance documents on the Yellow River basin, we identified ecology as the central factor for the region's sustainable development. We also found

Table 1. Government reports and policy documents related to the Yellow River basin.

Time	Source	Document	Related content
8 September 2021	The CPC Central Committee and the State Council	Outline of ecological protection and high-quality development plan for the Yellow River Basin	This planning outline is a programmatic document to guide the ecological protection and high-quality development of the Yellow River basin at present and in the future. It proposes to firmly take the road of green and sustainable high-quality development.
5 June 2020	Supreme People 's Court	Opinions of the Supreme People's Court on Providing Judicial Services and guarantees for the ecological protection and high-quality development of the Yellow River Basin	Courts at all levels are required to firmly establish the concept of 'green water and green mountains are golden mountains and silver mountains', and promote high-level protection of the ecological environment and high-quality economic development in the Yellow River basin.
28 May 2020	Ministry of Water Resources	Action plan for water resources supervision in the Yellow River Basin	It is proposed to organise and deploy the supervision of water resources in the Yellow River basin and to standardise the behaviour of water abstraction.
15 February 2022	Shandong Provincial Party Committee and Government	Ecological protection and high-quality development planning of the Yellow River Basin in Shandong Province	Shandong will innovate the mode of ecological environment protection and comprehensively improve the ecological environment.
24 February 2022	Inner Mongolia Autonomous Region Committee and Government	Ecological protection and high-quality development planning of the Yellow River Basin in Inner Mongolia Autonomous Region	Inner Mongolia will unswervingly follow a new path of high-quality development oriented by ecological priority and green development, and strive to achieve high-level protection in high-quality development and promote high-quality development in high-level protection.
6 May 2022	Shaanxi Provincial Party Committee and Government	Ecological protection and high-quality development planning of the Yellow	Shaanxi will accelerate the green transformation and development of the river basin, and make the Wei he

(Continued)

Table 1. (continued)

Time	Source	Document	Related content
		River Basin in Shaanxi Province	River a 'benchmark river' for ecological protection in the Yellow River basin.

Note: The 'CPC Central Committee' refers to the Central Committee of the Communist Party of China.

that the basin faces economic problems, including the issue of governance and people's livelihoods.

Materials and methods

Study motivation

We first reviewed previous literature and summarised government reports and guiding documents related to the Yellow River basin. Next, we determined our research method, constructed an econometric model and analysed the variables and data required for the study before, conducting statistical analysis. Finally, we developed specific policy recommendations based on our results. Our research framework is shown in Figure 1.

The possible contribution of our article to existing theory is mainly twofold.

On one hand, we combine the strong sustainability theory and TFP theory in order to advance green TFP towards ecological TFP in consideration of the following concepts. First, when neoclassical economists introduced technological progress into the production function, they found that the key element of economic growth is the rate of technological progress (TFP). Second, weak sustainable development paradigm, argues that natural and man-made capital are interchangeable and that the limits of economic growth can be overcome through technological progress and innovation. The strong sustainable development view emphasises the hard constraint and irreplaceability of natural capital and argues that economic growth cannot exceed the carrying capacity of the ecological environment. Finally, existing research incorporates energy and environment as input or output variables into the research framework of TFP, promoting a shift from traditional to green TFP. We construct more comprehensive ecological and environmental indicators based on strong sustainable development theory, highlighting the non-decreasing development of environmental welfare and the irreplaceability of key natural capital, in a move towards ecological TFP.

On the other hand, we seek solutions to the current problems facing the development of the Yellow River basin. The Yellow River basin has entered late-stage industrialisation. With rapid economic growth and continuous city expansion, the area faces tighter resource constraints, serious environmental pollution and ecosystem damage. The ecological environment of the Yellow River basin is fragile and the economic development is relatively behind. We put forward an ecological TFP model in
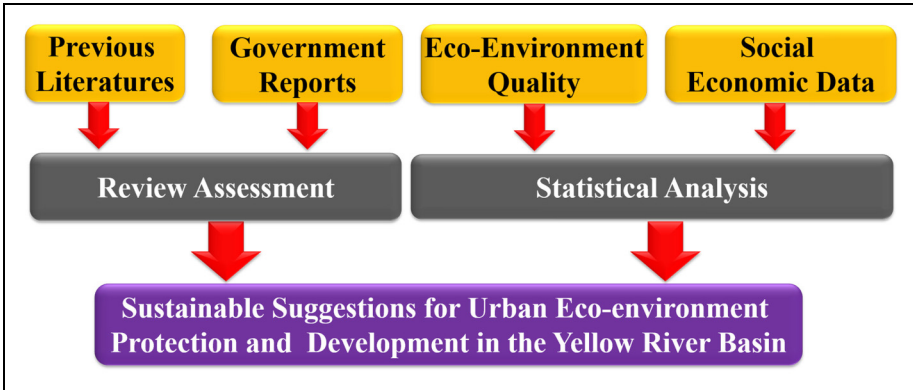
Figure 1. Research framework.

consideration of both factors to discuss how to carry out sustainable development in the Yellow River basin.

Methodology

Ecological environment evaluation method. Taking 2003 as the base period, we first standardised the original data using the fixed base efficiency coefficient method, then applied vertical and horizontal grading to determine basic indicator weights,[34] and finally used linear weighting to calculate the index of urban ecological environment quality in the Yellow River basin.

We used formula (1) to process the original data:

$$
s_{ij}(t_k) = \begin{cases} \dfrac{\max[x_j(t_0)] - x_{ij}(t_k)}{\max[x_j(t_0)] - \min[x_j(t_0)]} & x_j \text{ is a negative indicator} \\[2ex] \dfrac{x_{ij}(t_k) - \min[x_j(t_0)]}{\max[x_j(t_0)] - \min[x_j(t_0)]} & x_j \text{ is a positive indicator} \end{cases} \tag{1}
$$

where $x_{ij}(t_k)$ and $s_{ij}(t_k)$ represent the original and standardised values of the jth index of the ith city in the t_k year, respectively, and $max[x_j(t_0)]$ and $min[x_j(t_0)]$ represent the maximum and minimum values of the jth index of all cities in the base period, respectively.

Second, we estimated the objective weight coefficient ω. If the set of objects to be evaluated is $s = \{ s_1, s_2, \ldots s_n \}$, the evaluation function of year t_k is

$$
y_i(t_k) = \sum_{j=1}^{m} \omega_j X_{ij}(t_k), \, k = 1, 2, \ldots N, \, i = 1, 2 \ldots n \tag{2}
$$

where $\omega = (\omega_1, \omega_2, \ldots \omega_m)^T$ is the weight coefficient vector. The specific formula to describe the difference between evaluation objects by the sum of the squares of the

total deviations of $y_i(t_k)$ is

$$
\begin{cases}
\delta^2 = \sum_{k=1}^{N}\sum_{i=1}^{n}\big(y_i(t_k) - \bar{y}\big)^2 = \sum_{k=1}^{N}\sum_{i=1}^{n}(y_i(t_k))^2 = \sum_{k=1}^{N}\big[\omega^T H_k \omega\big] = \omega^T \sum_{k=1}^{N} H_k \omega = \omega^T H \omega \\
H = \sum_{k=1}^{N} H_k H_k = A_k^T A_k \\
A_k = \begin{Bmatrix} x_{11}(t_k) & \dots & x_{1m}(t_k) \\ \vdots & \ddots & \vdots \\ x_{n1}(t_k) & \dots & x_{nm}(t_k) \end{Bmatrix}, k = 1, 2, \dots N
\end{cases}
\tag{3}
$$

where H_k is $m \times n$-order symmetric matrix, $k = 1,2,\dots N$.

We prove three conclusions. First, if limited, $\omega^T\omega = 1$ when ω is taken as the maximum eigenvalue for matrix H. When $\lambda_{max}(H)$ corresponds to the characteristic vector, δ^2 takes the maximum and has $\omega^T H \omega = \lambda_{max}(H)$. Second, when $H_k > 0$, $t_k(k = 1,2,\dots N)$, at the time t_k, the order of S_i of the evaluated object obtained by applying the transverse scattered grade method is the same.

Third, the comprehensive assessment index of ecological environment quality can be calculated as follows:

$$
Q_i(t_k) = \sum_{j-1}^{m} \omega_j s_{ij}(t_k)
\tag{4}
$$

where $Q_i(t_k)$ is the assessment index of ecological and environmental quality in the t_k year of the ith city.

Theoretical derivation of ecological TFP. The strong sustainability theory emphasises the irreplaceable nature of key natural capital, such as resources and environment. It requires that the self-purification ability of the environment be constantly improved while damaging the ecological environment to ensure the non-reducibility of total environmental welfare. This article evaluates the overall environmental quality of the Yellow River basin from the two dimensions of ecological construction and ecological damage, and introduces environmental quality into the research framework of TFP. We use environmental construction as the input item and environmental damage as the undesirable output for the research framework of ecological TFP under a strong sustainable perspective.

