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Evolution of Cultivated Land Quality and Its Impact on Productivity in Three Arid Ecological Zones of Northern China

Haiyan Wang ^{1,†}, Ping Liu ^{2,†}, Paul N. Williams ³ , Xiaolan Huo ², Minggang Xu ^{2,4,*} and Zhiyong Yu ²

¹ Social Service Department, Shanxi Agricultural University, Taiyuan 030031, China; wanghy19830508@163.com

² College of Resources and Environment, Shanxi Agricultural University, Taiyuan 030031, China; lp709@163.com (P.L.)

³ Institute for Global Food Security, School of Biological Sciences, Queen's University Belfast, Belfast BT9 5DL, UK

⁴ Soil Health Laboratory of Shanxi Province, Institute of Eco-Environment and Industrial Technology, Shanxi Agricultural University, Taiyuan 030031, China

* Correspondence: xuminggang@caas.cn

† These authors contributed equally to this work.

Abstract

Cultivated land quality is critical for soil productivity and scientific fertilization. This study analyzed its evolution and impact on soil productivity across three ecological regions (southern, central, and northern Shanxi) in Shanxi Province, China, from 1998 to 2021). Using data from 8 long-term experimental sites (1998–2021) and 50 monitoring stations (2016–2021), we employed random forest analysis to evaluate temporal trends in key soil indicators. The results show the following: (1) Northern Shanxi exhibited the greatest improvement in soil fertility, with organic matter increasing by 98.2%, total nitrogen by 57.2%, available phosphorus by 131.7%, and available potassium by 17.1%. (2) Nitrogen fertilizer application increased across all regions, while phosphorus and potassium inputs generally declined. (3) Crop yields improved substantially—southern Shanxi wheat and maize increased by 15.3% and 20.9%, respectively, while central and northern Shanxi maize yields rose by 30.9% and 75.4%. Random forest models identified regional characteristics (40%), nitrogen fertilization (20%), and available phosphorus (18%) as primary influencing factors. Although cultivated land quality improved overall, soil fertility remained medium to low. Region-specific management strategies are recommended: rational nitrogen use in all regions; nitrogen control with phosphorus supplementation in the south; focused improvement of available phosphorus and potassium in the center; and increased organic fertilizer in the north. These measures support scientific nutrient management and sustainable agricultural production.

Keywords: Northern China; cultivated land quality; soil productivity; crop yield



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1. Introduction

Shanxi Province is located in the semi-arid region of the Loess Plateau in China, with features of complex topography, an arid climate, large hilly and mountainous areas, and severe soil erosion [1]. These features contribute to unstable agricultural productivity and low-quality cultivated land. In addition, the dryland agricultural areas of Shanxi Province have complex natural conditions; changeable terrain; and rich farming systems, such as a two-cropping system per year or a three-cropping system every two years in the southern region. Furthermore, the planting mode is mainly wheat–maize rotation, along with a

major production area of apples and pears. By contrast, in the central and northern regions, a one-cropping system is practiced, mainly growing maize, potatoes, millet, oats, flax, and mixed beans [2]. The ecological types are diverse; from south to north, they can be divided into warm and hot climate zones (southern Shanxi), warm and temperate climate zones (central Shanxi), and cold and cool climate zones (northern Shanxi). Therefore, it is of great significance to study the evolutionary law of cultivated land quality under different ecoclimatic regions and different use patterns in Shanxi Province to guide the scientific-based management and improvement of cultivated land quality.

Providing sufficient nutrients to crops through fertilization is one of the important ways to maintain high and stable crop yields [3–7]. Fertilization can significantly increase crop yield compared with no fertilization [8,9]. Nitrogen and phosphorus fertilizers greatly influence the change in the rice fertilizer contribution rate [10–12]. Compared with other soil fertility indicators, soil organic matter is a key soil fertility factor affecting changes in the rice fertilizer contribution rate [13]. In addition, studies have shown that basal soil fertility plays an important role in stabilizing and increasing yield [14–18], and an improvement in basal soil fertility significantly improves crop yield under fertilization conditions [19,20]. In a long-term positioning experiment in China, soil productivity increased with the improvement in soil fertility with or without fertilization [21]. There was a positive correlation between soil fertility and crop yield; crop yield showed a decreasing trend when soil fertility was low. Also, one study showed a significant positive correlation between the soil fertility contribution rate and basic soil fertility level, and improving basic soil fertility would reduce the demand for chemical fertilizers in wheat while ensuring a high and stable wheat yield [22].

Most studies on cultivated land quality in Shanxi Province only analyzed one or a few nutrient indicators, and the time spans used were small, with most of them only analyzing the nutrient changes within 10 years; additionally, those of a certain type or a specific soil type in a province or city have a small coverage and lack long-term data. Changes in the soil fertility index at a specific time or point cannot scientifically explain the evolution of soil fertility and, thus, cannot fully reveal the overall status of cultivated land quality in Shanxi Province or the evolution characteristics of fertility level in different regions. This study utilized long-term monitoring data from fixed-location experiments in Shanxi Province to systematically analyze the spatiotemporal evolution of cultivated land fertility and productivity levels across different regions. The research aims to provide a scientific basis and practical guidance for the sustainable agricultural development and scientific management of cultivated land resource in Shanxi Province.

2. Materials and Methods

2.1. Overview of Monitoring Sites

The data were derived from 8 national long-term positioning experimental sites (1998~2021) and 50 provincial positioning monitoring sites (2016~2021) in Shanxi Province in China. The topography of Shanxi Province can be divided into three ecological regions. The distribution of monitoring points is as follows: southern Shanxi (19 in total, 4 at the national level), central Shanxi (21 in total, 2 national), and northern Shanxi (18 in total, 2 national). The study was conducted over three periods: initial (1998~2005), middle (2006~2014), and recent (2015~2021). Data for the recent period are integrated from national long-term experimental sites and provincial monitoring sites. Table 1 shows the basic information on the monitoring points. The monitoring sites in southern Shanxi focus on wheat and maize in a two-crop annual system, while those in central and northern Shanxi focus on maize in a one-crop annual system. These ecological regions were chosen to reflect Shanxi Province's diverse ecological and agricultural conditions.

