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Research on influencing factors of cultivated land productivity of high-standard farmland projects in Hanzhong city of China – an empirical study based on PLS-SEM

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Based on 295 capacity monitoring sites in Hanzhong city, we used partial least squares structural equation model to construct a model of the factors influencing cultivated land productivity using soil nutrients, farmland water resources, geological characteristics and soil properties as latent variables to explore the main factors affecting cultivated land productivity in Hanzhong city. The research results show that: (1) Soil nutrients, farmland water conservancy and soil properties were the main factors influencing cropland productivity, and had direct or indirect positive effects on cropland productivity, with the total effects ranging from soil properties (0.587) > farmland water conservancy (0.552) > soil nutrients (0.464). (2) Geological characteristics had no direct effect on cropland productivity, but indirectly influenced cropland productivity by affecting soil nutrients. (3) Slope had a negative effect on cropland productivity. Cultivated land productivity in Hanzhong city is influenced by various factors. Integrating the interactions and influence effects among the influencing factors, it is recommended to achieve coordinated and sustainable regional food production by improving water conservancy facilities, strengthening farmland quality, improving agricultural product quality, and building healthy capacity of cultivated land.

KEYWORDS

cultivated land productivity, food security, productivity calculation, partial least squares structural equation model, Hanzhong city

1. Introduction

As a rapidly developing and populous country, the issue of food security in China has been a major concern in academic research. Brown's article "Who will feed China" caused a sensation and brought the issue of China's food security to the forefront of world opinion (Fukase and Martin, 2016). Obviously, Brown reported that branded with Western politics and exaggerates the "China threat theory," but as an early warning, it helps strengthen the country's attention to the issue of food security. At present, China's food security still faces many challenges. On the one hand, from an international perspective, the spread of the new pneumonia epidemic has accelerated globally (Muthamilarasan and Prasad, 2021), and the impact of trade conflicts and local wars such as the Russian-Ukrainian conflict on global food security has further increased, and global food market volatility is likely to further escalate (Falkendal et al., 2021). On the other hand, domestic food supply and demand have been in a tight balance (Yuneng et al., 2020), and in the face of the impact of the epidemic and its trade frictions and the uncertainty brought about by local wars, how to enhance food production capacity, and improve the stability of the food production system is an important challenge facing China's food security at present (Lu et al., 2022). Chinese leaders pointed out that "to ensure national food security, the Chinese people's rice bowl firmly in their own hands" (Peng, 2023). At the same time, it is necessary to "store grain in land and store grain in technology," that is, to turn cultivated land into the largest grain warehouse by stabilizing and increasing the yield of cultivated land (Du et al., 2018). This strategy has found a new way to ensure China's food security (Zhang et al., 2018). In order to fully develop the production potential of cultivated land, it is of practical significance to carry out research on the influencing factors of cultivated land productivity and scientifically grasp the influencing factors of cultivated land productivity and their interactions to reveal the main driving factors of regional cultivated land productivity (Cortner et al., 2019), ensure national food security and improve regional grain productivity.

At present, the academic community has carried out many studies on cultivated land productivity and its influencing factors. Among them, the research on grain production capacity in developed countries is more macro. Welch et al. (2010) and Lobell et al. (2013) found that the increase of temperature led to the decrease of crop yield. Alhaj Hamoud et al. (2019) found that irrigation system and soil texture and their interaction can significantly affect rice yield. Senghor et al. (2017) pointed out that the increase of CO_2 concentration had different effects on the yield of wheat, rice and other food crops. Denardin et al. (2019) found that the no-tillage system was more conducive to the improvement of soil organic matter than the traditional tillage system, which helped to increase rice yield. Chinese research focuses more on the impact of natural factors on cultivated land productivity. Liu et al. (2019) combined with climate, water resources, CO_2 fertilizer efficiency, landform type, organic matter and other influencing factors to explore the degree and direction of its impact on cultivated land productivity. Some scholars have also analyzed the effects of single factor such as fertilizer application, climate change and land use change on cultivated land productivity (Fang et al., 2021; Liang et al., 2021; Zhang et al., 2022).

Cultivated land production is an organic combination of social reproduction and natural reproduction. Cultivated land productivity is affected by many factors such as nature, soil fertility, society and technology. Wan et al. (2020) selected 11 factors, and found that the influence of each factor index classification on grain yield increasing ability was different through multiple group model analysis. Gao et al. (2019) believed that the grain yield of cultivated land depends on four factors: cultivated land area, multiple cropping index, sown area and grain yield per unit area. Yang et al. (2022) identified the factors through the factor dimension reduction model, and the influencing factors after optimization and identification mainly included the difference vegetation index (DVI), landform type, slope, black soil layer thickness, organic matter, mechanization degree and irrigation potential. Among them, the degree of mechanization has the greatest impact on productivity, the thickness of black soil layer has the least impact, and slope has a negative effect on cultivated land productivity. Yuan et al. (2022) found that organic matter, agricultural irrigation and drainage conditions and utilization coefficient are the dominant factors affecting the yield of cultivated land at the provincial scale.