Using the Cobb–Douglas production function for reference, we define a production function that includes capital (K), labour (L), energy (E) and ecological environment construction (EC):

$$
Y = AK^{\partial_K} L^{\partial_L} E^{\partial_E} EC^{\partial_{EC}}
\tag{5}
$$

wherein A refers to TFP, and ∂_K, ∂_L, ∂_E and ∂_{EC}, respectively, represent the output elasticity of capital, labour, energy and ecological EC. Logarithmic transformation produces

$$
\ln Y_t = \ln A_t + \partial_K \ln K_t + \partial_L \ln L_t + \partial_E \ln E_t + \partial_{EC} \ln EC_t
\tag{6}
$$

Through further differential derivation, capital productivity, labour productivity, energy productivity and ecological EC productivity can be represented by the following equations:

$$\ln\frac{Y_t}{K_t} = \ln A_t + \partial_{L,t}\ln\frac{L_t}{K_t} + \partial_{E,t}\ln\frac{E_t}{K_t} + \partial_{EC,t}\ln\frac{EC_t}{K_t} + \ln\frac{K_t^{\partial_{L,t}+\partial_{E,t}+\partial_{EC,t}+\partial_{K,t}}}{K_t} \tag{7}$$

$$\ln\frac{Y_t}{L_t} = \ln A_t + \partial_{K,t}\ln\frac{K_t}{L_t} + \partial_{E,t}\ln\frac{E_t}{L_t} + \partial_{EC,t}\ln\frac{EC_t}{L_t} + \ln\frac{K_t^{\partial_{L,t}+\partial_{E,t}+\partial_{EC,t}+\partial_{K,t}}}{L_t} \tag{8}$$

$$\ln\frac{Y_t}{E_t} = \ln A_t + \partial_{K,t}\ln\frac{K_t}{E_t} + \partial_{E,t}\ln\frac{L_t}{E_t} + \partial_{EC,t}\ln\frac{EC_t}{E_t} + \ln\frac{E_t^{\partial_{K,t}+\partial_{L,t}+\partial_{EC,t}+\partial_{E,t}}}{E_t} \tag{9}$$

$$\ln\frac{Y_t}{EC_t} = \ln A_t + \partial_{K,t}\ln\frac{K_t}{EC_t} + \partial_{L,t}\ln\frac{L_t}{EC_t} + \partial_{EC,t}\ln\frac{E_t}{EC_t} + \ln\frac{EC_t^{\partial_{K,t}+\partial_{L,t}+\partial_{E,t}+\partial_{EC,t}}}{EC_t} \tag{10}$$

Factor productivity growth can be decomposed into changes in factor density and output elasticity. After summing up equations (7) to (10), we obtain

$$\ln\frac{Y_t}{K_t}+\ln\frac{Y_t}{L_t}+\ln\frac{Y_t}{E_t}+\ln\frac{Y_t}{EC_t} = 4\ln A_t + \partial_{K,t}\ln\frac{K_t^3}{L_tE_tEC_t} + \partial_{L,t}\ln\frac{L_t^3}{K_tE_tEC_t} + \partial_{E,t}\ln\frac{E_t^3}{K_tL_tEC_t}$$

$$+ \partial_{EC,t}\ln\frac{EC_t^3}{K_tL_tE_t} + \ln\frac{(K_tL_tE_tEC_t)^{\partial_{K,t}+\partial_{L,t}+\partial_{E,t}+\partial_{EC,t}}}{K_tL_tE_tEC_t} \tag{11}$$

Further simplifying the dynamic changes of ecological TFP growth and subfactor productivity growth produces

$$\ln A_t = \frac{1}{4}(\ln\frac{Y_t}{K_t}+\ln\frac{Y_t}{L_t}+\ln\frac{Y_t}{E_t}+\ln\frac{Y_t}{EC_t}) - \frac{1}{4}(\partial_{K,t}\ln\frac{K_t^3}{L_tE_tEC_t} + \partial_{L,t}\ln\frac{L_t^3}{K_tE_tEC_t}$$

$$+ \partial_{E,t}\ln\frac{E_t^3}{K_tL_tEC_t} + \partial_{EC,t}\ln\frac{EC_t^3}{K_tL_tE_t}) - \frac{1}{4}\ln\frac{(K_tL_tE_tEC_t)^{\partial_{K,t}+\partial_{L,t}+\partial_{E,t}+\partial_{EC,t}}}{K_tL_tE_tEC_t} \tag{12}$$

In equation (12), the left-hand side represents the growth of ecological TFP, the first item on the right represents the sum of the growth of subfactor productivity, the second item on the right represents the mismatch value between subfactor productivity under the framework of ecological TFP and the third item on the right represents the output elasticity heterogeneity of subfactor productivity. When the output elasticity of subfactor productivity in the second mismatch value on the right is equal, the composition relationship between ecological TFP and subfactor productivity can be depicted, identifying the growth of ecological TFP in a strong sustainable perspective. From this simplification, we obtain

$$\ln A_t = \frac{1}{4}(\ln\frac{Y_t}{K_t}+\ln\frac{Y_t}{L_t}+\ln\frac{Y_t}{E_t}+\ln\frac{Y_t}{EC_t}) + \ln\frac{K_t^{1/4}L_t^{1/4}E_t^{1/4}EC_t^{1/4}}{K_t^{\partial_K}L_t^{\partial_L}E_t^{\partial_E}EC_t^{\partial_{EC}}} \tag{13}$$

Equation (13) shows that the growth of ecological TFP can be decomposed into the items on the right-hand side of the equation. The first part on the right of the equation signifies the growth of subitem factor productivity and the second part reflects the degree of heterogeneity of ecological TFP in the period. The subelements cannot be completely replaced by other elements. Only when the output elasticity of the subelements is consistent do the ecological TFP and the subelement productivity reach a balanced configuration state.

Ecological TFP measurement model. Based on strong sustainability theory, we evaluated the ecology and integrated the comprehensive evaluation index of ecological and environmental quality from a strong sustainability perspective into an analysis framework to build the ecological TFP index.

Supposing N decision-making units, and each decision-making unit is put into m types of factors to generate s types of outputs in period T, then one decision-making unit j uses the ith input and obtains r outputs in period t, which can be expressed as x_{ij}^t and y_{rj}^t. If the production frontier is constructed, the production decision-making planning of unit o in period t is

$$\vec{M}_t(x^t, y^t) = \max \frac{1}{m}(\beta_1 + \cdots + \beta_m) \tag{14}$$

$$s.t \begin{cases} \sum_{j=1}^{n} \lambda_j x_{ij}^t \leq x_{io}^t(1 - \beta_i) \\ \sum_{j=1}^{n} \lambda_j y_{rj}^t \geq y_{ro}^t \\ \lambda_j \geq 0, \beta_j \geq 0 \end{cases} \tag{15}$$

According to Chambers (1996), the intertemporal *MIL* is defined as

$$MIL_t^{t+1} = \frac{1}{2}\{[(\vec{M}_T(T) - \vec{M}_T(T+1)) + (\vec{M}_{T+1}(T) - \vec{M}_{T+1}(T+1))]\} \tag{16}$$

wherein $\vec{M}_T(T)$, $\vec{M}_{T+1}(T+1)$, respectively, indicate the redundancy degree of the investment in phases T and $T+1$ under the current production boundary; $\vec{M}_T(T+1)$ and $\vec{M}_{T+1}(T)$ denote the redundancy degree of phase $T+1$ and phase T inputs under the production boundary of phases T and $T+1$, respectively.

With reference to the decomposition concept of Chambers et al.,[35] we build the modified input-oriented Luenberger productivity index (*MIL*), and allow the *MIL* productivity index to decompose into ecological efficiency change (*MILEC*) and technological progress change (*MILTC*):

$$MILEC_t^{t+1} = \vec{M}_T(T) - \vec{M}_{T+1}(T+1) \tag{17}$$

$$MILTC_t^{t+1} = \frac{1}{2}\{[\vec{M}_{T+1}(T+1) - \vec{M}_T(T+1)] + [\vec{M}_{T+1}(T) - (\vec{M}_T(T)]\} \tag{18}$$

The input factors include physical capital, human capital, energy input and eco-environmental construction. The input-oriented directional distance functions of K,

L, E and EC can be constructed separately. MIL_T^{T+1} can measure the productivity of each single factor according to the type of input factors, as shown in equations (19), (20), (21) and (22):

$$MIL_{K,t}^{t+1} = \frac{1}{2}\{[(\vec{M}_{K_T}(T) - \vec{M}_{K_T}(T+1)) + (\vec{M}_{K_{T+1}}(T) - \vec{M}_{K_{T+1}}(T+1))]\} \quad (19)$$

$$MIL_{L,t}^{t+1} = \frac{1}{2}\{[(\vec{M}_{L_T}(T) - \vec{M}_{L_T}(T+1)) + (\vec{M}_{L_{T+1}}(T) - \vec{M}_{L_{T+1}}(T+1))]\} \quad (20)$$

$$MIL_{E,t}^{t+1} = \frac{1}{2}\{[(\vec{M}_{E_T}(T) - \vec{M}_{E_T}(T+1)) + (\vec{M}_{E_{T+1}}(T) - \vec{M}_{E_{T+1}}(T+1))]\} \quad (21)$$

$$MIL_{EC,t}^{t+1} = \frac{1}{2}\{[(\vec{M}_{EC_T}(T) - \vec{M}_{EC_T}(T+1)) + (\vec{M}_{EC_{T+1}}(T) - \vec{M}_{EC_{T+1}}(T+1))]\} \quad (22)$$

$\vec{M}_T(T)$ is the arithmetic mean of all input factor distance functions $\vec{M}_{iT}(T)$; thus, ecological TFP index MIL_T^{T+1} has the following ' total-separate' logical relationship with $MIL_{K,t}^{t+1}$, $MIL_{L,t}^{t+1}$, $MIL_{E,t}^{t+1}$ and $MIL_{EC,t}^{t+1}$:

$$MIL_t^{t+1} = \frac{MIL_{K,t}^{t+1} + MIL_{L,t}^{t+1} + MIL_{E,t}^{t+1} + MIL_{EC,t}^{t+1}}{4} \quad (23)$$

Spatial panel model. We investigated the influencing factors and spatial effects of ecological TFP in the Yellow River basin. The spatial econometric model is very sensitive to spatial weight matrix selection; therefore, based on theoretical analysis, we primarily selected the spatial weight matrices of urban geographical adjacency (W_1) and economic distance (W_2) to examine the robustness of the spatial model's empirical results. W_1 is the binary adjacency spatial weight matrix. $W_1 = 1$ when two cities are geographically adjacent, and 0 otherwise. W_2 is weighted by the reciprocal of annual absolute difference between the per capita gross domestic product (GDP) of city i and of city j.