Table 1. Properties of field soils in the tillage layer (0–20 cm) of every monitored site for different time periods.

Type	Number	Area	Crop Rotation	Crop Type	pH	Organic Matter (g·kg ^{−1})	Total Nitrogen (g·kg ^{−1})	Available Phosphorus (mg·kg ^{−1})	Available Potassium (mg·kg ^{−1})
National	4	Southern Shanxi	Two crops a year	Wheat, Maize	7.9–9.4	8.6–23.6	0.53–1.64	1.6–27.1	72–329
National	2	Central Shanxi	One crop a year	Maize	7.8–8.9	13.5–28.3	0.71–1.55	2.4–31.6	90–236
National	2	Northern Shanxi	One crop a year	Maize	7.8–8.7	4.3–13.3	0.31–1.22	2.0–26.0	60–241
Provincial	15	Southern Shanxi	Two crops a year	Wheat, Maize	7.7–9.1	7.5–34.3	0.54–1.63	2.1–40	80–410
Provincial	19	Central Shanxi	One crop a year	Maize	7.7–9.0	2.4–27.6	0.18–1.34	1.6–32.5	80–341
Provincial	16	Northern Shanxi	One crop a year	Maize	7.6–9.1	5.3–39.6	0.31–1.93	1.4–46	55–375

Notes: National—national long-term experimental sites, Provincial—provincial positioning monitoring sites.

2.2. Experimental Design

The area of each monitoring point was greater than 334 m², and there was no duplication of conventional fertilization and blank areas. For both the conventional fertilization (CF) and no-fertilization (NF) plots, crop sowing, seedling management, irrigation, pest and weed control, and straw management were carried out in accordance with the unified standards set by the local agricultural bureau. Recorded data include the crop types, fertilizer types, fertilizer amounts, and fertilizer nutrient content. Blank areas received no fertilization (NF), while other management practices matched those of the conventional fertilization (CF) areas. Based on the practices of different farmers at each site, the ranges of fertilizer application rates (in kg/ha) in the CF plots across the monitoring were as follows:

- Southern Shanxi wheat: N (67.5–718), P₂O₅ (10.5–618), and K₂O (24–744);
- Southern Shanxi maize: N (12.9–561), P₂O₅ (7.5–414), and K₂O (7.5–319);
- Central Shanxi maize: N (75–624), P₂O₅ (2.3–568), and K₂O (9.8–623);
- Northern Shanxi maize: N (34.5–645), P₂O₅ (33–435), and K₂O (21–607).

The yield of each plot was measured separately at the harvest period, and it was measured using actual harvest and random sampling threshing. After the harvest in autumn every year, the fertilization treatment was performed on the tillage layer (0–20 cm) of soil, and the sampling was sent to the provincial soil testing center for determination. The tested parameters were soil organic matter, total nitrogen, available phosphorus, available potassium content, and pH value. The determination of fertility indicators adopts conventional methods [23]: Soil organic matter (SOM) was determined using the potassium dichromate oxidation method with external heating and titration with ferrous sulfate (a modified Walkley–Black procedure). Total nitrogen (TN) was measured by the semi-micro Kjeldahl method following digestion with H₂SO₄. For calcareous soils, available phosphorus was extracted with 0.5 M NaHCO₃ (pH 8.5) and quantified by the molybdenum blue method (Olsen method). Available potassium was extracted with 1 M ammonium acetate (NH₄OAc, pH 7.0) and analyzed by flame photometry. Soil pH was measured potentiometrically in a 1:2.5 (*w/v*) soil-to-water suspension using a glass electrode.

2.3. Data Processing

In this study, inherent soil productivity was evaluated using no-fertilizer (NF) plots, which received neither organic fertilizers (i.e., crop straw and manure) nor chemical fertilizers. Conventional fertilization (CF) plots received mineral N, P, and K fertilizers at local farmer practice rates.

The contribution percentage of inherent soil productivity (CPISP) was calculated using

$$\text{CPISP (\%)} = (\text{YieldNF} / \text{YieldCF}) \times 100 \quad (1)$$

where YieldNF and YieldCF represent crop yields from the NF and CF plots, respectively [24].

Agronomic nitrogen use efficiency (ANUE) was determined using [25]

$$\text{ANUE (kg/kg)} = (\text{YieldCF} - \text{YieldNF}) / \text{N application rate} \quad (2)$$

Prior to conducting additional analyses, the normality distribution was verified using the Kolmogorov–Smirnov test, and the homogeneity of variances was assessed using Levene’s test across all raw datasets. One-way ANOVA was utilized to evaluate the significance of the treatment differences in wheat and maize yield, soil nutrition, fertilizer input, contribution index of inherent soil productivity, and nitrogen agronomic efficiency. Data points from multiple sites within each region and across different years were analyzed as independent replicates.

Paired comparisons of treatment means were performed using Tukey’s HSD test at $p < 0.05$, utilizing SPSS 16.0 software (SPSS Inc., Chicago, IL, USA). Pearson correlation analysis was employed to examine the relationship between the soil nutrition and yield. Microsoft Excel 2010 was used for data organizing and plotting. Origin 2019 was employed for box plots.

A random forest model was constructed using the randomForest package (version 4.1.3) in R to quantify the relative importance of soil nutrient indicators and fertilization practices on the crop yield. The predictor variables consisted of eight features: soil organic matter, N fertilizer, P fertilizer, K fertilizer, total N, available P, available K, and C/N, with the crop yield as the response variable. The model parameters were set as $\text{n tree} = 500$ and $\text{n rep} = 1000$ to assess the stability of variable importance and calculate the corresponding significant p -values. The model performance was evaluated using the percentage of variance explained (%Var explained) derived from the out-of-bag (OOB) error, while all other parameters were maintained at their default settings.