In general, there are many factors affecting cultivated land productivity, and the mechanism is complex. At the research level, most of the existing studies choose the influencing factors from a macro perspective, and there are few studies on the analysis of the characteristics of local cultivated land productivity in the hilly area of southern Shaanxi. In terms of research objects, most of the current studies only focus on the impact of various factors on cultivated land productivity, ignoring the interaction between factors. In terms of research methods, traditional methods such as factor analysis, regression analysis, and correlation analysis are often used, and it is difficult to reveal the relationship and influence between latent variables.

Hanzhong city is close to the Chengdu Plain commodity grain base, one of the nine major commodity grain bases in China. In recent years, the rapid economic and social development of Hanzhong city has occupied a large amount of cultivated land, and the number of regional cultivated land has continued to decrease. Moreover, with the increase of farming years, the soil degradation of cultivated land is serious, the yield of cultivated land fluctuates and uncertain, and there are great problems and risks in regional grain production. In short, this study aims to accomplish two main objectives:

- To explore the internal mechanism of soil properties, farmland water conservancy, soil nutrients, geological characteristics affecting cultivated land productivity.
- This study attempts to construct a theoretical framework of "cultivated land productivity."

Therefore, this study chooses Hanzhong city as the research area. Based on the calculation of cultivated land productivity, the partial least squares structural equation model is used to analyze the influencing factors of cultivated land productivity. It overcomes the shortcomings of traditional analysis methods, deals with the relationship between multiple latent variables, and describes the complex interaction between variables. This paper discusses the dominant factors and limiting factors of cultivated land productivity, in order to provide a theoretical basis for formulating relevant policies according to local conditions, optimizing limiting factors, improving regional cultivated land quality and improving cultivated land productivity.

2. Materials and methods

2.1. Overview of the study area

Hanzhong City is a prefecture-level city under the jurisdiction of Shaanxi Province (Figure 1). It is located in the southern part of Shaanxi Province. The geographical coordinates are between 105°30′ ~ 108°24′E, 32°15′ ~ 33°56′N, near the Chengdu Plain. As an advanced grain production city in China, Hanzhong's grain output will reach 1.15 billion kg in 2023. The elevation of Hanzhong city is 40 ~ 100 m. The terrain in the territory is high in the north and low in the south, and the middle is smooth and flat. It is a "saddle-shaped" landform between low hills and valley plains. Hanzhong city is rich in arable land resources, arable land area of 262208.01 hm^2, accounting for about 19.6% of the city's land area, including: paddy field 95787.53 hm^2, irrigated land

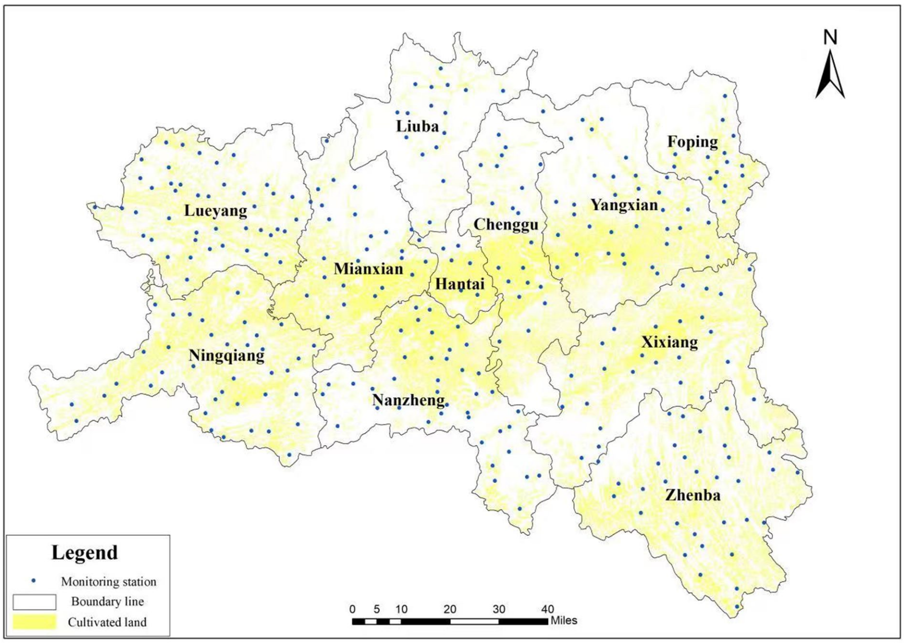

FIGURE 1
The location of study area.

6767.22 hm^2, dry land 159653.26 hm^2. According to the evaluation results of cultivated land quality, the quality of cultivated land in Hanzhong City is concentrated in three grades: four level, five level, six level.

2.2. Data source and processing

Based on the existing literature research, combined with the status of cultivated land in Hanzhong City, and considering the availability of data, indicators were selected from four aspects: soil nutrients, farmland water conservancy, geological characteristics and soil properties (Figure 2). Finally, 14 observation variables were determined as the measurement factors affecting the cultivated land productivity in Hanzhong City (Table 1).