We used the spatial Durbin model (SDM) to capture the spatial correlation of ecological TFP in the Yellow River basin caused by regional interaction. Following Lesage and Pace,[36] we set the static SDM as follows:

$$M_{it} = \alpha_0 + \alpha_2 FD_{it} + \alpha_3 X_{it} + \beta_1 \sum_{i=1}^{n} W_{it} M_{it} + \beta_2 \sum_{i=1}^{n} W_{it} FD_{it} + \beta_3 \sum_{i=1}^{n} W_{it} X_{it} + \varepsilon_{it}$$
$$+ \lambda_{it} + \mu_{it} \quad (24)$$

We set the dynamic SDM as follows:

$$M_{it} = \theta_0 + \theta_1 M_{it-1} + \theta_2 FD_{it} + \theta_3 X_{it} + {}_1\sum_{i=1}^{n} W_{it} M_{it} + {}_2\sum_{i=1}^{n} W_{it} FD_{it} + {}_3\sum_{i=1}^{n} W_{it} X_{it}$$
$$+ \varepsilon_{it} + \lambda_{it} + \mu_{it} \quad (25)$$

where subscripts i and t represent city and year, respectively; W is the selected spatial weight matrix. α_1, α_2, α_3 and θ_1, θ_2, θ_3 are the estimation coefficients of static SDM

and dynamic SDM, respectively; and β_1, β_2, β_3 and σ_1, σ_2, σ_3 are the spatial interaction term coefficient of the corresponding variable. M_{it} is the explained variable, which represents the ecological TFP (MIL_{it}) and its decomposition terms ($MILEC_{it}$, $MILTC_{it}$). Fiscal decentralisation (FD) is the core explanatory variable. M_{it-1} represents the first-order lag term of the ecological TFP (MIL_{it-1}) and its decomposition terms ($MILEC_{it-1}$, $MILTC_{it-1}$) for each city and serves as the core explanatory variable of the dynamic SDM. X_{it} refers to relevant control variables used to control other exogenous factors that affect ecological TFP and its decomposition. ϵ_{it} is a random error term. λ_{it} and μ_{it} refer to individual and time fixed effects, respectively, which we used to capture the impact of unobservable factors and macro policy shocks on ecological TFP and its decomposition.

Research data

Input and output variables. Regarding physical capital (K), the capital stock was estimated using the perpetual inventory method with 2003 as the base period.[37] The calculation formula is as follows:

$$K_{it} = K_{it-1}(1 - \delta) + I_{it} / P_{it} \qquad (26)$$

where I_{it} is the current investment of the ith city in the tth year, and the actual fixed asset investment in the current year is used as the annual data of investment, P_{it} is the price index of fixed asset investment in the tth year, and the depreciation rate δ is 9.6%.

To characterise human capital (L), we used employed persons in urban units. For energy input (E), energy consumption is expressed by the total amount of urban electricity consumption. For the eco-environmental construction index (EC), we adopted 13 indicators to measure the level of eco-environmental construction from the self-purification ability of the ecosystem and eco-environmental governance. For the desired output (GDP), we took 2003 as the base period, used cities' real GDP. For the undesirable output (ED), we measured the degree of ecological environment damage from water resource consumption and air, water and solid pollution, including 11 indices. EC and ED were calculated using the vertical and horizontal scatter grade method.

We built a comprehensive evaluation system of the ecological environment of the Yellow River basin. Table 2 shows the specific evaluation indicators and weights.

Dependent variable. MIL, MILEC and MILTC were the explained variables, representing the ecological TFP growth rate of cities in the Yellow River basin.

Independent variable. FD was the independent variable. In the Yellow River basin, FD is reflected in the biased investment of different local governments, which has a significant impact on the construction of ecological civilisation and improvement of ecological TFP.

Control variables. We controlled for several variables. (ER) reflected the strength of local government restrictions on polluting industries and environmental management.[41] For industrial

Table 2. Evaluation index system of ecological environment quality in the Yellow River basin.

Dimension	Criterion	Specific index	Unit	Type	Weight
Ecological environment construction index	Self-purification of ecological environment	Total water resources	100 million m^3	+	0.004
		Annual rainfall[38]	ml	+	0.032
		Annual average temperature	°C	+	0.049
		Annual sunshine hours	hour	+	0.035
		Per capita green area[39]	m^2/person	+	0.013
	Ecological environment governance	Industrial sulfur dioxide removal	10,000 tons	+	0.015
		Industrial dust removal	10,000 tons	+	0.007
		Industrial wastewater discharge reaches scalar	10,000 tons	+	0.015
		Comprehensive utilisation rate of industrial solid waste	%	+	0.050
		Urban domestic sewage treatment rate	%	+	0.053
		Harmless treatment rate of domestic waste	%	+	0.061
		Proportion of environmental protection and water conservancy management personnel	%	+	0.016
		Output value of products of comprehensive utilisation of three waste types	10,000 yuan	+	0.010
Ecological environment damage index	Water resource consume	Ecological water consumption	100 million m^3	−	0.062
		Domestic water consumption	100 million m^3	−	0.066
		Production water consumption[40]	100 million m^3	−	0.050
	Air pollution	PM2.5 concentration	micrograms / m^3	−	0.041
		Industrial NOx emissions	10,000 tons	−	0.061
		Industrial sulphur dioxide emissions	10,000 tons	−	0.058
		Industrial smoke emission	10,000 tons	−	0.063
	Water pollution	Industrial wastewater discharge	10,000 tons	−	0.061

(Continued)

Table 2. (continued)

Dimension	Criterion	Specific index	Unit	Type	Weight
		Domestic wastewater discharge	10,000 tons	—	0.060
	Solid pollution	Production of industrial solid waste	10,000 tons	—	0.060
		Domestic waste removal volume	10,000 tons	—	0.058

structure (*IND*), if the development of the tertiary industry-added value is at its peak, and the pollution-added value is smaller than that of industry, it can promote *MIL*. We found that financial development (*FIN*) resulted in an expanded enterprise scale, which in turn stimulated large energy consumption demand. However, FIN can also promote a service-oriented and clean IND, thereby improving *MIL*.[42] Regarding urbanisation level (*URB*), from the perspective of unexpected output, the urbanisation process creates domestic pollutant emissions, leading to the deterioration of the environment. However, increased environmental demand, infrastructure improvement and urban development mode transformation can promote *MIL*. For opening level (*OPEN*), the 'pollution refuge' hypothesis posits that foreign capital causes environmental quality deterioration due to highly polluting enterprises. Conversely, the 'pollutant paradise' hypothesis argues that attracting foreign investment will bring environmentally friendly products and technological progress, thereby improving *MIL* in the inflow area.[43] The higher the level of research and development investment (*RD*), the faster the technological progress and the higher the *MIL* growth rate. The greater the population density (*POP*), the fewer per capita resources in the region, the weaker the environmental carrying capacity and the easier the formation of pollution accumulation; thus, higher *POP* may negatively impact *MIL*.

Table 3 provides the specific calculation methods and data sources of the regression variables.

Data description

We selected panel data from 78 cities in the Yellow River basin between 2003 and 2019. The data for each indicator was collected from the Urban Statistical Yearbooks of cities in the Yellow River basin (2004–2020) and China Urban Statistical Yearbook (2004–2020). Some missing data was supplemented by the Wind Database and the yearbooks and Statistical Bulletins of various cities. Table 4 shows descriptive statistics for each variable.

Spatial–temporal evolution of ecological TFP in the Yellow River basin

According to the authoritative programmatic document 'Outline of ecological protection and high-quality development planning of the Yellow River Basin', our study objects were 78 prefecture-level cities in 9 provinces and the regions of Qinghai, Sichuan, Gansu, Ningxia, Inner Mongolia, Shanxi, Shaanxi, Henan and Shandong through

Table 3. Definitions of variables and data sources.