3. Results

3.1. Evolution and Status of Soil Nutrients in the Three Ecoregions

During the 23 years of monitoring (1998–2021), the soil organic matter content increased with time, showing an overall enriched trend in southern and northern Shanxi (Figure 1A), and it depleted slightly in central Shanxi. Integrated data from national long-term experimental sites and provincial monitoring sites for the recent period (2015–2021) show that the average organic matter content at the monitoring sites in southern, central, and northern Shanxi was 17.7, 15.5, and 13.7 g·kg^{−1}, respectively. The majority of monitoring sites fell within the 10.0–20.0 g·kg^{−1} range, accounting for 68.1%, 62.9%, and 62.0% of sites in southern, central, and northern Shanxi, respectively. The secondary distribution peak occurred in the 20.0–30.0 g·kg^{−1} range for southern and central Shanxi, representing 20.4% and 23.7% of sites, while in northern Shanxi, the secondary distribution was observed in the <10 g·kg^{−1} range, comprising 27.8% of sites (Figure 1B). The most marked increase in soil organic matter content was observed in northern Shanxi, where it rose from 6.9 g·kg^{−1} in the initial period (1998–2004) to 13.7 g·kg^{−1} in the recent period, representing a significant increase of 98.2% (Figure 1A).

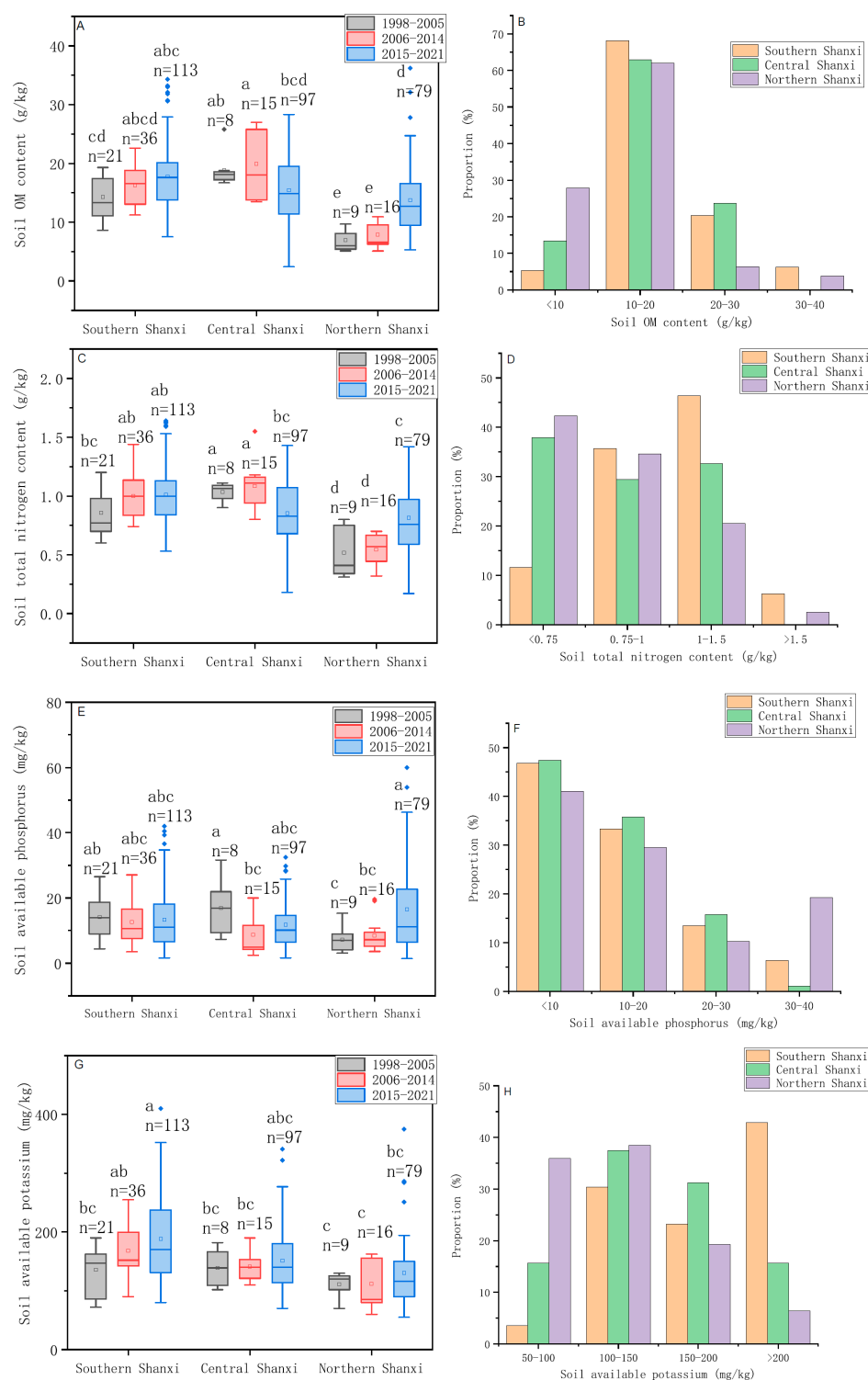


Figure 1. Current status and temporal changes of conventional soil fertility indicators. Panels (A,C,E,G) display the temporal trends of soil organic matter (OM), total nitrogen, available phosphorus (AP), and available potassium (AK), respectively, across the three ecological regions. Panels (B,D,F,H) present the current status (2015–2021) of each fertility indicator, showing the proportional distribution of monitoring sites across different concentration ranges within each region. Different lowercase letters within the same ecological region indicate statistically significant differences at the 0.05 probability level.

The variation trend of soil total nitrogen content was consistent with that of organic matter. Recent monitoring data show that the average total nitrogen contents in southern, central, and northern Shanxi were 1.0, 0.9, and 0.8 g·kg^{−1}, respectively. Spatially, 46.4%

of the monitoring sites in southern Shanxi had total nitrogen concentrations within the 1.0–1.5 g·kg^{−1} range, while in central and northern Shanxi, the majority of sites (37.9% and 42.3%, respectively) exhibited levels below 0.75 g·kg^{−1} (Figure 1D). Compared with the baseline period (1998–2004), northern Shanxi demonstrated the most significant increase in the total nitrogen content, reaching 57.2% (Figure 1C).

For the available phosphorus, the recent mean values were 13.3, 11.8, and 16.5 mg·kg^{−1} in southern, central, and northern Shanxi, respectively. Across all regions, the <10.0 mg·kg^{−1} range predominated (southern Shanxi 46.8%, central Shanxi 47.4%, northern Shanxi 41.0%), followed by the 10.0–20.0 mg·kg^{−1} range (Figure 1F). A longitudinal comparison revealed decreasing trends in southern Shanxi (−6.5%) and central Shanxi (−30.3%), while northern Shanxi showed a remarkable 131.7% increase (Figure 1E).