The data used were from 295 cultivated land productivity monitoring points set up by the research group in Hanzhong City in 2022. Total nitrogen, available phosphorus, available potassium, available zinc, pH, organic matter, soil texture and soil bulk density data were obtained by soil sampling and testing. The data of irrigation and drainage conditions were obtained through field research. The data of plough layer thickness, terrain location and landform type are the area data in the annual update database of cultivated land quality in 2021. The spatial link tool in ArcGIS 10.8 is used to assign these three types of data to 295 monitoring points. The slope data is based on the GDEM DEM 30 m resolution digital elevation model (DEM) downloaded from the geospatial data cloud[1] and processed by ArcGIS 10.8 software. In addition, the grain yield per unit area of agricultural land corresponding to these 295 samples was obtained through field investigation. The theoretical capacity and achievable capacity are calculated according to the soil fertility level of the sample points obtained from the agricultural land classification results in Shaanxi Province.

Based on the obtained data, the data of total nitrogen, available phosphorus, available potassium, available zinc, pH, organic matter and soil bulk density were standardized according to the "soil nutrient grading standard." The irrigation conditions, drainage conditions, slope, topsoil thickness, topography, soil texture and other data were standardized according to the "Agricultural Land Quality Classification Regulations." Based on the study of Qian et al. (2021), the geomorphic types are scored and assigned according to the actual values and grading standards of the variables, so as to realize the unity and comparability of different scales and different types of variables.

2.3. Research method

2.3.1. Cultivated land productivity calculation

The cultivated land productivity analyzed in this paper includes theoretical unit area yield, achievable unit area yield and actual unit area yield.

(1) Theoretical unit area yield. According to the natural quality index of agricultural land, the theoretical productivity of agricultural land was calculated. Taking the secondary index area as a unit, the functional relationship between the theoretical unit area yield of the designated crop and the natural quality index of the agricultural land where the sample point is located was established:

1 http://www.gscloud.cn/

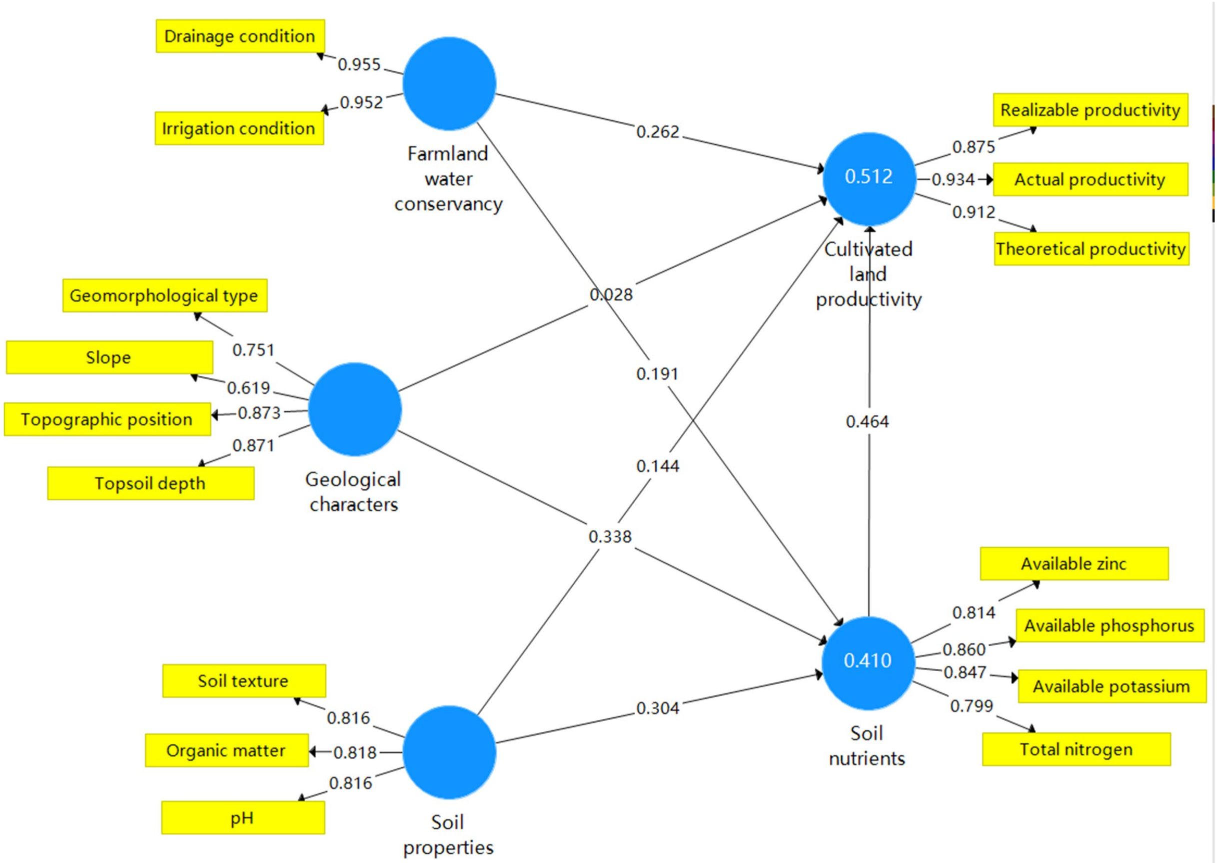

FIGURE 2
Research model.

