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Bio-Regulatory Mechanisms of Straw Incorporation in Haplic Phaeozem Region: Soil Ecosystem Responses Driven by Multi-Factor Interactions

Yucui Ning, Zhipeng Chen, Rui Xu, Yu Yang, Shuo Wang and Dongxing Zhou *

College of Resources and Environment, Northeast Agricultural University, Harbin 150030, China; yucuining@neau.edu.cn (Y.N.); s230202042@neau.edu.cn (Z.C.); s230202071@neau.edu.cn (R.X.); s230202055@neau.edu.cn (Y.Y.); s230202020@neau.edu.cn (S.W.)

* Correspondence: zhouboshi@neau.edu.cn

Abstract

With the increasing global food production year by year, the effective return of crop straw to the field has become an urgent problem to be solved. This study examined the impact of straw decomposition under different return methods on soil ecosystems, focusing on changes in soil biological characteristics. Simulating modern mechanized agricultural practices, an orthogonal experiment was conducted in the haplic Phaeozem region of Northeast China. The factors studied included the amount, length, and burial depth of straw returning. A comprehensive analysis model was built using path analysis, factor analysis, and response surface methodology to investigate the response of soil ecosystem during straw decomposition. This was assessed from four aspects: soil basic nutrients, organic carbon pool, enzyme activity, and microbial community structure. The study found evidence of a strong synergistic relationship between the soil enzyme system and straw decomposition. Notably, during the mid-phase of straw return (60 days), phosphatase and particulate organic carbon (POC) acted as "mirror" antagonistic indicators. Catalase, soil nitrate nitrogen, and POC were identified as key response indicators in the soil ecosystem post-straw return. The appropriate supplementation of nitrogen during the early (0–45 days) and late (75–90 days) stages of straw return was found to facilitate straw decomposition. These findings provide experimental evidence for the return of corn straw in cold haplic Phaeozem regions and offer scientific support for sustainable agricultural practices and national food security.

Keywords: soil ecosystem; path analysis; factor analysis; response surface methodology

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1. Introduction

The haplic Phaeozem area is the "ballast stone" for ensuring national food security, while a large amount of crop straw is left behind during grain production. Crop straw is a vital source of organic fertilizer for agricultural soils. Returning straw to the field can enhance soil physical structure [1,2], improve soil water and nutrient retention [3,4], and significantly increase carbon sequestration [5,6]. This practice is widely regarded as an effective method for improving soil fertility and stabilizing agricultural productivity [7,8].

In recent years, numerous studies have investigated various methods of straw return. Zhang et al. [9] explored the impact of straw crushing length on soil physical properties, finding that different straw lengths significantly improved soil porosity, bulk density, and other key physical characteristics. Similarly, Deng et al. [10] demonstrated

that the amount of straw returned to the field is crucial for maintaining the soil's physical and chemical environment. Additionally, studies by Zou et al. [11] and Liu et al. [12] highlighted the burial depth of straw significantly expands the soil's water storage capacity and improves the water regulation ability of soil, which in turn influences soil ecosystem dynamics. However, these studies mainly use laboratory analysis methods and focus on one or two individual factors related to straw return and do not fully capture the interactions between multiple factors. As a result, they fail to provide a comprehensive understanding of how straw return affects soil ecosystems under modern large scale agricultural machinery operations.

This study focuses on the haplic Phaeozem in the cold region of northern China, where unique production conditions form the core motivations for this research: Firstly, the specificity of large-scale operations and agricultural machinery requirements must be considered. Farmlands in this area are concentrated and contiguous, making traditional small and medium-sized machinery inefficient and inadequate for meeting the demands of large-scale, high-efficiency cultivation [13]. In contrast, large agricultural machinery has become an inevitable choice for the region due to its advantages of wide working width and high operational speed. Such machinery not only shortens the farming timeline, ensuring completion within the brief suitable agricultural window [14], but also serves as a key solution to the practical challenge of significant seasonal temperature variations and tight agricultural production windows in northern regions. Secondly, there are unique contradictions under large agricultural machinery operations. A sharp conflict arises between "controlling high energy consumption costs" and "optimizing straw incorporation methods (length, depth, and amount)" when implementing straw return under large machinery operations [15,16]. For instance, shallow application or coarse crushing aimed at reducing power consumption may hinder straw decomposition and soil fertility enhancement, whereas pursuing ideal straw incorporation outcomes could lead to a sharp increase in energy consumption, making practical adoption difficult. This balance between "energy consumption and benefits" emerging under specific operational parameters of large machinery, represents a substantive challenge not deeply addressed in traditional small-scale studies. Thirdly, the complexity of ecological processes in cold regions is important. Farmland soil constitutes a complex ecosystem. During the decomposition of incorporated straw, the region-specific dynamics of soil temperature and moisture are critical environmental factors influencing the decomposition rate [17–19], and they drive responses in the soil enzyme system [20], microbial community [21,22], and organic carbon pool [23], among other ecological processes. The coupling of these multiple variables and processes renders the research highly complex.