The available potassium monitoring results exhibit distinct regional variations, with mean values of 188.2, 151.4, and 129.8 mg·kg^{−1} in southern, central, and northern Shanxi, respectively. The 100–150 mg·kg^{−1} range was the most prevalent in central Shanxi (37.5%) and northern Shanxi (38.5%), whereas southern Shanxi showed the highest proportion (42.9%) in the >200 mg·kg^{−1} category (Figure 1H). A temporal analysis indicated sustained increases in the available potassium for southern and northern Shanxi, while central Shanxi displayed an initial rise followed by a decline. Compared with the baseline period, the increases were 38.5%, 8.9%, and 17.1% for southern, central, and northern Shanxi, respectively (Figure 1G).

3.2. Evolution and Current Status of Fertilization Rates in the Three Ecological Regions

Monitoring data reveal that the application ratios of N/P₂O₅/K₂O fertilizers in the three ecological regions fluctuated within the range of 1: 0.3–1.43: 0.41–1.71 (Figure 2). The specific patterns were as follows: nitrogen fertilizer application showed a consistent increasing trend across all regions, with the most pronounced growth rate of 29.5% observed in the maize area of central Shanxi (Figure 2A). Phosphate inputs demonstrated an overall decline, where they decreased by 32.2–57.0% in the final monitoring period (2015–2021) compared with the initial stage (1998–2005) (Figure 2C). Potassium application also exhibited a decreasing trend, with reductions of 43.3–67.1% in the final period, where the wheat-growing area of southern Shanxi showed the most significant decline: the recent average of 140.9 kg·hm^{−2} represented only 32.9% of the initial value (Figure 2E).

Notable changes in the fertilizer composition were observed: during the initial period, nitrogen accounted for a relatively low proportion, with the southern Shanxi maize area showing nitrogen proportions merely 38.4% and 80.0% higher than phosphate and potassium, respectively (Figure 2B). From 2015 to 2021, the nitrogen proportion increased significantly by 27.5–87.2%, peaking at 87.2% in central Shanxi's maize area. The proportion of phosphate generally decreased, except in northern Shanxi, with the maximum reduction (40.4%) occurring in central Shanxi's maize area (Figure 2D). The proportion of potassium reached its peak during the initial period (24.4–38.8%), with northern Shanxi's maize area showing the largest final-period decline of 39.2% (Figure 2F).

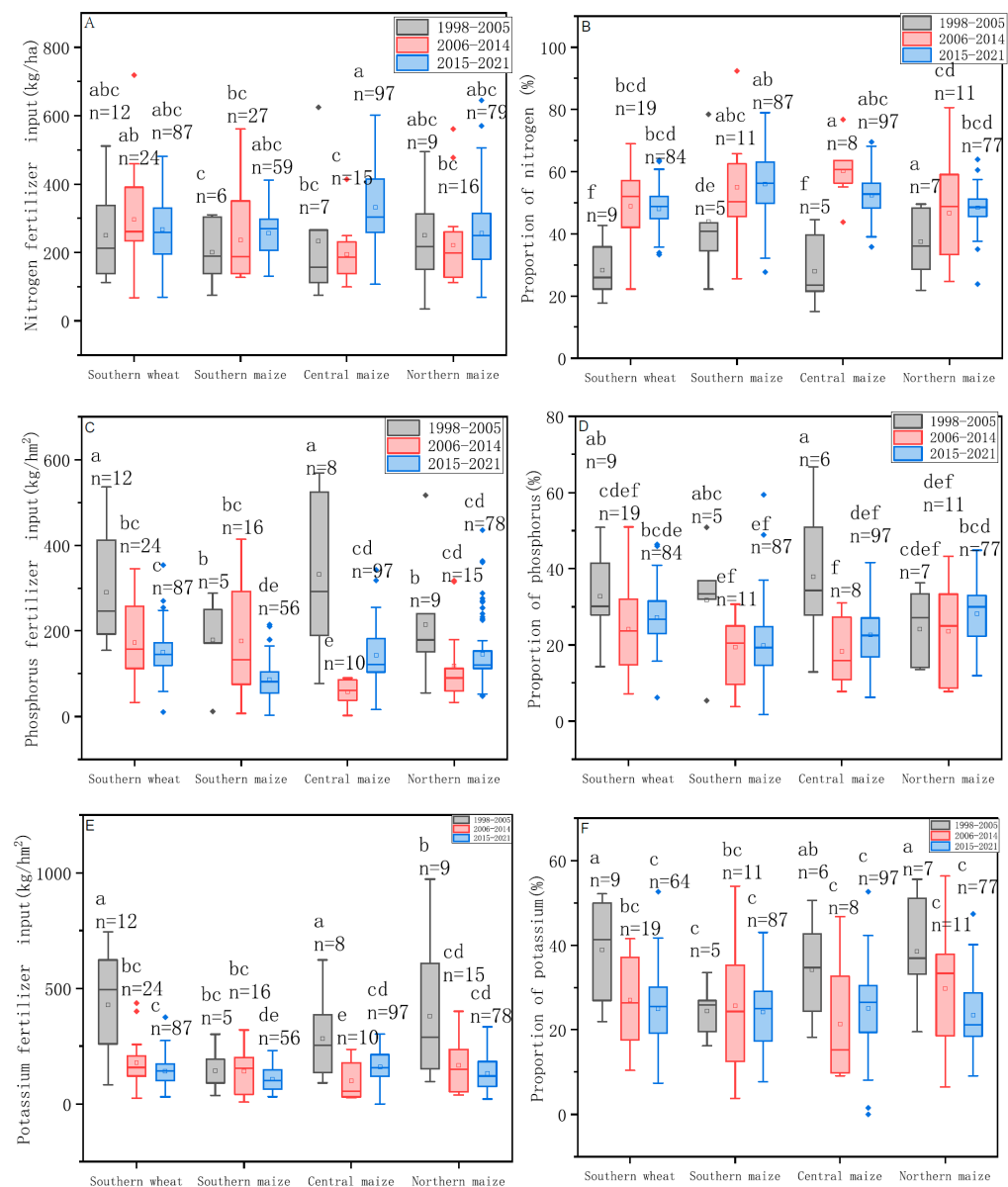


Figure 2. The inputs (A–C) and proportions (D–F) of total nitrogen, available phosphorus, and available potassium fertilizers in three ecological regions at different stages, with significant differences at the 0.05 level indicated by different lowercase letters in the same ecological regions.