$$y_i^{''} = aR_i + b \quad (1)$$

In Eq. (1): $y_i^{''}$ is the sample value of theoretical yield per unit area of agricultural land corresponding to survey point *i*; R_i is the natural index of agricultural land corresponding to survey point *i*; *a* and *b* are regression coefficients. Hanzhong City belongs to the plain area along the Yangtze River. Through mathematical analysis and demonstration test, the theoretical unit area yield accounting model of the index area is determined as follows:

$$y_i^{''} = 0.2758R_i + 361.2 \quad (2)$$

The natural index of agricultural land in Hanzhong City in 2022 was substituted into the mathematical model to calculate the theoretical yield per unit area of each sample plot.

(2) Achievable unit area yield. According to the agricultural land use quality index, the achievable productivity of agricultural land was calculated. Taking the secondary index area as a unit, the functional relationship between the achievable unit area yield of the designated crop and the agricultural land use index of the sample point was established:

$$y_i^{'} = cY_i + d \quad (3)$$

In Eq. (3): y_i' is the sample value of the achievable yield per unit of agricultural land corresponding to the survey point *i*; Y_i is the index of agricultural land use corresponding to survey point *i*; *c* and *d* are regression coefficients. After demonstration test, it is determined that the index area can realize the yield accounting model:

$$y_i^{'} = 0.3094Y_i + 265.45 \quad (4)$$

The agricultural land use index of Hanzhong City in 2022 was substituted into the mathematical model to calculate the achievable unit area yield of the field corresponding to each sample point.

(3) Actual unit area yield. The main idea is to calculate the actual production capacity of the field where each sample point is located according to the single-season yield and tillage system. Firstly, the field survey was carried out to measure the yield of the field where each sample point was located. Then, the actual production capacity of the field where the sample point was located was obtained by combining the statistical yearbook data of the local agricultural department and the farming system of Hanzhong City. The actual production capacity

TABLE 1 Influencing factors and sources of cultivated land productivity in Hanzhong City.

Latent variable	Observation variable	Selection basis	Obtaining method
Soil nutrients	Total nitrogen	Comprehensively reflect the status of nutrients required by cultivated land	Soil sampling and testing
	Available phosphorus	Comprehensively reflect the status of nutrients required by cultivated land	Soil sampling and testing
	Available potassium	Comprehensively reflect the status of nutrients required by cultivated land	Soil sampling and testing
	Available zinc	Comprehensively reflect the status of nutrients required by cultivated land	Soil sampling and testing
Farmland water conservancy	Irrigation condition	Reflect the degree of irrigation water satisfaction	Field survey
	Drainage condition	Reflect the ability of cultivated land to immediately remove surface water	Field survey
Geological characters	Slope	The steep slope of field affects soil physiochemical properties	Download DEM data based on geospatial data cloud
	Topsoil depth	Reflect soil fertility	Annual updated data on cultivated land quality
	Topographic position	Reflect the location and terrain of the field	Annual updated data on cultivated land quality
	Geomorphological type	Reflect the different types of the surface shape	Annual updated data on cultivated land quality
Soil properties	pH	Reflect the degree of soil acidity and alkalinity, which has an important impact on soil nutrients and crop growth	Soil sampling and testing
	Organic matter	Reflect the fertility and nutrient status of cultivated soil	Soil sampling and testing
	Soil texture	Reflect soil particle size and its combination	Soil sampling and testing
	Soil bulk density	Reflect soil porosity，soil permeability and water permeability of cultivated land	Soil sampling and testing

divided by the corresponding area was regarded as the actual unit area yield of the sample point.

2.3.2. Partial least squares structural equation model

Partial least squares structural equation model (PLS-SEM) is a multivariate statistical analysis technique. Different from traditional statistical methods (such as linear regression, multiple regression, etc.), in a broader sense, SEM can be used as a simultaneous multi-equation estimation model, which can include single or/and multiple variables on both sides of the equation, and contribute to the appropriate and complete mediation effect analysis of very complex models. In the literature, there are many debates about the advantages and disadvantages of covariance-based SEM (COV-SEM) and PLS-SEM (Henseler et al., 2014). PLS-SEM is usually considered as a complementary method to COV-SEM (Venturini and Mehmetoglu, 2019). According to the suggestion of Hair et al. (2019), PLS-SEM is generally used in the following cases: (1) the target is to predict the key target structure; (2) The construction of formal metrics is part of the structural model; (3) The structural model is complex, including many indicators/structures; (4) Small sample size; (5) The plan is to use latent variable scores in further analysis.

The PLS-SEM model is mainly composed of two parts, the measurement model describing the relationship between latent variables and explicit variables and the structural model describing the relationship between latent variables and latent variables (Dash and Paul, 2021). The parameter estimation method is divided into two steps: first, the estimation value of latent variable is obtained through repeated iteration; secondly, the partial least squares method is used for linear regression to obtain the parameter estimates of the structural model and the measurement model.