Moreover, traditional one-way ANOVA does not always meet the conditions for effective analysis, particularly when inter group parameters of different indicators do not show significant differences ($p < 0.05$) [24], which can undermine the reliability of the results obtained through conventional biostatistical methods. A single mathematical model is also limited, as it often fails to validate the model in the early stages, leading to excessive loss of information during data extraction and a lack of biological relevance in the analysis outcomes [25,26]. These issues restrict the understanding of soil ecosystem responses during straw return for decomposition.

Based on this, this study aims to clarify the impact of three factors, namely straw returning amount, length, and burial depth, on the ecosystem of cold haplic Phaeozem area under the operation conditions of modern large-scale agricultural machinery, and to find ways and solutions to promote straw decomposition and improve soil ecosystems. By designing a three factor orthogonal experiment, the following scientific questions are analyzed: (1) The dynamic coupling relationship between soil basic nutrients, soil

organic carbon pool, soil enzyme activity system, and soil microbial community during straw decomposition process; (2) Construction of comprehensive response indicators for soil ecology; (3) The influence of different straw returning factors on soil comprehensive response indicators. The research results provide theoretical support for the sustainable development of agriculture in China and the upgrading of soil conservation technology in the main grain producing areas of Northeast China.

2. Materials and Methods

2.1. Test Materials

The experiment was conducted at the Experimental Internship Base of Northeast Agricultural University (45°45′27″–45°46′33″ N, 126°35′44″–126°55′54″ E). The study area is located in a temperate continental monsoon climate zone, with an average annual temperature of 3.6 °C, annual precipitation ranging from 500 to 600 mm, an average frost-free period of 135 to 140 days, and an effective accumulated temperature of 2700 °C. The average temperature in summer 2022 was 20.9 °C.

The soil in the experimental area is classified as haplic phaeozem, and the straw used in the study was corn straw. The basic physicochemical properties of the soil are summarized in Table 1. Mesh bags used for the experiment were made of 100-mesh polyamide fiber, measuring 35 cm in length and 25 cm in width.

Table 1. Physical and chemical properties of soil and straw.

Type	Total N g/kg	Total P g/kg	Available K mg/kg	Total K g/kg	Total C g/kg	pH
Soil	2.13 ± 0.10	2.79 ± 0.06	180.20 ± 0.14		23.12 ± 0.18	6.27 ± 0.08
Straw	13.23 ± 0.12	4.63 ± 0.03		15.76 ± 0.09	481.0 ± 0.53	

2.2. Test Design

A three-factor, five-level quadratic orthogonal rotational design was employed, with straw length, straw return amount, and burial depth as the experimental factors. Based on previous studies [27,28], the maximum and minimum values of each factor were determined, corresponding to encoded values of +1.682 and −1.682, respectively. The actual values at other encoding levels were calculated through equivalent conversion between encoded and actual values, as summarized in Table 2.

According to the experimental design, straw of varying weights and lengths was placed in mesh bags (35 cm × 25 cm), soaked in water until the moisture content reached 40%, and then buried in the soil. Each treatment was randomly assigned, with four replicates. The experimental plot dimensions were 15 m in length and 1 m in width [27,28]. During the straw return period, no agricultural activities were conducted on the above-ground part of the field (Figure 1).