3.3. Evolution of Productivity in the Three Ecoregions

During the 23-year monitoring period (1998~2021), wheat in southern Shanxi and maize in all three ecological regions showed consistent upward trends in relative yield (Figure 3). In the initial monitoring phase (1998~2005), the relative yield of maize in northern Shanxi was the lowest, being 20.2% and 32.9% lower than in southern and central Shanxi, respectively (Figure 3). By the final monitoring period (2015~2021), northern Shanxi's maize relative yield became significantly higher than that in southern Shanxi, and there was a significant difference between the relative yields at the end of the monitoring period and the initial stage, except for southern Shanxi ($p < 0.05$) (Figure 3). The relative yields of southern wheat, southern maize, central maize, and northern maize ranged from 2394 to 3795 kg·hm⁻², showing increases of 15.3%, 20.9%, 30.9%, and 75.4%, respectively, compared with the initial levels.

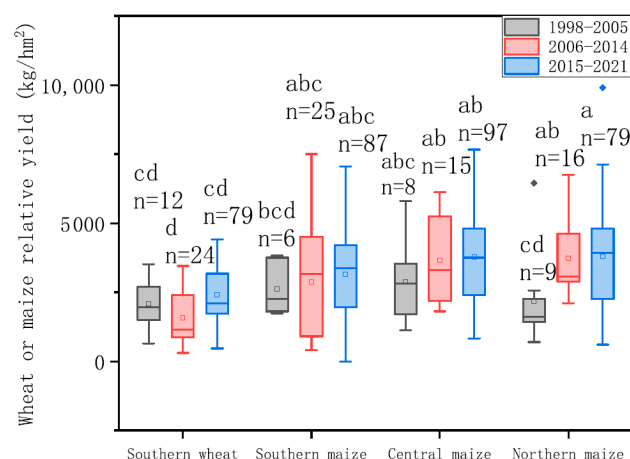


Figure 3. Relative yield change in wheat and maize under long-term fertilizer application in three regions, with significant differences at the 0.05 level indicated by different lowercase letters in the same ecological region.

3.3.1. Relationships Between Yield and Soil Nutrients in Unfertilized and Conventional Plots Across Ecological Regions

Table 2 shows that for southern Shanxi wheat, the unfertilized plot yields showed highly significant ($p < 0.01$) correlations with the soil organic matter, total nitrogen, C/N ratio, and available phosphorus, while the conventional plot yields showed highly significant ($p < 0.01$) correlations with the soil organic matter, total nitrogen, and C/N ratio. For southern Shanxi maize, the unfertilized plot yields were highly significantly ($p < 0.01$) correlated with the C/N ratio, whereas the conventional plot yields were highly significantly ($p < 0.01$) correlated with the soil organic matter.

Table 2. Relationships between yield and soil nutrition in unfertilized and conventional plots across ecological regions.

Crop	Yield	Soil Nutrition				
		OM	TN	C/N	AP	AK
Southern Shanxi wheat (n = 109)	Unfertilized plots	0.322 **	0.205 **	0.261 **	0.270 **	-
	Conventional plots	0.327 **	0.187 *	0.255 **	-	-
Southern Shanxi maize (n = 116)	Unfertilized plots	-	-	0.206 **	-	-
	Conventional plots	0.199 *	-	-	-	-
Central Shanxi maize (n = 125)	Unfertilized plots	-	-	-	-	-
	Conventional plots	-	-	-	0.229 **	0.174 *
Northern Shanxi maize (n = 83)	Unfertilized plots	0.474 **	0.430 **	0.217 *	0.316 **	-
	Conventional plots	0.486 **	0.418 **	0.261 *	0.360 **	0.247 *

Notes: Significant correlations are marked with one ($p < 0.05$) and two ($p < 0.01$) asterisks. OM: organic matter; TN: total nitrogen; AP: available phosphorus; AK: available potassium.

For central Shanxi maize, only the conventional plot yield showed highly significant ($p < 0.01$) correlations with the available phosphorus and available potassium. For northern Shanxi maize, the unfertilized plot yield correlated highly significantly ($p < 0.01$) with the soil organic matter, total nitrogen, C/N ratio, and available phosphorus; meanwhile, the conventional plot yield was correlated highly significantly with all this plus the available

potassium. The results indicate that the available phosphorus significantly affected the yield in all three ecological regions.

3.3.2. Nitrogen Fertilizer Agronomic Efficiency and Soil Productivity Contribution Coefficients Across Regions

Figure 4A shows that the soil productivity contribution coefficient in central and northern Shanxi was significantly ($p < 0.05$) lower than that for wheat and maize in southern Shanxi, indicating the soil fertility contributed more to the yield in southern Shanxi. Nitrogen agronomic efficiency followed the order central Shanxi > northern Shanxi > southern Shanxi maize > southern Shanxi wheat (Figure 4B), demonstrating that nitrogen fertilizer had the greatest yield effect on southern maize.