Variable	Definition	Source
GDP	Economic growth: cities' real GDP	CUSY
ED	Ecological environment damage: cities' eco-environment damage index	Calculation
K	Physical capital: estimated using 'perpetual inventory method'	Calculation
L	Human capital: employed persons in urban units	CUSY
E	Energy input: annual total urban electricity consumption	USY
EC	Ecological environment construction: cities' eco-environment construction index	Calculation
MIL	Modified Input-oriented Luenberger productivity indicator: ecological total factor productivity of cities in the Yellow River Basin	Calculation
FD	Fiscal decentralisation: urban annual per capita fiscal expenditure / (urban annual per capita fiscal expenditure + national annual per capita fiscal expenditure)	Wind Database
ER	Environmental regulation: urban pollution treatment cost / cities' added value of secondary industry	Wind Database
IND	Industrial structure: cities' tertiary sector value added/ cities' GDP	CUSY
FIN	Financial development: balance of deposits and loans of financial institutions / cities' GDP	USY
URB	Urbanisation level: size of cities' urban population / total population	CUSY
OPEN	Opening level of cities: total foreign direct investment / cities' GDP	USY
RD	Research and development investment: cities' R&D investment / cities' GDP	CUSY
POP	Population density: total cities' annual average / total urban area	USY

Notes: Calculation: Calculated by vertical and horizontal scatter grade method, CUSY: China Urban Statistical Yearbook, USY: Urban Statistical Yearbooks of cities in the Yellow River basin. For the data used in this study, the timeframe was from 2003 to 2019.

which flow the trunk and tributaries of the Yellow River. Among them, Xining, Haidong, Haibei, Hainan, Huangnan, Haixi, Yushu, Guoluo, Aba, Ganzi, Lanzhou, Jinchang, Baiyin, Tianshui, Wuwei, Zhangye, Pingliang, Jiuquan, Qingyang, Dingxi, Longnan, Yinchuan, Shizuishan, Wuzhong, Guyuan and Zhongwei are in the upstream region. Xi'an, Tongchuan, Baoji, Xianyang, Weinan, Yan'an, Yulin, Ankang, Shangluo, Taiyuan, Datong, Yangquan, Changzhi, Jincheng, Shuozhou, Jinzhong, Yuncheng, Xinzhou, Linfen, Luliang, Hohhot, Baotou, Wuhai, Ordos, Bayannaoer and Wulanchabu are in the midstream region. Jinan, Qingdao, Zibo, Zaozhuang, Dongying, Yantai, Weifang, Jining, Tai'an, Linyi, Dezhou, Liaocheng, Binzhou, Heze, Zhengzhou, Kaifeng, Luoyang, Pingdingshan, Anyang, Hebi, Xinxiang, Jiaozuo, Puyang, Xuchang, Luohe and Sanmenxia are in the downstream region.

Ecological TFP and decomposition items

We used MAXDEA 8 Ultra® to measure *MIL*, *MILEC* and *MILTC* for cities in the Yellow River basin between 2003 and 2019. Then, we totalled the data for the cities in the upper, middle and lower reaches (Table 5).

From 2003 to 2019, the ecological TFP of cities in the Yellow River basin showed an overall positive growth trend, with an average annual growth of 0.627%, cumulative

Table 4. Descriptive statistics of variables.

Variable	Obs	Mean	SD	Min	Max
GDP	1326	972.037	1109.166	33.182	7738.417
ED	1326	0.654	0.069	0.546	0.889
K	1326	3510.166	4350.057	156.757	33430.68
L	1326	38.446	41.815	4.841	207.555
E	1326	962.448	919.089	1.806	7550.552
EC	1326	0.340	0.042	0.181	0.428
MIL	1326	0.101	0.029	−0.035	0.226
L1_MIL	1248	0.100	0.029	−0.035	0.226
MILEC	1326	0.021	0.009	−0.068	0.108
L1_MILEC	1248	0.021	0.009	−0.068	0.108
MILTC	1326	0.081	0.021	−0.008	0.162
L1_MILTC	1248	0.080	0.021	−0.008	0.162
FD	1326	0.458	0.139	0.004	0.855
ER	1326	0.044	0.050	0.005	0.401
IND	1326	0.372	0.101	0.114	0.687
FIN	1326	2.219	1.201	0.508	11.173
URB	1326	0.345	0.172	0.096	0.831
OPEN	1326	0.124	0.156	0.0001	0.209
RD	1326	0.147	0.205	0.008	0.631
POP	1326	3.690	3.054	0.500	14.400

EC: environment construction; ER: environmental regulation; FD: fiscal decentralisation; GDP: gross domestic product; IND: industrial structure; FIN: financial development; MIL: modified input-oriented Luenberger productivity index; MILEC: *MIL* productivity index to decompose into ecological efficiency change; MILTC: *MIL* productivity index to decompose into ecological efficiency change and technological progress change; OPEN: opening level; POP: population density; RD: research and development; URB: urbanisation level.

growth of 10.032%, average annual growth of 0.018% for changes in ecological efficiency, cumulative growth of 0.306%, average annual growth of 0.609% for technological progress and overall cumulative growth of 10.353%. For ecological TFP (*MIL*), the distribution characteristics indicated that downstream cities (0.751) were larger than midstream (0.611) and upstream cities (0.520). From the perspective of ecological efficiency (*MILEC*), downstream cities (0.032) were larger than upstream (0.014) and midstream cities (0.008). Finally, from the perspective of scientific and technological progress (*MILTC*), we observed an evolutionary pattern in which downstream cities (0.719) were greater than midstream (0.603) and upstream (0.505) cities.

As shown in Figure 2, the urban ecological TFP in the Yellow River basin displayed a continuous growth trend, in which technological progress was the main driving force. The change and improvement trend for ecological efficiency was obvious, which further promoted ecological TFP growth. From 2003 to 2010, *MIL* grew rapidly. After 2010, the ecological TFP growth rate in the entire basin showed a W-type cyclical fluctuation upward trend. The periodic improvement of technological progress was the main driving force, reflecting that policy adjustments in sustainable development strategy could have significant effects. The open economic development of cities in the Yellow River basin has released the dividends of policy and system reform, and technology

Table 5. Urban ecological TFP and its decomposition items in the upper, middle and lower reaches of the Yellow River basin (%).

Year	MIL				MILEC				MILTC			
	Whole Basin	Up stream	Mid stream	Down stream	Whole basin	Up stream	Mid stream	Down stream	Whole basin	Up stream	Mid stream	Down stream
2003	0.537	0.450	0.516	0.646	0.026	0.025	0.005	0.049	0.511	0.425	0.511	0.597
2004	0.535	0.449	0.496	0.660	−0.004	−0.007	−0.023	0.017	0.540	0.457	0.519	0.643
2005	0.579	0.511	0.551	0.674	0.019	0.015	0.012	0.030	0.560	0.495	0.540	0.644
2006	0.601	0.523	0.562	0.719	0.015	0.038	−0.006	0.012	0.586	0.485	0.568	0.706
2007	0.625	0.481	0.620	0.772	0.015	0.007	0.004	0.034	0.610	0.475	0.617	0.738
2008	0.629	0.510	0.580	0.798	0.017	0.006	0.011	0.035	0.612	0.504	0.569	0.763
2009	0.641	0.546	0.602	0.773	0.010	0.001	−0.003	0.031	0.631	0.545	0.605	0.742
2010	0.645	0.548	0.613	0.774	0.017	0.032	0.008	0.012	0.627	0.516	0.604	0.762
2011	0.599	0.432	0.621	0.745	0.013	−0.017	0.018	0.038	0.586	0.449	0.603	0.707
2012	0.610	0.500	0.625	0.705	0.014	0.009	0.014	0.021	0.596	0.491	0.612	0.684
2013	0.679	0.603	0.675	0.760	0.008	0.008	0.008	0.008	0.671	0.595	0.667	0.752
2014	0.634	0.527	0.601	0.775	0.015	0.013	0.000	0.031	0.620	0.514	0.601	0.744
2015	0.631	0.507	0.627	0.759	0.011	0.003	0.005	0.026	0.620	0.504	0.623	0.733
2016	0.659	0.533	0.677	0.767	0.022	0.019	0.022	0.024	0.637	0.514	0.655	0.743
2017	0.683	0.501	0.673	0.877	0.063	0.035	0.032	0.122	0.621	0.466	0.641	0.754
2018	0.678	0.562	0.693	0.779	0.021	0.012	0.033	0.017	0.657	0.549	0.660	0.762
2019	0.697	0.657	0.656	0.777	0.025	0.048	−0.001	0.028	0.672	0.609	0.657	0.749
Mean value	0.627	0.520	0.611	0.751	0.018	0.014	0.008	0.032	0.609	0.505	0.603	0.719

MIL: modified input-oriented Luenberger productivity index; MILEC: *MIL* productivity index to decompose into ecological efficiency change; MILTC: *MIL* productivity index to decompose into ecological efficiency change and technological progress change; TFP: total factor productivity.
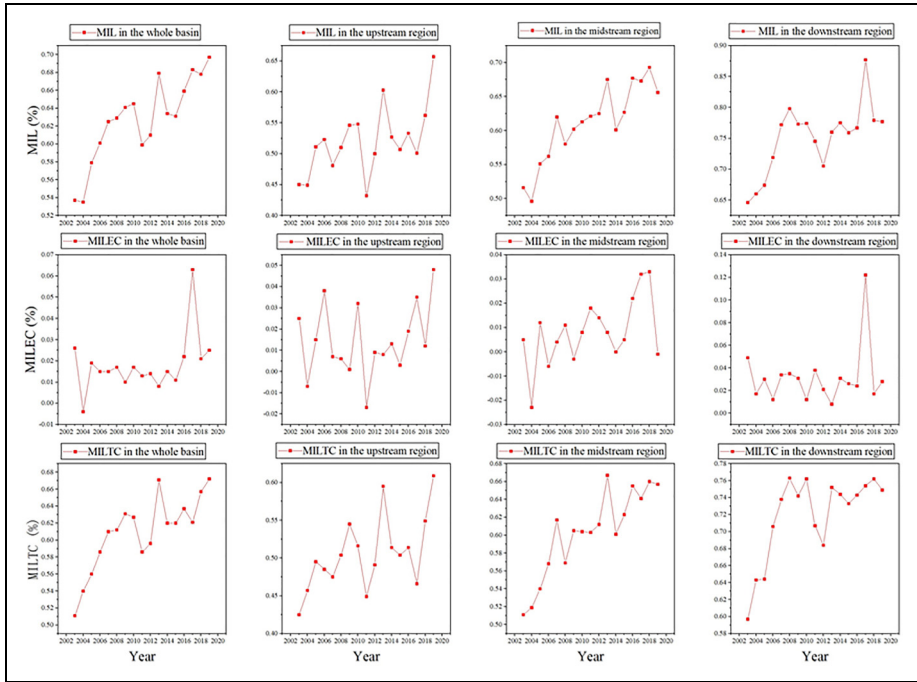
Figure 2. Evolution of urban ecological total factor productivity (TFP) and its decomposition terms in the upper, middle and lower reaches of the Yellow River basin.

transfer and diffusion have promoted rapid industrial expansion. Technological progress showed a fluctuating growth rate, while ecological efficiency improved relatively slowly.