Taking into account the climate conditions in the cold haplic phaeozem region and referring to previous studies [29], all straw was buried according to the experimental design at the beginning of summer in 2022 (5 May). After 15 days of equilibration in the soil, samples were collected every 15 days until the end of summer (21 August). The total experimental duration consisted of six sampling cycles: t-1, 30 days of straw return; t-2, 45 days of straw return; t-3, 60 days of straw return; t-4, 75 days of straw return; t-5, 90 days of straw return; t-6, 105 days of straw return.

Table 2. Test design.

Treatment Number	Code Value			Actual Value		
	Test Factor A	Test Factor B	Test Factor C	Straw Length cm	Straw Amount kg/hm^2	Straw Buried Depth cm
1	1	1	1	20	6800	20
2	1	1	−1	20	6800	10
3	1	−1	1	20	2800	20
4	1	−1	−1	20	2800	10
5	−1	1	1	10	6800	20
6	−1	1	−1	10	6800	10
7	−1	−1	1	10	2800	20
8	−1	−1	−1	10	2800	10
9	1.682	0	0	25	4800	15
10	−1.682	0	0	5	4800	15
11	0	1.682	0	15	8000	15
12	0	−1.682	0	15	1600	15
13	0	0	1.682	15	4800	25
14	0	0	−1.682	15	4800	5
15	0	0	0	15	4800	15
16	0	0	0	15	4800	15
17	0	0	0	15	4800	15
18	0	0	0	15	4800	15
19	0	0	0	15	4800	15
20	0	0	0	15	4800	15

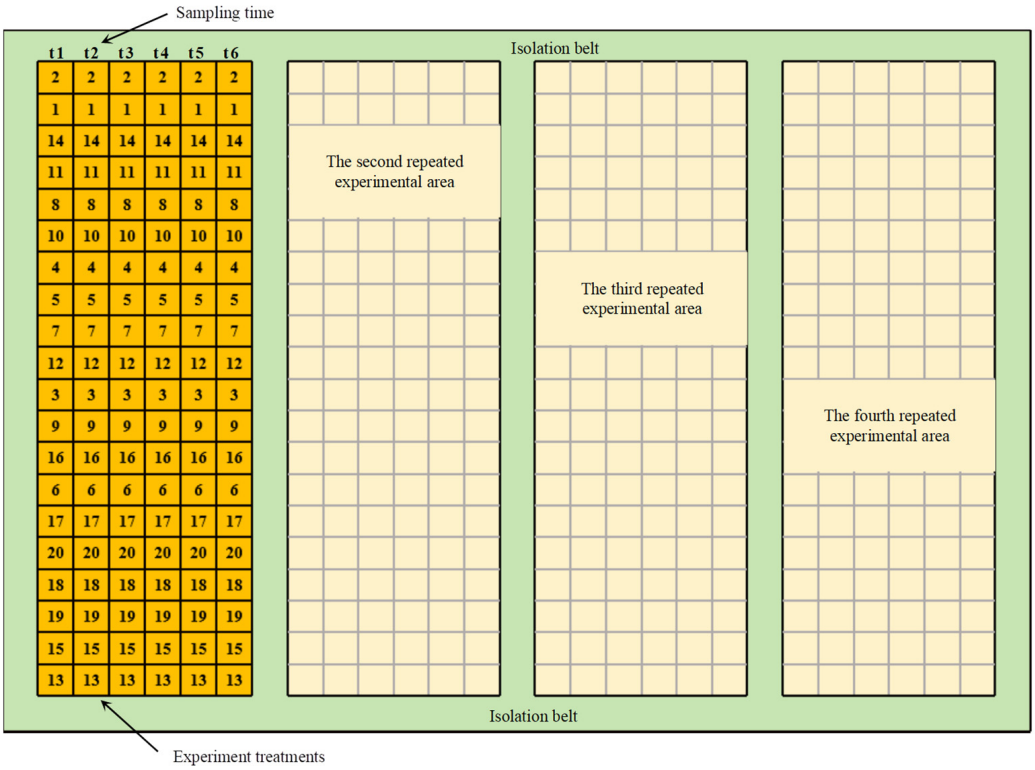


Figure 1. Test schematic diagram.

2.3. Sample Collection

Soil samples were collected from the rhizosphere soil surrounding the mesh bags and placed into sterile bags. The samples were transported to the laboratory at 4 °C for further analysis. A portion of the soil was used for determining microbial community composition, microbial biomass carbon, microbial biomass nitrogen, ammonium nitrogen, and nitrate nitrogen. The remaining soil was air dried naturally, and any impurities were removed.