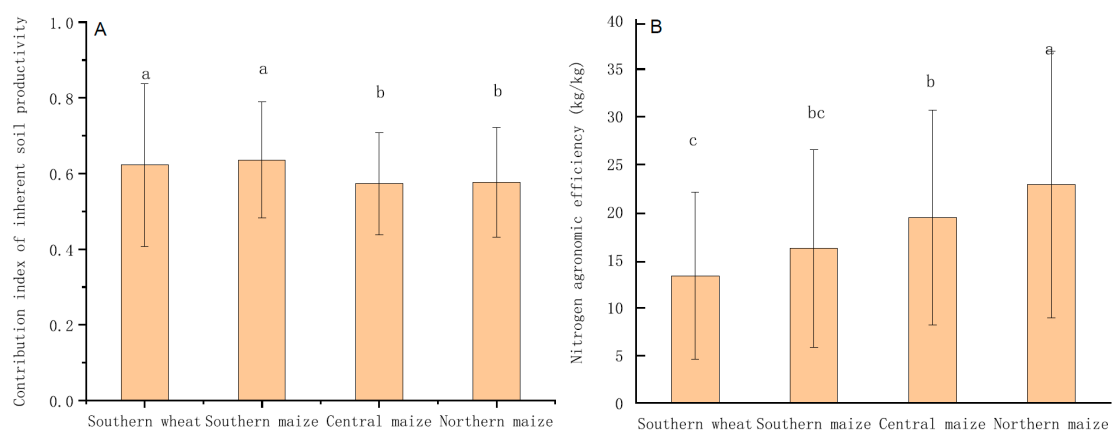


Figure 4. Contribution index of inherent soil productivity (A) and nitrogen agronomic efficiency (B) under long-term fertilizer application in three areas, with significant differences at the 0.05 level indicated by different lowercase letters in the same ecological region.

Figure 5 further shows highly significant ($p < 0.01$) negative correlations between the agronomic efficiency and soil productivity contribution coefficients for southern Shanxi wheat, southern Shanxi maize, and northern Shanxi maize, with a significant ($p < 0.05$) correlation for central Shanxi maize, confirming that nitrogen fertilizer's yield-increasing effect decreases significantly as the native soil fertility improves.

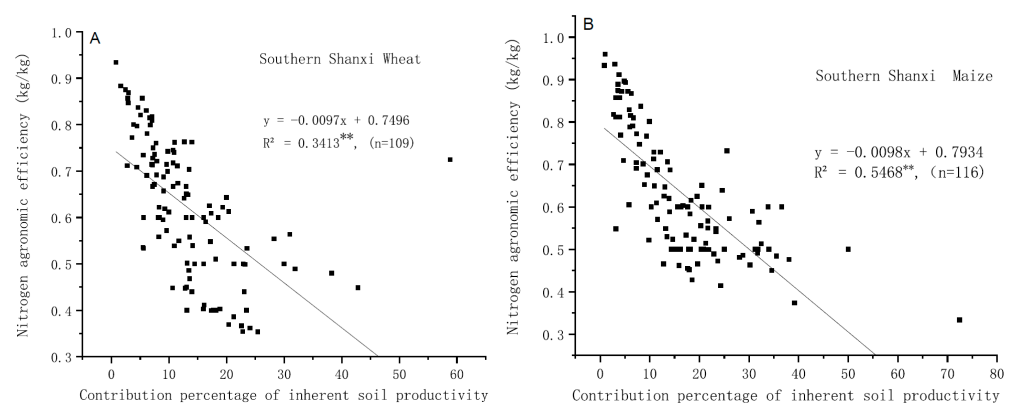


Figure 5. Cont.

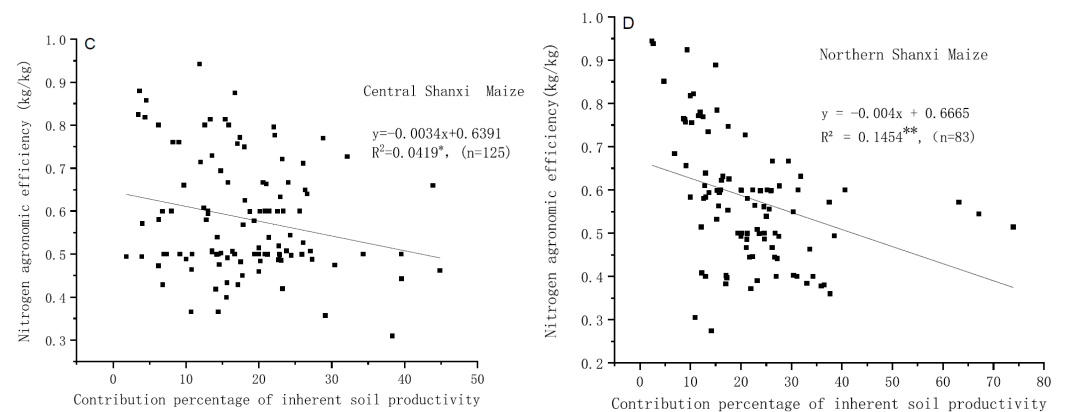


Figure 5. Relationship between nitrogen agronomic efficiency and contribution percentage of inherent soil productivity under long-term fertilizer application in three areas. * and ** represent significance at $p < 0.05$ and $p < 0.01$, respectively. (A): Southern Shanxi Wheat, (B): Southern Shanxi Maize, (C): Central Shanxi Maize, (D): Northern Shanxi Maize.

3.3.3. Analysis of Influencing Factors of Productivity

Overall, the region had the greatest influence on productivity (~40%), followed by nitrogen fertilizer (~20%) and soil available phosphorus (~18%) (Figure 6A). The specific regional productivity patterns were as follows: for southern Shanxi wheat, N fertilizer (8.8%) * > total N (8.1%) * > K fertilizer (6.9%) * $\approx$ P fertilizer (6.9%) * (Figure 6B); for southern Shanxi maize, P fertilizer (18.8%) ** > K fertilizer (15%) ** > N fertilizer (8.8%) ** > available K (8.7%) ** > organic matter (7.5%) * (Figure 6C); for central Shanxi maize, N fertilizer (10.6%) ** > total N (5.8%) * > available P (4.6%) * (Figure 6D); for northern Shanxi maize, organic matter (9%) * > N fertilizer (7.6%) * (Figure 6E).