Time evolution

We used ArcGIS 10® to draw a *MIL* distribution map. Figure 3 (a) to (d) shows the changing trend of *MIL* in the Yellow River basin in 2003, 2011 and 2019 and the mean value. The *MIL* of the Yellow River basin was divided into four categories from low to high. The darker the red shading, the higher the year's *MIL*. The *MIL* data is based on the manual calculations.

Figure 3 shows temporal evolution maps of the *MIL* in Yellow River basin. In 2003, the *MIL* index of urban agglomeration in the upstream and downstream regions were the highest These regions benefited from high ecological endowment in the upper reaches and strong economic foundation in the lower reaches. In 2011, the *MIL* index in the midstream region of Inner Mongolia began to improve because its energy endowment brought large benefits to promote ecological TFP improvement. In 2019, the *MIL* indices of cities in the midstream region of Shaanxi and downstream region of Shandong were the highest, owing to the absolute advantage of scientific and technological innovation strength in those cities.
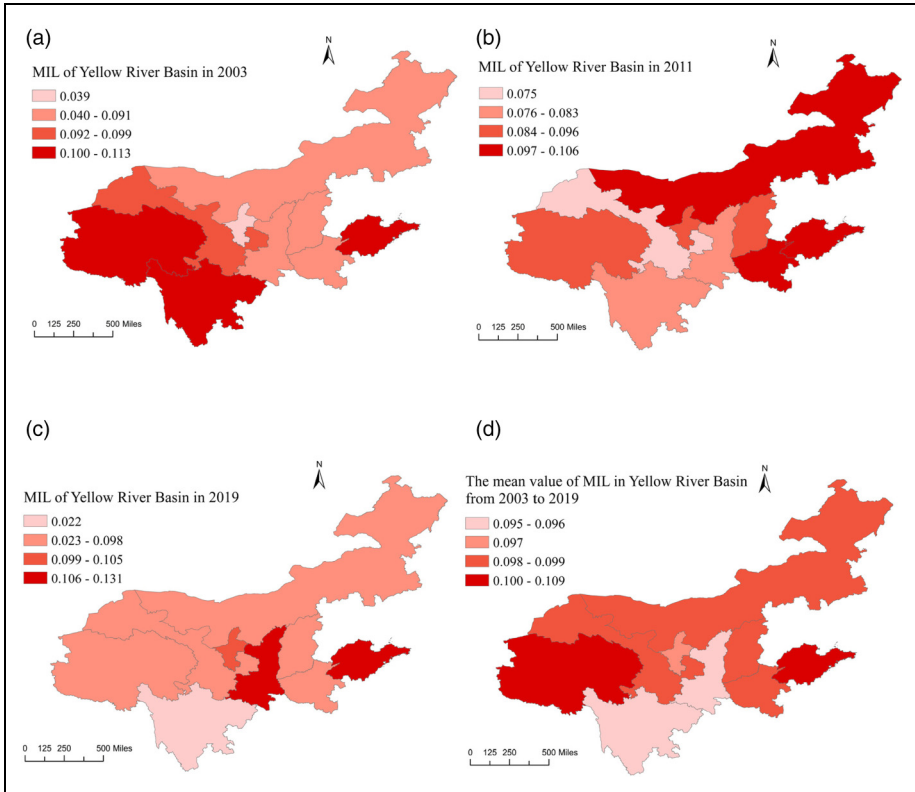
Figure 3. Temporal evolution maps of modified input-oriented Luenberger productivity index (*MIL*) in the Yellow River basin: (a) *MIL* distribution map 2003, (b) *MIL* distribution map 2011, (c) *MIL* distribution map 2019 and (d) *MIL* mean value map 2003–2019.

Combined with the results in Table 5, we can conclude from the average *MIL* value between 2003 and 2019 that the average *MIL* values for cities in Shandong and Qinghai were the highest, reaching 0.109 and 0.103, respectively. Average *MILEC* was highest in cities in Shandong and Qinghai, with both at 0.0531. Average *MILTC* was highest for cities in Shandong. These findings reflect that the *MIL* index was the most sensitive to ecological effects and technological progress.

Spatial evolution

We used MATLAB R 2021® to create a kernel density distribution map of *MIL* in the entire basin and upstream, midstream and downstream regions between 2003 and 2019. Figure 4 (a) illustrates the main peak of the *MIL* index in cities across all regions was skewed left in the distribution. The bandwidth distribution was left-tailed and slightly expanded. The *MIL* index for cities in the Yellow River basin generally showed a fluctuating growth trend between 2003 and 2019, with an apparent extreme

value effect. These results reflect that central and provincial capital cities occupy an absolutely dominant position in the investment of resources, such as the economy, science and technology, human resources and ecological EC. The siphon effect was evident; their ecological TFP continuously maintained a leading trend.

Figure 4 (b), (c) and (d) shows the main peak of *MIL* in the upstream region had a small, rapid increasing trend and fluctuated in stages. An evident upward trend was observed for 2003–2019; the gap between high- and low-*MIL* cities gradually narrowed. The main peak of *MIL* in the midstream region ended with a shift to the left after a small range. This primarily manifested in a slight decline between 2003 and 2006, and an increase between 2006 and 2017 as the bandwidth continued shrinking from a left-tailing
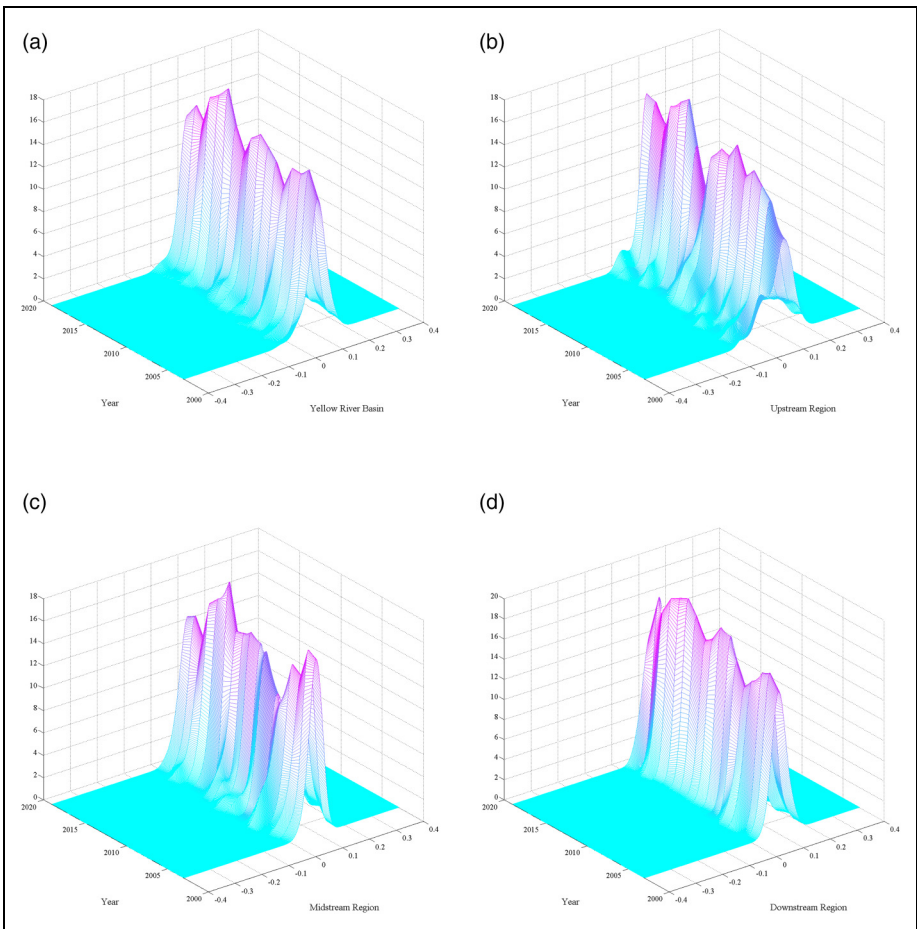

Figure 4. Spatial evolution maps of modified input-oriented Luenberger productivity index (*MIL*) in Yellow River basin: (a) Whole basin, (b) upstream region, (c) midstream region and (d) downstream region.

trend and ductility decreased. The downstream region exhibited a right-tailing phenomenon and ductility increased. *MIL* in the region was relatively stable; cities with high *MIL* expanded their regional differences, but cities with low *MIL* experienced a 'catch-up effect', and the interregional differences narrowed.