If there are k latent variables, then there are k groups of explicit variables. Each group contains m variables. Then each group of explicit variables can be expressed as:

$$X_i = \{x_{i1}, x_{i2}, x_{i3}, \ldots, x_{im}\} \qquad i = \{1,2,3,\ldots,k\} \tag{5}$$

At the same time, it is assumed that there is a linear combination relationship between latent variables and latent variables, latent variables and explicit variables, and each explicit variable is associated with a unique latent variable. The equation of the measurement model is:

$$x_{ij} = \lambda_{ij}\xi_i + \sigma_{ij} \qquad (i = 1,2,3,\ldots,k;\ j = 1,2,3,\ldots,m_i) \tag{6}$$

The equation of partial least squares structural equation model is:

$$\xi_i = \sum_{i \neq j} \beta_{ij} \xi_j + \varepsilon_i \quad (7)$$

In the above equation, ξ_i is a normalized latent variable, λ_{ij} is the factor load, β_{ij} is the path coefficient, σ_{ij}, ε_i is the error correction term, and is not related to the predictor variable, the mean is 0.

2.4. Model construction

Since this study was carried out at the county scale, factors such as policy system, climatic conditions, and precipitation that are not significantly different in small regions are not considered in this paper. Based on the characteristics of the study area and the existing research, this paper summarizes four factors that have a greater impact on cultivated land productivity at the county scale: First, soil properties. Soil is the basis and carrier of grain production. The quality of cultivated land depends largely on the quality of soil properties, which may directly affect the productivity of cultivated land. The second is farmland water conservancy. Most of China's agriculture is irrigated agriculture, which is also true in southern Shaanxi where water resources are abundant. Water conservancy is the lifeblood of agriculture, and the water conservancy situation is quite different in a small area. Therefore, the difference between farmland water conservancy facilities and irrigation conditions may be an important factor affecting grain yield. Third, soil nutrients. The ability of soil to store and supply fertilizer is the guarantee of crop yield. Shaanxi soil is mostly yellow loam, strong acidity, easy to harden, poor nutrients, low organic matter content, poor soil background quality, and poor fertilizer storage capacity. Therefore, the regional soil nutrient status may be the determinant of cultivated land productivity. Fourth, geological characteristics. The geographical environment of cultivated land has a restrictive effect on the redistribution of surface water heat and the determination of cultivated land use form, so it may have an important impact on cultivated land productivity.

Based on the above analysis and the characteristics of the study area, the following seven research hypotheses are proposed:

> *Hypothesis 1 (H1)*: Soil nutrient status has a significant positive impact on cultivated land productivity;
>
> *Hypothesis 2 (H2)*: Farmland water conservancy has a significant positive impact on cultivated land productivity;
>
> *Hypothesis 3 (H3)*: Soil properties have a significant positive impact on cultivated land productivity;
>
> *Hypothesis 4 (H4)*: Geological characteristics have a significant positive impact on cultivated land productivity;
>
> *Hypothesis 5 (H5)*: Farmland water conservancy has a significant positive impact on soil nutrients;
>
> *Hypothesis 6 (H6)*: Soil properties have a significant positive effect on soil nutrients;
>
> *Hypothesis 7 (H7)*: Geological characteristics have a significant positive impact on soil nutrients.

3. Data analysis and research results

3.1. Model measurement evaluation

3.1.1. Model reliability evaluation

In this study, the reliability of the scale was evaluated mainly through the internal consistency test of the measurement items. The internal consistency was tested by Composite Reliability value and Cronbach's Alpha coefficient (Hair et al., 2019). In the exploratory study, the Composite Reliability value was required to be above 0.7, and the Cronbach's Alpha coefficient was greater than 0.6 (Hair et al., 2012). It can be seen from Table 2 that the Composite Reliability value and Cronbach's Alpha coefficient of all latent variables meet the requirements, which indicates that the measurement model has good reliability.

3.1.2. Model validity evaluation

Generally speaking, all factor loading greater than 0.5 can reasonably explain the latent variables (Dijkstra and Henseler, 2015). From Table 2, it can be seen that all factor loading in this study meets the structural validity requirements. In addition, the convergence validity and discriminant validity of PLS model are mainly based on Average Variance Extracted (AVE), which requires AVE greater than 0.5, and the square root of AVE value is greater than the correlation coefficient of other latent variables. From Table 3, the research data meet the above conditions, indicating that there is a good linear equivalence relationship between the measured variables and the latent variables, and the measured variables can better explain the latent variables. In order to assess redundancy, we utilized the variance inflation factor (VIF) to test for multicollinearity across the various measurement variables. The resulting VIF values for each measurement model can be found in Table 2. Notably, all 16 observed variables had VIF values under 5 (Chuah et al., 2021), indicating an absence of multicollinearity among the measurement variables.

3.1.3. Evaluation of model prediction ability

The model predictive ability of this study is evaluated by R^2 (multiple determination coefficient) through the internal model explanatory power. The larger the value of R^2, the stronger the explanatory ability of the measurement variable to the latent variable. In this study, soil nutrients explained 40.8% of the model, and cultivated land productivity explained 51.1% of the model. In general, R^2 has a weak explanatory power between 0.25–0.5 and a moderate explanatory power between 0.5 and 0.75 (Nayyar, 2022), indicating that the explanatory power of the model basically meets the requirements.