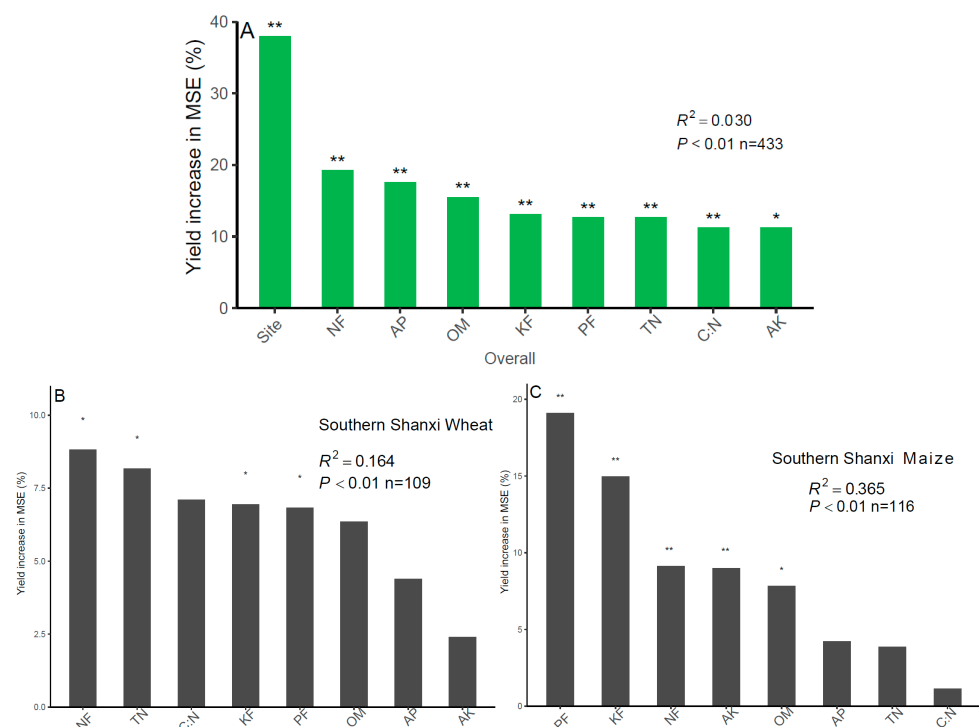


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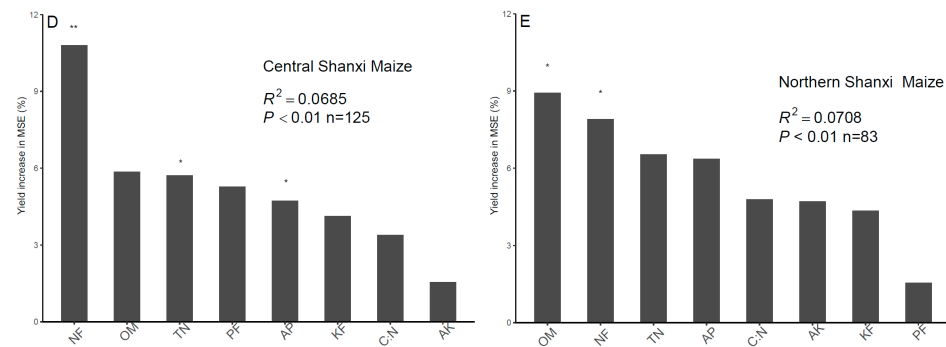


Figure 6. Effects of regional factors and fertilization on productivity. Notes: NF, N fertilizer; PF, P fertilizer; KF, K fertilizer; OM, organic matter; TN, total N; AP, available P; AK, available K; * and ** mean 0.05 and 0.01 significance levels. (A): Overall, (B): Southern Shanxi Wheat, (C): Southern Shanxi Maize, (D): Central Shanxi Maize, (E): Northern Shanxi Maize.

These results demonstrate that soil nutrients and fertilization factors contribute differently to the soil productivity across regions. Nitrogen fertilizer had primary effects on the yields of wheat and maize in all regions. The total soil nitrogen content substantially increased the productivity in southern and central Shanxi. Organic matter not only played a leading role in the productivity of northern Shanxi with a low fertility level but also had a significant impact on maize yield in southern Shanxi. Additionally, phosphate and potassium fertilizers had significant effects on the wheat and maize in southern Shanxi.

4. Discussion

4.1. Evolution and Current Status of Cultivated Land Quality in Three Ecological Regions

Long-term fertilization is one of the key strategies to improve soil quality [26,27]. Studies have demonstrated that sustained fertilization significantly improves soil organic matter, total nitrogen, and available phosphorus content [8,28] while also enhancing the comprehensive fertility of soils [28]. Our findings reveal that, after 23 years of fertilization management, conventional fertility indicators across Shanxi's three ecological regions showed measurable improvement, consistent with previous research [4,28]. The most significant improvements in organic matter (+98.2%), total nitrogen (+57.2%), and available phosphorus (+131.7%) were observed in northern Shanxi, which are attributable to its initially lower fertility level and cool climate, which promotes organic matter sequestration and strong nutrient correlations [29]. Southern Shanxi's available potassium increased by 38.5%, which is attributable to its warmer climate and potassium-rich parent material. It is noteworthy that the significant increases in soil organic matter and total nitrogen were not only due to chemical fertilizer inputs but were also closely related to long-term straw return practices. Long-term experiments in the North China Plain have validated continuous straw return effectively promotes the formation of soil aggregates and the sequestration of organic carbon [30]. Overall, the improvement in fertility in the three ecological regions is related to the increase in nitrogen fertilizer application and its proportion in fertilizers, which is consistent with findings from cinnamon soil studies [31]. Despite the reduction in potassium fertilizer input, the available potassium content increased in both northern and southern Shanxi. This increase may stem from potassium supplementation via straw return and the slow weathering release of potassium-bearing minerals in the soil [32]. Studies have shown that under straw return conditions, the soil potassium balance can be maintained or even show a slight surplus, even when chemical potassium fertilizer application is reduced [33,34]. Long-term straw incorporation also enhanced the soil organic carbon (SOC) in the 0–40 cm soil layer [34–38]. However, insufficient organic fertilizer inputs maintained the overall fertility at medium-to-low levels (Figure 1B).

4.2. Analysis of Yield Determinants Across Ecological Regions

Fertilization significantly impacts crop yields, with combined organic–inorganic applications demonstrating superior yield enhancement and stabilization effects [39–44]. Numerous studies confirmed that organic-chemical fertilization maximizes cultivated land productivity and soil fertility [9,45,46]. The soil productivity contribution coefficient, reflecting cultivated land quality, depends on regional characteristics, inherent soil properties, and fertilization practices. Its negative correlation with the yield variation coefficient indicates higher contribution coefficients with greater yield stability [47,48]. Enhanced native soil fertility increases the crop yield response to fertilization while improving sustainability and reducing fertilizer dependence [11,18], consistent with our observed negative correlation between nitrogen agronomic efficiency and soil productivity contribution coefficients.