Empirical results and discussion

Global spatial autocorrelation measure

The analysis results shown in Table 6 indicate that the global Moran's I index of ecological TFP in the Yellow River basin from 2003 to 2019 was all positive. All years were significant at the 1% level, indicating a strong spatial correlation effect of ecological TFP in cities in the Yellow River basin, with a significant degree of agglomeration. Further analysis showed that the agglomeration degree fluctuated over time.

Dynamic spatial panel regression analysis

Regression analysis of ecological TFP. To determine whether spatial interaction effects occur in a model, Burridge[44] and Anselin et al.[45] proposed the Lagrange multiplier (LM) test method to examine spatial lag-explained variables and error correlation. We then used the LM test method. The LM spatial lag, robust LM spatial lag, LM spatial error and robust LM spatial error of both the and dynamic SDM all rejected the original assumption of a spatial correlation between the model lag term and the error term. Therefore, it was reasonable to adopt the dynamic SDM.

Before the regression analysis, we conducted a Hausmann's test of the panel data. The test resulted in a p-value of 0.000, which strongly rejected the null hypothesis and indicated the use of fixed effects. Accordingly, cities and years were fixed in the regression. We used a dynamic SDM for regression analysis. To ensure the robustness of the estimation results, we also used a static SDM to quantitatively identify the influencing factors of ecological TFP in the Yellow River basin. Table 7 shows the relevant estimation results.

Table 6. Moran's I test of ecological total factor productivity in the Yellow River basin (2003–2019).

Year	Moran's I	P-value	Year	Moran's I	P-value
2003	0.581***	0.000	2012	0.205**	0.016
2004	0.585***	0.000	2013	0.318***	0.003
2005	0.425***	0.000	2014	0.325***	0.001
2006	0.539***	0.000	2015	0.319***	0.003
2007	0.538***	0.000	2016	0.318***	0.003
2008	0.358***	0.000	2017	0.354***	0.000
2009	0.327***	0.003	2018	0.293***	0.007
2010	0.202**	0.016	2019	0.315***	0.003
2011	0.289***	0.008			

Note: *, * * and * * * are significant at the 10%, 5% and 1% levels, respectively.

Table 7 shows that the first-order autocorrelation, AR (1), of the residuals was significant at the 1% level. However, neither the second-order autocorrelation, AR (2), nor the Sargan statistic were significant. This supports our original assumption of no excessive identification of instrumental variables.

From the estimation results, *L1_MIL* was significant at the 1% level, indicating path dependence in ecological TFP improvement; it was reasonable to include in the estimation model. Additionally, the estimation results using the geographical adjacency spatial weight matrix (W_1) and the economic distance spatial weight matrix (W_2) were not significantly different from the estimation results of the dynamic SDM. The coefficients of the first-order and spatial lag terms of ecological TFP and the main explanatory variables were significant at least at the 5% level, and the symbols had not changed, indicating that the regression results were robust.

According to the estimation results of the dynamic SDM, the spatial autocorrelation coefficients (ρ) of the geographical adjacency spatial weight matrix (W_1) and economic distance spatial weight matrix (W_2) were 0.197 and 0.610, respectively, and significantly positive at least at the 5% level; this indicated a spatial spillover feature of ecological TFP in the Yellow River basin. Specifically, the *MIL* in this city was closely related to the ecological TFP level in cities with close geographical or economic distance. Under the geographical spatial weight and the economic distance spatial weight, the coefficients of *L1_MIL* were 0.069 and 0.125, respectively, and significantly positive at least at the 10% level, which indicates that the ecological TFP also has time lag. The improvement of the ecological TFP of the adjacent cities in a prior period can promote the improvement of the ecological efficiency of the city in question in the current period.

In the regression results for the dynamic SDM (W_1) and dynamic SDM (W_2), or for every 1% increase in the independent variable *FD*, *MIL* in the current period increases by 0.172% and 0.254%, respectively, which was significant at the 1% level. However, for every 1% increase in *FD* in cities with close geographical proximity and economic distance, *MIL* in this region decreased by 0.102% and 0.022%, respectively. This is due to the siphon effect of adjacent cities. The control variables *IND*, *FIN*, *URB* and *RD* all significantly promoted *MIL*. In contrast, *ER* had an inhibitory effect on *MIL*. All the variables were significant at the 5% levels, except for *OPEN* and *POP*, which also inhibited the *MIL*, but not significantly.

Analysis of direct and indirect effects. To further explore the direct and indirect impact of various factors on ecological TFP, we used the method of Lesage and Pace[36] to decompose the impact of various factors (Table 8).

Under both the geographical adjacency spatial weight matrix (W_1) and economic distance spatial weight matrix (W_2), the direct effect of the core independent variable *FD* on the ecological TFP of the Yellow River basin was significantly positive while, the indirect effect was significantly negative. Furthermore, the negative effect was more significant in geographically adjacent cities. This indicates that local *FD* has a negative spillover effect on the ecological TFP level of surrounding areas. Specifically, with increased *FD*, the siphon effect of ecological TFP in geographically adjacent cities increased, resulting in the decline of ecological TFP in local cities.[46]

Table 7. Regression results of influencing factors for ecological total factor productivity in the Yellow River basin.

Variable	Dynamic SDM (W$_1$)	Dynamic SDM (W$_2$)	Static SDM (W$_1$)	Static SDM (W$_2$)
LI_MIL	0.347***	0.479***	/	/
	(0.077)	(0.067)		
FD	0.172***	0.254***	0.505***	0.397**
	(0.049)	(0.055)	(0.145)	(0.172)
ER	−0.191**	−0.143**	−0.127*	−0.080
	(0.086)	(0.056)	(0.070)	(0.114)
IND	0.017***	0.020**	0.029***	0.030***
	(0.005)	(0.008)	(0.005)	(0.011)
FIN	0.038***	0.042***	0.052***	0.069*
	(0.007)	(0.016)	(0.018)	(0.036)
URB	0.033**	0.024**	0.063***	0.055***
	(0.015)	(0.011)	(0.011)	(0.017)
OPEN	−0.012	−0.016	−0.021	−0.019*
	(0.013)	(0.012)	(0.013)	(0.010)
RD	0.270***	0.295**	0.360***	0.427**
	(0.056)	(0.124)	(0.081)	(0.184)
POP	−0.438	−0.446	−0.669*	−0.622
	(0.439)	(0.377)	(0.371)	(0.653)
W × LI_MIL	0.069**	0.125*	/	/
	(0.027)	(0.065)		
W × FD	−0.102***	−0.022	−0.156	−0.191*
	(0.030)	(0.015)	(0.169)	(0.102)
W × ER	0.121*	0.067***	0.095***	0.118**
	(0.062)	(0.018)	(0.033)	(0.046)
W × IND	0.012**	0.007*	0.245*	0.010***
	(0.005)	(0.004)	(0.123)	(0.002)
W × FIN	0.016	0.026	0.015	0.012
	(0.012)	(0.029)	(0.025)	(0.014)
W × URB	0.015**	0.011**	0.148**	0.157*
	(0.007)	(0.005)	(0.075)	(0.083)
W × OPEN	−0.027***	−0.069***	−0.211***	−0.278*
	(0.004)	(0.024)	(0.035)	(0.146)
W × RD	0.137*	0.211***	0.194*	0.213**
	(0.071)	(0.049)	(0.108)	(0.101)
W × POP	−0.237	−0.064	−0.446	−0.401
	(0.162)	(0.081)	(0.458)	(0.408)
ρ	0.197**	0.610***	0.175**	0.438***
	(0.081)	(0.156)	(0.074)	(0.168)
Adj.R^2	0.542	0.505	0.451	0.460
Sigma2_e	6.370***	6.965***	6.119***	6.505***
	(1.622)	(1.831)	(1.447)	(1.601)
Obs	1248	1248	1248	1248

(Continued)

Table 7. (continued)

Variable	Dynamic SDM (W₁)	Dynamic SDM (W₂)	Static SDM (W₁)	Static SDM (W₂)
Diagnostic test			Value	
Hausman test			43.245***	
AR (1)			−3.211***	
AR (2)			−1.181	
Sargan			23.916	

Notes: *, * * and * * * are significant at 10%, 5% and 1% levels, respectively. Standard errors are shown in parentheses.
ER: environmental regulation; FD: fiscal decentralisation; FIN: financial development; IND: industrial structure; FIN: financial development; MIL: modified input-oriented Luenberger productivity index; OPEN: opening level; POP: population density; SDM: spatial Durbin model; RD: research and development; URB: urbanisation level.

Table 8. Effect decomposition results of various factors.