3.2. Model results and analysis

It can be seen from Table 4 that except for Hypothesis 4, the other six hypotheses are all valid. The results showed that irrigation and

TABLE 2 Reliability and validity.

Variables	Observation variable	Loadings	Cronbach's α	CR	AVE	VIF
Cultivated land productivity	Theoretical productivity	0.912	0.892	0.933	0.823	2.996
	Realizable productivity	0.875				2.210
	Actual productivity	0.934				3.653
Soil nutrients	Total nitrogen	0.798	0.850	0.899	0.690	1.633
	Available phosphorus	0.861				2.362
	Available potassium	0.847				2.071
	Available zinc	0.815				2.024
Farmland water conservancy	Irrigation condition	0.952	0.900	0.952	0.909	3.014
	Drainage condition	0.955				3.014
Geological characters	Slope	0.619	0.784	0.864	0.617	1.145
	Topsoil depth	0.871				2.774
	Topographic position	0.873				2.834
	Geomorphological type	0.751				1.605
Soil properties	pH	0.818	0.783	0.860	0.605	1.721
	Organic matter	0.788				1.562
	Soil texture	0.784				1.507
	Soil bulk density	0.719				1.472

CR, composite reliability; AVE, average variance extracted; VIF, variance inflation factors.

TABLE 3 Discriminant validity - Fornell-Larcker criterion and Heterotrait-Monotrait ratio.

	1	2	3	4	5
1.Cultivated land productivity	**0.907**	0.554	0.528	0.745	0.535
2.Farmland water conservancy	0.496**	**0.953**	0.468	0.460	0.290
3.Geological characters	0.442**	0.393**	**0.786**	0.659	0.554
4.Soil nutrients	0.655**	0.402**	0.541**	**0.83**	0.601
5.Soil properties	0.451**	0.248**	0.436**	0.496**	**0.778**

**Correlation is significant at the 0.01 level (2-tailed), Bold diagonal entries are square root of AVEs, Heterotrait-Montrait ratios (HTMT; Underlined) are below 0.85.

water conservancy, soil nutrients and soil properties had significant direct effects on farmland productivity, with path coefficients of 0.264, 0.464, and 0.144, respectively. Farmland water conservancy and soil properties not only directly affect the productivity of cultivated land, but also have an indirect positive impact on the productivity of cultivated land through the mediating effect of soil nutrients. The path coefficients are 0.091 and 0.140, respectively. The geological characteristics do not directly affect the productivity of cultivated land, but indirectly affect the productivity of cultivated land by affecting soil nutrients, with a path coefficient of 0.154. In the structural equation model, under the premise of significant correlation, the greater the absolute value of the path coefficient, the greater the degree of influence between the factors (Grace and Keeley, 2006). Therefore, in the model of influencing factors of cultivated land productivity: soil nutrients have the greatest direct impact on cultivated land productivity; farmland water conservancy and soil properties have both direct and indirect effects on cultivated land productivity, and the impact of farmland water conservancy is greater than that of soil properties. Geological characteristics have an indirect effect on cultivated land productivity by affecting soil nutrients.

Soil nutrients have a very significant positive impact on cultivated land productivity, hypothesis 1 is established, and its standardized path coefficient is 0.464, that is, when soil nutrients change 1, cultivated land productivity changes 0.464, indicating that soil nutrients have a huge impact on cultivated land productivity. Soil nutrient variables are endogenous latent variables in the model, which are affected by many factors. Human behavior and natural changes will change soil nutrients to varying degrees. As an important way to improve soil nutrient status, the marginal return of fertilization has entered a decreasing stage. According to the results of model analysis, soil nutrients are affected by many factors such as geological characteristics, soil properties and farmland water conservancy. In order to further improve grain yield, we should focus on improving farmland water conservancy conditions and soil geological conditions, and combine human management and modern technology to better play the role of soil nutrients in increasing grain yield of cultivated land.

Farmland water conservancy has a very significant positive impact on cultivated land productivity and soil nutrients, and the path coefficients are 0.264 and 0.197, respectively, and the total effect is 0.552, indicating that farmland water conservancy construction is an important guarantee for food security, which is consistent with the research of Lu H. et al. (2019) and Zhu et al. (2023). The situation of

TABLE 4 Results of hypothesis testing.