Our study revealed that regional differences contributed most significantly to productivity (40%), followed by nitrogen fertilizer (20%) and soil available phosphorus (18%). Crop yields in southern and central Shanxi were more influenced by nitrogen input, whereas northern Shanxi's productivity primarily depended on organic matter improvement. Notably, although northern Shanxi initially had lower soil fertility levels, it demonstrated the greatest improvement in all soil fertility indicators after long-term fertilization, resulting in the highest yield increase (maize +75.4%). Other studies have similarly confirmed that enhancing the soil fertility can significantly boost crop yields [18].

Furthermore, maintaining current productivity levels in southern Shanxi requires not only guaranteed nitrogen supply but also phosphorus and potassium inputs, along with improvements in soil organic matter and total nitrogen content. This is because the same soil must support both wheat and maize in the double-cropping system. For the low-fertility northern Shanxi region, the priority task remains enhancing soil organic matter to achieve higher productivity. Previous research showed that the content of soil organic carbon (SOC) is a key indicator for soil productivity in the North China Plain [20,49].

4.3. Scientific Fertilization Recommendations for Three Ecological Regions

Overall, regional factors had the greatest impact on productivity (approximately 40%). Therefore, customized fertilization strategies should be developed for each ecological region based on their specific factors influencing wheat and maize yields. In the high-fertility southern Shanxi region, nitrogen application should be controlled while increasing the phosphorus input during the maize season, whereas nitrogen and phosphorus supplies should be ensured during the wheat season, along with improvements in the soil organic matter and total nitrogen contents. For maize cultivation in central Shanxi, rational nitrogen application is recommended, with a focus on enhancing the soil available phosphorus and rapidly available potassium. In the low-fertility northern Shanxi region, appropriate nitrogen application should be maintained while improving the overall soil fertility, particularly by optimizing the organic matter content and C/N ratio. The pattern of change in available phosphorus showed distinct regional differences: a significant increase (+131.7%) in northern Shanxi but decreases in southern and central Shanxi. This phenomenon is highly correlated with the trends in phosphorus fertilizer application (Figure 2C). The increased application of phosphorus fertilizer in northern Shanxi directly raised the soil available phosphorus pool, while the reduced application in southern and central Shanxi led to soil phosphorus depletion exceeding replenishment. More importantly, the mean available phosphorus level in northern Shanxi soils ($16.5 \text{ mg} \cdot \text{kg}^{-1}$) has exceeded the agronomic Olsen-P threshold for maize in cinnamon soil ($14.2 \text{ mg} \cdot \text{kg}^{-1}$) [50], indicating excessive phosphorus, which poses environmental risks. In contrast, southern Shanxi ($13.3 \text{ mg} \cdot \text{kg}^{-1}$) and central Shanxi ($11.8 \text{ mg} \cdot \text{kg}^{-1}$) remain below this threshold, necessitating targeted phosphorus supplementation. Data from this study show that the percentages of monitoring

sites exceeding this threshold in southern, central, and northern Shanxi were 35.9%, 27.7%, and 33.9%, respectively, directly supporting the necessity for region-specific phosphorus management recommendations.

Higher soil fertility levels reduce the effect of nitrogen fertilizer on narrowing yield gaps; thus, nitrogen application should be moderately reduced in high-fertility soils. It is crucial to emphasize that the formulation of fertilization recommendations must consider environmental sustainability. To sustain high yields in southern Shanxi, organic matter and nitrogen–phosphorus inputs should still be increased, especially during the maize season, but as a high-fertility region, nitrogen control and phosphorus supplementation are advisable. To ensure crop yield increases while avoiding nitrogen waste and environmental risks, nitrogen application rates should not exceed the balance point [51,52]. Combined application of organic and chemical fertilizers significantly improves soil organic matter content, whereas long-term exclusive use of chemical fertilizers leads to a notable decline in organic matter [9]. Therefore, increasing organic fertilizer inputs is essential for improving soil organic matter in the low-fertility northern Shanxi.

However, this study's conclusions should also be understood within the context of specific limitations. First, the dataset was derived from long-term experimental sites and monitoring points established during different periods. Although we integrated these data, slight differences in site establishment times and management practices may have influenced the precision of the results. Second, over the 23-year study period, farmers' management practices (such as irrigation and crop variety changes) may have evolved. These factors were not fully quantified and may represent uncontrolled variables. Most importantly, climatic factors (e.g., interannual variations in rainfall and temperature) are key drivers affecting soil nutrient cycling and crop yield. Due to data availability constraints, these factors were not incorporated into our model, representing an important direction for future research.

5. Conclusions

This study systematically evaluated the impact of long-term fertilization on cultivated land quality across three ecological regions in Shanxi Province using longitudinal data. Although most areas maintained medium-to-low fertility levels, conventional fertility indicators improved variably. Northern Shanxi exhibited the most pronounced increases in organic matter (98.2%), total nitrogen (57.2%), and available phosphorus (131.7%) during 2015–2021 compared to 1998–2004, accompanied by a 75.4% rise in maize yield. Available potassium increased by 75.4%.

Region-specific management strategies should be developed for wheat and maize crops based on quantitative thresholds and the current soil status.

Southern Shanxi: As a high-fertility region, the focus should be on controlled nitrogen application and increased phosphorus supplementation, particularly during the maize season, to achieve balanced nutrition and mitigate potential environmental risks associated with nitrogen surplus.

Central Shanxi: Priority should be given to rational nitrogen use and targeted improvement of soil available phosphorus and rapidly available potassium.

Northern Shanxi (Jinbei): Given that soil available phosphorus ($16.5 \text{ mg} \cdot \text{kg}^{-1}$) exceeds the Olsen-P threshold, indicating a potential environmental risk, strategies must include controlled phosphorus application. The primary objective remains enhancing the overall soil fertility by increasing organic fertilizer inputs to boost the soil organic matter and optimize the C/N ratio.

In summary, tailored nitrogen management—reducing nitrogen in high-fertility soils and enhancing organic matter in low-fertility areas—is essential for sustainable productivity.

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