Variable	Geographical adjacency spatial weight matrix (W₁)			Economic distance spatial weight matrix (W₂)		
	Direct effects	Indirect effects	Total effects	Direct effects	Indirect effects	Total effects
FD	0.174***	−0.060***	0.113***	0.261***	−0.017	0.243
	(0.061)	(0.018)	(0.032)	(0.070)	(0.013)	(0.174)
ER	−0.172*	−0.035**	−0.206***	−0.151**	−0.071***	−0.224***
	(0.102)	(0.017)	(0.069)	(0.066)	(0.018)	(0.080)
IND	0.017***	0.011**	0.028***	0.022**	0.012*	0.035**
	(0.004)	(0.005)	(0.006)	(0.009)	(0.007)	(0.014)
FIN	0.047***	0.008	0.060	0.047***	0.021	0.068*
	(0.009)	(0.015)	(0.050)	(0.016)	(0.017)	(0.037)
URB	0.040**	0.023***	0.066***	0.028*	0.002**	0.031**
	(0.017)	(0.007)	(0.015)	(0.015)	(0.001)	(0.013)
OPEN	−0.014	−0.025***	−0.039*	−0.018	−0.087**	−0.106**
	(0.016)	(0.007)	(0.023)	(0.014)	(0.037)	(0.045)
RD	0.280***	0.090*	0.375***	0.302**	0.154***	0.457**
	(0.042)	(0.051)	(0.073)	(0.114)	(0.043)	(0.196)
POP	−0.448	−0.271	−0.719	−0.456	−0.167	−0.624
	(0.391)	(0.221)	(0.778)	(0.297)	(0.157)	(0.440)

Notes: *, * * and * * * are significant at 10%, 5% and 1% levels, respectively. Standard errors are shown in parentheses.
ER: environmental regulation; FD: fiscal decentralisation; FIN: financial development; IND: industrial structure; FIN: financial development; OPEN: opening level; POP: population density; RD: research and development; URB: urbanisation level.

IND, *FIN*, *URB* and *RD* had significant roles in promoting the improvement of ecological TFP in the region and its geographical and economic adjacent areas. The effects of *ER*, *OPEN* and *POP* on local and surrounding areas was negative, but this was not statistically significant for *POP*.

Regression analysis of decomposition terms of ecological TFP

We introduced the *MIL* index to decompose into *MILEC MILTC*. We further analysed the decomposition terms of ecological TFP and judged their influencing factors.

Before we applied the SDM to *MILEC* and *MILTC*, we first performed the Hausman test on the two panel data sets. The tests resulted in a p-value of 0.000, which strongly rejected the null hypothesis and indicted the use of fixed effects. We then used the LM test method. The LM spatial lag, robust LM spatial lag, LM spatial error and robust LM spatial error of both the and dynamic SDM all rejected the original assumption of a spatial correlation between the model lag term and the error term. Therefore, it was reasonable to adopt the dynamic SDM. Finally, as shown in Tables 9 and 10, the first-order autocorrelation AR (1) of the residuals of these two panel models are significant at the 1% level; second-order autocorrelation AR (2) and Sargan statistics are not significant. This supports our original approach of not over identifying tool variables. We proceeded to analyse the regression results of *MILEC* and *MILTC*.

Regression analysis of ecological efficiency change. As shown in Table 9, *L1_MILEC* was significant at the 5% level; it was reasonable to include it in the estimation model. According to the estimation results of the dynamic SDM, the estimation results using the geographical adjacency spatial weight matrix (W_1) and the economic distance spatial weight matrix (W_2) were not significantly different. The coefficients of the first-order and spatial lag terms of ecological efficiency change and the main explanatory variables were significant at least at the 10% level, and the symbols had not changed, indicating that the regression results were robust.

According to *MILEC* regression estimation results, the spatial autocorrelation coefficients (ρ) of the geographical adjacency spatial weight matrix (W_1) and economic distance spatial weight matrix (W_2) were 0.101 and 0.210, respectively; these were significantly positive at the 10% and 5% levels, respectively, indicating that the changes in ecological efficiency in the Yellow River basin have significant spatial spillover effects. Specifically, the *MILEC* of the city is closely related to the ecological efficiency level of neighbouring cities geographically or economically. In addition, under the geographical spatial weight and the economic distance spatial weight, the coefficients of *L1_MILEC* were 0.032 and 0.063, respectively; both passed the 10% significance test, which indicates that *MILEC* also has time lag. The improvement of the ecological efficiency of geographically and economically adjacent cities in the prior period promotes the improvement of the ecological efficiency of the local city in the current period.

In the regression results for the dynamic SDM (W_1) and dynamic SDM (W_2), the coefficients of the independent variable *FD* were 0.052 and 0.104, respectively, which was significant at the 10% level. However, the increase of *FD* in the cities adjacent to the geographical distance and economic distance will lead to the decline of the city's ecological efficiency, which reflects the economic competition among the cities. The winner of the urban competition absorbs the adjacent superior resources, leading to the weakening of the ecological governance capacity of adjacent cities. Regarding control variables, *ER*, *IND* and *FIN* significantly promoted *MILEC*. Contrastingly, *OPEN* and *POP* inhibited *MILEC*, but not significantly.

Table 9. Regression results of influencing factors for ecological efficiency change in the Yellow River basin.

Variable	Dynamic SDM (W₁)	Dynamic SDM (W₂)	Static SDM (W₁)	Static SDM (W₂)
LI_MILEC	0.135***	0.218**	/	/
	(0.034)	(0.102)		
FD	0.052*	0.104*	0.055	0.118**
	(0.029)	(0.057)	(0.035)	(0.055)
ER	0.225**	0.163*	0.184	0.142**
	(0.102)	(0.086)	(0.123)	(0.063)
IND	0.014*	0.032	0.008*	0.029
	(0.008)	(0.020)	(0.005)	(0.021)
FIN	0068**	0.102**	0.044*	0.079
	(0.032)	(0.046)	(0.024)	(0.056)
URB	0.033	0.054	0.103	0.115*
	(0.031)	(0.043)	(0.142)	(0.150)
OPEN	−0.069	−0.106	−0.118	−0.096
	(0.053)	(0.076)	(0.113)	(0.081)
RD	0.011	0.025**	0.030	0.057**
	(0.009)	(0.012)	(0.022)	(0.027)
POP	−0.221	−0.136	−0.146*	−0.089*
	(0.148)	(0.088)	(0.081)	(0.050)
W × LI_MILEC	0.032*	0.063*	/	/
	(0.059)	(0.077)		
W × FD	−0.039**	−0.018*	−0.055*	−0.102*
	(0.018)	(0.010)	(0.032)	(0.057)
W × ER	0.023	0.012*	−0.044	0.086*
	(0.016)	(0.006)	(0.036)	(0.048)
W × IND	0.025**	0.011*	0.058*	0.029
	(0.012)	(0.006)	(0.033)	(0.019)
W × FIN	0.044	0.019	0.011	0.006**
	(0.039)	(0.017)	(0.008)	(0.003)
W × URB	0.047	0.032	0.086*	0.053
	(0.035)	(0.029)	(0.046)	(0.036)
W × OPEN	−0.264	−0.170**	−0.282	−0.355
	(0.171)	(0.075)	(0.194)	(0.240)
W × RD	0.068*	0.154	0.148*	0.210
	(0.037)	(0.103)	(0.086)	(0.173)
W × POP	−0.125	−0.078	−0.113*	−0.086
	(0.094)	(0.062)	(0.066)	(0.069)
ρ	0.101*	0.210**	0.137**	0.279**
	(0.055)	(0.098)	(0.062)	(0.130)
Adj.R^2	0.497	0.455	0.423	0.474
Sigma2_e	5.786***	5.962***	5.248***	5.611***
	(1.272)	(1.366)	(1.254)	(1.368)
Obs	1248	1248	1248	1248
Diagnostic test			Value	
Hausman test			23.271***	
AR (1)			−5.806***	

(Continued)

Table 9. (continued)

Variable	Dynamic SDM (W$_1$)	Dynamic SDM (W$_2$)	Static SDM (W$_1$)	Static SDM (W$_2$)
AR (2)			−1.251	
Sargan			21.916	

Notes: *, * * and * * * are significant at 10%, 5% and 1% levels, respectively. Standard errors are shown in parentheses.
ER: environmental regulation; FD: fiscal decentralisation; FIN: financial development; IND: industrial structure; FIN: financial development; MILEC: *MIL* productivity index to decompose into ecological efficiency change; OPEN: opening level; POP: population density; SDM: spatial Durbin model; RD: research and development; URB: urbanisation level.

Regression analysis of technological progress change. As shown in Table 10, *L1_MILTC* was significant at the 1% level, and it was reasonable to include it in the estimation model. From the estimation results of the dynamic SDM, we concluded that the estimation results using the geographical adjacency spatial weight matrix (W$_1$) and the economic distance spatial weight matrix (W$_2$) were not significantly different. The coefficients of the first-order and spatial lag terms of technological progress and the main explanatory variables were significant at least at the 5% level, and the symbols had not changed, indicating that the regression results were robust

According to the *MILTC* regression estimation results, the spatial autocorrelation coefficients (ρ) of the geographical adjacency spatial weight matrix (W$_1$) and economic distance spatial weight matrix (W$_2$) were 0.203 and 0.312, respectively. They were both significant at the 5% level, showing that technological progress has a significant diffusion effect among cities in the Yellow River basin. In addition, under the geographical and economic distance spatial weight, the coefficients of *L1_MILTC* were 0.134 and 0.175, respectively; they passed the 5% significance test, which indicates that *MILTC* also has time lag. The improvement of the technological progress of geographically and economically adjacent cities in the prior period promotes the improvement of the ecological efficiency of the specific city in the current period.

In the regression results for the dynamic SDM (W$_1$) and dynamic SDM (W$_2$), the coefficients of the independent variable *FD* were 0.203 and 0.312, respectively; they were significant at least at the 5% level. Under the geographical spatial weight (W$_1$) and the economic distance spatial weight (W$_2$), the coefficients of *FD* were −0.093 and −0.064, respectively, and they were significant at least at the 5% level. That means the increase of *FD* in adjacent cities will lead to the decline of the city's technological progress. Regarding control variables, *IND*, *FIN* and *RD* significantly promoted *MILTC*. On the contrary, *ER* and *POP* inhibited *MILTC*.