Hypothesis	Effect	Path	Path coefficient	Lower (2.5%)	Upper (97.5%)	*t*-statistics	*p*-value	Decision
Direct Relationships								
H1	Direct	Soil nutrients -> Cultivated land productivity	0.463	0.331	0.588	7.078	0.000***	Accept
H2	Direct	Farmland water conservancy -> Cultivated land productivity	0.258	0.124	0.395	3.844	0.000***	Accept
H3	Direct	Soil properties -> Cultivated land productivity	0.144	0.034	0.252	2.562	0.01**	Accept
H4	Direct	Geological characters -> Cultivated land productivity	0.032	−0.098	0.168	0.354	0.723	Refuse
H5	Direct	Farmland water conservancy -> Soil nutrients	0.192	0.068	0.321	3.058	0.002**	Accept
H6	Direct	Soil properties -> Soil nutrients	0.299	0.166	0.434	4.359	0.000***	Accept
H7	Direct	Geological characters -> Soil nutrients	0.338	0.182	0.495	4.132	0.000***	Accept
Mediating Relationships								
H5*H1	Indirect	Farmland water conservancy -> Soil nutrients -> Cultivated land productivity	0.09	0.069	0.219	2.554	0.011*	Accept
H6*H1	Indirect	Soil properties -> Soil nutrients -> Cultivated land productivity	0.139	0.028	0.168	3.558	0.000***	Accept
H7*H1	Indirect	Geological characters -> Soil nutrients -> Cultivated land productivity	0.155	0.083	0.234	3.953	0.000***	Accept

SRMR composite model = 0.047. $R^2_{\text{Soil nutrients}} = 0.408$; $Q^2_{\text{Soil nutrients}} = 0.269$. $R^2_{\text{Cultivated land productivity}} = 0.512$; ${}^2_{\text{Cultivated land productivity}} = 0.412$. Significant level: $p < 0.10$; $*p < 0.05$; $**p < 0.01$; $***p < 0.001$.

farmland water conservancy is mainly determined by irrigation and drainage conditions. Although Hanzhong City is rich in water resources and abundant in annual rainfall, there are some problems, such as disorderly layout of irrigation and drainage facilities for cultivated land, most of the ditches are irrigation and drainage dual-purpose ditches, and there are still many soil channels. The backwardness of irrigation and drainage infrastructure is not conducive to timely irrigation and drainage. These problems constrain the utilization efficiency of water resources in Hanzhong City, thereby reducing the utilization efficiency of cultivated land, so the irrigation and drainage conditions of farmland will have a significant direct impact on the productivity of cultivated land. In addition, according to the results of model analysis, farmland water conservancy also had a significant effect on soil nutrients. Unreasonable irrigation methods and irrigation water may cause problems such as soil nutrient loss and soil salinization. Reasonable irrigation methods and irrigation water are conducive to soil nutrient conservation and crop absorption, which is consistent with the research of Singh (2021). At the same time, since farmland water conservancy conditions are the main human driving factors affecting the productivity of cultivated land in Hanzhong City, attention should be paid to the countermeasures to improve the productivity of cultivated land.

Soil properties had significant positive effects on productivity and soil nutrients, with path coefficients of 0.144 and 0.302, respectively, and the total effect was 0.587, indicating that soil properties had a great influence on productivity and soil nutrients. The soil types in Hanzhong City are mainly paddy soil and yellow cinnamon soil. The soil is poor in nutrients, heavy in texture, easy to harden, and acidic, which limits the effect of soil original characteristics on crop yield. The results of the model analysis showed that the three observed variables of organic matter, pH and soil texture had a high contribution rate to soil properties, and the contribution rate was pH > soil texture > organic matter. At the same time, soil properties had a very significant effect on soil nutrients, indicating that soil properties could affect soil nutrient content, and then indirectly affect cultivated land productivity through the mediating effect of soil nutrients. Although the original conditions of soil in southern Shaanxi are poor, Hanzhong City has made more efforts in the improvement of soil physical and chemical properties, including soil acidification improvement, soil conditioner test, etc., which has laid a good foundation for the improvement of cultivated land quality and cultivated land productivity in Hanzhong City.

The geological characteristics had a significant positive effect on soil nutrient status, and the path coefficient was 0.332. From the results of the model, the geological characteristics do not directly affect the productivity of cultivated land, but indirectly affect the productivity of cultivated land by affecting the soil nutrient status. This is different from the study of Oliver and Gregory (2015) in Reading County. Reading County is located in the transition zone from plain to mountain, and the terrain is undulating, so the slope, landform and soil thickness have a direct impact on the local cultivated land productivity. Hanzhong City belongs to the hilly area, the overall terrain is relatively flat. The difference of geomorphological characteristics between the two places is the main reason for the difference of different research results. In terms of topsoil thickness, Vogeler et al. (2009) found that topsoil thickness had a significant effect on crop yield and soil nutrient accumulation, and the increase of topsoil thickness could improve soil nutrient status, which was consistent with the results of model analysis. In addition, the path coefficient of slope is 0.619, although the path coefficient is small, it is the only variable with reverse effect. Therefore, when proposing measures to improve the quality of cultivated land, we should pay attention to the impact of field slope on cultivated land productivity.

4. Discussion

In this paper, when screening the influencing factors of indicators, the influencing factors with little difference in the county are eliminated, such as temperature, precipitation, policy system and other macro factors. The key variables such as soil properties, farmland water conservancy, geological characteristics and soil nutrients were selected as the latent variables to analyze the impact of cultivated land productivity, which makes the research results more targeted (Lu S. et al., 2019). The results show that soil nutrient was the most important factor affecting the productivity of cultivated land, and slope is a variable that has a negative effect on the productivity of cultivated land. This is consistent with the research carried out by Belachew et al. (2020) and Qiao et al. (2018) at the county scale. The difference is that Xu et al. (2021) divided the study area and analyzed the influencing factors of cultivated land productivity by region. From the perspective of research scale, although the research scale of county scale is more targeted to cultivated land productivity, there are also great limitations, ignoring the influence of macro factors such as temperature, precipitation and policy on cultivated land productivity (Qiu et al., 2020).

Lu et al. (2018) and Suriyavirun et al. (2019) analyzed the influence of single factor on cultivated land productivity. Within the scope of retrieval, there are few studies on the analysis of the synergy between factors, and even fewer on the analysis of the relationship between factors. Cultivated land production is a complex dynamic equilibrium system, and there are complex interactions among the influencing factors. Suriyavirun et al. (2019) showed that slope, topography and other factors had an effect on soil pH, physical and chemical properties and trace element content, which was consistent with the analysis results of this paper. In addition, the interaction between farmland water conservancy, geological characteristics, soil properties and soil nutrients can also provide a basis for improving the quality of cultivated land and increasing the productivity of cultivated land.

From the perspective of research methods, when analyzing the influencing factors of cultivated land productivity, different from traditional factor analysis, correlation analysis and other methods, this paper explores the structural equation model as a tool to analyze the influencing factors of cultivated land productivity. Therefore, this paper has the following advantages: First, because the cultivated land productivity is affected by many factors, the traditional analysis method can not well explain and deal with the relationship between multiple latent variables. In this paper, the model of influencing factors of cultivated land productivity is established, and the model is fitted and estimated by SmartPLS 3.0. The main influencing factors affecting cultivated land productivity and the variables restricting cultivated land productivity can be analyzed, so that the analysis of the influencing factors of cultivated land productivity is more scientific. Secondly, with the help of the model analysis results, not only the degree and direction of the influence of various factors on the cultivated land productivity are obtained, but also the influence path and coefficient between the variables are obtained, and the relationship between the variables is clarified, thus providing a basis for further analysis of the cultivated land productivity. Thirdly, this study analyzes the overall reliability and validity of the index system and model to ensure the scientificity of the results. Finally, by calculating the path coefficient and the score of latent variables, the influence degree of each influencing factor can be sorted, so as to improve the quality of cultivated land and improve the productivity of cultivated land.

5. Conclusion

In this paper, Hanzhong City is taken as the research area, and the structural equation model was used to construct the model of the relationship between latent variables and latent variables, latent variables and observed variables. The multi-factor comprehensive influence of regional cultivated land productivity was analyzed, and the main driving factors and their influence path and influence degree are clearly revealed. The results show that farmland water conservancy, soil properties and soil nutrients are the main driving factors affecting cultivated land productivity, which have a significant direct impact on cultivated land productivity. In addition, farmland water conservancy and soil properties can also indirectly affect the productivity of cultivated land through the mediating effect of soil nutrients. The total effect of each factor on cultivated land productivity from large to small is soil properties (0.587) > farmland water conservancy (0.552) > soil nutrients (0.464). In this study, geological characteristics do not directly affect the productivity of cultivated land, but have a significant positive impact on soil nutrients, thus indirectly affecting the productivity of cultivated land. Slope has a negative effect on cultivated land productivity. The research area selected in this paper belongs to the typical hilly area of southern Shaanxi. The research results can provide reference for the study of the influencing factors of cultivated land productivity in similar areas in the central and western regions.

According to the research results, this paper puts forward the following suggestions: First, improve the construction of farmland water conservancy and improve the conditions of agricultural production. Southern Shaanxi is rich in water resources, but seasonal water shortage and flood disasters coexist. Renovating the existing water conservancy facilities in Hanzhong City and improving the ability of cultivated land to resist natural disasters are conducive to ensuring regional food security. Second, improve the quality of cultivated land and transform low-yield fields. Through soil testing and formulated fertilization, soil fertility and soil properties were improved, so as to further tap the production potential of low-yielding fields in Hanzhong City. Third, accelerate farmland land remediation. Through land leveling, the slope is transformed into terraces to reduce the negative impact of limiting factors on cultivated land productivity.

6. Limitations and future research directions

The research results of this paper are based on the current data of a certain time point, which is static, while the interaction between various factors is a dynamic process. The data of influencing factors and variables will change constantly, and with the change of data, the structural equation model will also change to some extent. This study is still unable to grasp the development trend of data, which is the limitation of this paper and most experimental articles. When conditions permit, the survey data of different periods should be collected, the structural equation model of different data in different periods should be established, and the model and results should be compared and analyzed to make the results more scientific.

Data availability statement

The original contributions presented in the study are included in the article/supplementary material, further inquiries can be directed to the corresponding author.

Author contributions

HD and JH: methodology and software. HD and YZ: formal analysis. HD: resources and data curation and writing-original draft preparation. CW: investigation. HD and HF: writing-review and editing. TC: supervision and project administration. All authors contributed to the article and approved the submitted version.

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Conflict of interest

HD, JH, YZ, TC, HF, and CW were employed by Shaanxi Provincial Land Engineering Construction Group Co., Ltd.

Publisher's note

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