Discussion

From the estimation results of the static and dynamic SDMs, we concluded that financial decentralisation has significantly increased the growth rate of ecological TFP. Good

governance of the Yellow River supported by fiscal policy will greatly impact the lives of river basin residents, who hope to not only live in a good ecological environment but also to experience a richer life and improved social welfare. To achieve this, the government must increase financial investment, implement urban flood control planning,[47] create employment opportunities and provide diversified public products.

IND, FIN, URB and RD investment improved growth rates indicating that the government should strengthen these factors. For example, increases in local environmental protection and scientific and technological investment, strengthened the spillover effect of environmental protection technology. This was in turn conducive to a mutual exchange and learning of environmental protection and emission reduction technologies among cross-regional enterprises, thereby effectively promoting ecological TFP. In contrast, ER, OPEN of cities, and POP suppressed the rise of ecological TFP. The government should address these negative effects. For instance, when introducing foreign capital for development, local governments should prevent its adverse impact on the local ecological environment.

Conclusions, policy recommendations and limitations

Conclusions

Based on strong sustainable development theory, we constructed the urban ecological environment evaluation system of the Yellow River basin from the dimensions of ecological damage and construction and incorporated it into the ecological TFP framework. We created a new ecological TFP indicator – *MIL* – to dynamically measure ecological TFP and used the kernel density estimation and dynamic SDM to analyse the spatial and temporal evolution of urban ecological TFP in the Yellow River basin along with its influencing factors. We additionally conducted further analysis on the direct and indirect effects of various influencing factors.

From 2003 to 2019, *MIL* in cities along the Yellow River basin showed an increasing trend, with average annual growth rates of 0.627%. The findings indicate that urban ecological TFP in the Yellow River basin showed a gradient increase of 'upstream (0.520)-midstream (0.611)-downstream (0.751)', and that technological progress (*MILTC*) was the main driving force.

In terms of time evolution, between 2003 and 2010, *MIL* in the Yellow River basin increased rapidly. After 2010, the ecological TFP growth rate in the entire basin showed a W-type cyclical fluctuation upward trend. From a spatial evolution perspective, the main peak of the *MIL* index in cities in all regions of the Yellow River basin showed a left-skewed distribution, and the bandwidth was distributed in a left-tailed manner and slightly expanded, with a fluctuating peak value.

By analysing the global Moran's I index and dynamic SDM, we found that urban ecological TFP in the Yellow River basin had a spatial agglomeration effect. Under the geographical adjacency (W_1) and economic distance (W_2) spatial weight matrices, different cities had strong spatial correlation effects. FD, IND, FIN, URB and RD investment promoted the improvement of *MIL* in specific and adjacent regions through direct and indirect effects. Contrastingly, ER, OPEN of cities, and POP were obstacles to *MIL*.

Table 10. Regression results of influencing factors for technological progress change in the Yellow River basin.

Variable	Dynamic SDM (W₁)	Dynamic SDM (W₂)	Static SDM (W₁)	Static SDM (W₂)
L1_MILTC	0.376***	0.491***	/	/
	(0.095)	(0.106)		
FD	0.167***	0.263**	0.543**	0.365**
	(0.051)	(0.121)	(0.257)	(0.181)
ER	−0.115	−0.074*	−0.155**	−0.083
	(0.142)	(0.040)	(0.073)	(0.114)
IND	0.026*	0.031**	0.035	0.048*
	(0.014)	(0.013)	(0.105)	(0.025)
FIN	0.147***	0.162**	0.155**	0.176*
	(0.032)	(0.074)	(0.071)	(0.094)
URB	0.023	0.034*	0.033	0.045**
	(0.015)	(0.018)	(0.021)	(0.022)
OPEN	0.040	0.057ˑ	0.051	0.069*
	(0.035)	(0.044)	(0.040)	(0.038)
RD	0.349***	0.310*	0.405**	0.486**
	(0.073)	(0.171)	(0.193)	(0.232)
POP	−0.017	−0.052	−0.028*	−0.076
	(0.105)	(0.194)	(0.114)	(0.205)
W × L1_MILTC	0.134***	0.175**	/	/
	(0.037)	(0.080)		
W × FD	−0.093***	−0.064**	−0.104	−0.128*
	(0.027)	(0.029)	(0.070)	(0.075)
W × ER	0.098*	0.076*	0.101	0.122*
	(0.054)	(0.043)	(0.068)	(0.068)
W × IND	0.010**	0.003*	0.107	0.042*
	(0.005)	(0.002)	(0.091)	(0.026)
W × FIN	0.011	0.017	0.008	0.010
	(0.010)	(0.015)	(0.011)	(0.016)
W × URB	0.127	0.144*	0.155**	0.169*
	(0.101)	(0.081)	(0.074)	(0.095)
W × OPEN	0.019	0.036**	0.104	0.128*
	(0.013)	(0.017)	(0.115)	(0.072)
W × RD	0.102*	0.178**	0.155*	0.211**
	(0.059)	(0.080)	(0.088)	(0.095)
W × POP	−0.223	−0.164	−0.304*	−0.254
	(0.201)	(0.107)	(0.172)	(0.170)
ρ	0.203**	0.312**	0.198**	0.326***
	(0.088)	(0.140)	(0.087)	(0.079)
Adj.R²	0.558	0.512	0.476	0.440
Sigma2_e	6.245***	6.703***	6.224***	6.530***
	(1.821)	(1.833)	(1.669)	(1.732)
Obs	1248	1248	1248	1248
Diagnostic test			Value	
Hausman test			28.177***	
AR (1)			−4.554***	

(Continued)

Table 10. (continued)

Variable	Dynamic SDM (W_1)	Dynamic SDM (W_2)	Static SDM (W_1)	Static SDM (W_2)
AR (2)		−1.008		
17.503				

Notes: *, * * and * * * are significant at 10%, 5% and 1% levels, respectively. Standard errors are shown in parentheses.
ER: environmental regulation; FD: fiscal decentralisation; FIN: financial development; IND: industrial structure; FIN: financial development; MILTC: *MIL* productivity index to decompose into ecological efficiency change and technological progress change; POP: population density; SDM: spatial Durbin model; RD: research and development; URB: urbanisation level.

Policy recommendations

This study provides the following relevant policy recommendations. Owing to sporadic domestic epidemics and their unexpected impact on China's economy, many cities in the Yellow River basin have encountered financial deficits and sluggish economic development in recent years. Major water conservancy projects attract large investments, have a long industrial chain and create many employment opportunities. It is estimated that every 100 billion yuan invested in major water conservancy projects can drive GDP growth by 0.15% and create 490,000 new jobs, playing an important role in promoting stable economic growth. Given this, the state should strengthen macro-control, and promote the construction of Gu Xian, Hei Shan Gorge and Qi Kou, and other major water conservancy projects on the Yellow River.[48]

However, the discharge of a large number of pollutants, deforestation and destruction of wetlands driven by economic interests along the Yellow River has weakened the connectivity of the river's aquatic habitat and the self-healing ability of the water environment, further damaging the overall ecosystem and ecological balance. All localities should strengthen oversight on ecological environment damage in the Yellow River basin, comprehensively improve water ecological protection and governance, increase the speed of constructing digital twin basins and digital twin projects, implement total factor and whole process governance and management, and further promote ecological TFP improvement through innovation. Meanwhile, in the basin, management behaviour (or lack thereof), in the upstream region could have an impact on the downstream region. Thus, it is necessary to promote coordinated governance of the regional ecological environment and to collaborate across regions to protect the environment and ensure that the environment and ecological TFP of the Yellow River basin improve qualitatively.

Further consideration is needed to improve the interregional ecological compensation mechanism; formulate objectives, approaches, methods and standards related to ecological compensation[49]; increase financial support and ecological environment regulation and promote coordinated and sustainable development of the Yellow River basin's urban ecological environment and economy by improving the ecological

TFP. For example, in 2021, Shandong (downstream) and Henan (upstream) provinces signed a 'gambling agreement'. If the water quality averages the class III standard throughout the year, the two provinces do not compensate each other. If the water quality improves from class III to class II, Shandong will give Henan 60 million yuan in compensation. However, if the water quality deteriorates to category III, Henan will pay Shandong 60 million yuan in compensation. When Shandong paid Henan 126 million yuan from the Yellow River Ecological Compensation Fund the two provinces realised it was a win-win situation. We believe that it is important to realise ecological compensation goals in the form of an agreement. Moreover, it may be necessary to form an effective ecological protection coordination mechanism that fully considers all relevant regions' actual situations.

Limitations

Several limitations of this study deserve discussion. We were not able to analyse regional differences in urban ecological TFP in the Yellow River basin, given length constraints. In the future, we can use the Dagum Gini coefficient method to reveal how the inter- and intra-regional differences in ecological TFP evolve in the Yellow River basin. Furthermore, we used SDM to identify influencing factors. In the future, we will use a spatial convergence model to further examine the spatial convergence effect and the convergence speed of urban ecological TFP. Finally, it is necessary for us to conduct in-depth research on ecological compensation in the region, not only through governmental policies, such as FD, but also from market-oriented ecological compensation methods, such as the value of ecological products.

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