Afterward, the soil was stored in self-selling bags, sieved through various pore sizes, and used for the determination of available soil nutrients, organic carbon indicators, and soil enzyme activity.

2.4. Indicator Determination

2.4.1. Soil Nutrient Determination

Soil ammonium nitrogen and nitrate nitrogen were measured using the SKALAR analysis method [30]. Available soil potassium was determined by the NH_4OAc leaching method [31]. Available phosphorus was extracted using a $NaHCO_3$ solution and measured by the molybdenum antimony colorimetric method [31]. Soil microbial biomass carbon and nitrogen were extracted using the chloroform fumigation method [32].

2.4.2. Soil Enzyme Activity Determination

Soil FDA hydrolase activity was determined using the fluorescein diacetate colorimetric method [32]. Soil dehydrogenase activity was measured using the TTC colorimetric method [32]. The activity of soil sucrase was determined by the 3,5-dinitrosalicylic acid colorimetric method [33]. Urease activity in the soil was measured using the indophenol blue colorimetric method [33]. Soil acid phosphatase activity was determined by the sodium phenylphosphate colorimetric method [33]. Finally, catalase activity in the soil was measured by titration with 0.005 mol/L $KMnO_4$ [32].

2.4.3. Soil Carbon Pool Determination

Particulate organic carbon (POC) content was determined using the sodium hexametaphosphate dispersion method [34]. Water-soluble organic carbon (WDOC) was measured using a TOC analyzer (Elementar Liquid TOC II, Frankfurt am Main, Germany) after extracting the soil with water and filtering through a 0.45 μm membrane, following the method described by Jiang et al. [35]. Easily oxidizable organic carbon (ROC) was determined using the potassium permanganate oxidation method [36]. Total organic carbon (TOC) in the soil was measured by the potassium dichromate external heating method [31]. Microbial biomass carbon (MBC) was determined using the chloroform fumigation potassium sulfate extraction method [31].

2.4.4. Soil Microbial Community Determination

Following the method outlined by Ning et al. [29], the absorbance (OD) at 590 nm was measured after a 24-h cultivation period, and measurements were continued for a total of seven cycles (168 h). The total changes in the utilization of 31 carbon sources on the ECO plate during the first cultivation cycle were recorded. Specifically, $y_t = \sum_{i=1}^{31} x_i^t$, among which, $x_i^t = \left(OD_i^t - OD_i^{t-1}\right)^2 / \left|OD_i^{t-1}\right|$. i represents the type of carbon source, $i = 31$; $t = 1, 2, 3, \ldots, 7$.

Dimensionless processing was performed on the data to obtain $Q_i^t = x_i^t / y_t \times 100\%$.

Therefore, the utilization intensity of microbial community i on carbon sources is $Z_i = \sum_{t=1}^{7} Q_i^t$.

Based on the distribution of carbon sources in the ECO plate (Table S1 (see Supplementary Materials)) and previous studies [37,38], the carbon sources were classified into different categories:

$$\begin{cases} W_1 = \sum_{n=1}^{11} Z_n^t\left(m_{\text{Carbohydrate}}\right); \quad m_{\text{Carbohydrate}} = A2, A3, B2, B3, C2, D2, F2, G1, G2, H1, H2 \\ W_2 = \sum_{n=1}^{6} Z_n^t(m_{\text{Aminoacid}}); \quad m_{\text{Aminoacid}} = A4, B4, C4, D4, E4, F4 \\ W_3 = \sum_{n=1}^{5} Z_n^t\left(m_{\text{Carboxylicacid}}\right); \quad m_{\text{Carboxylicacid}} = B1, E3, F3, G3, H3 \\ W_4 = \sum_{n=1}^{4} Z_n^t\left(m_{\text{Polymer}}\right); \quad m_{\text{Polymer}} = C1, D1, E1, F1 \\ W_5 = \sum_{n=1}^{2} Z_n^t(m_{\text{Phenolicacid}}); \quad m_{\text{Phenolicacid}} = C3, D3 \\ W_6 = \sum_{n=1}^{3} Z_n^t(m_{\text{Amine}}); \quad m_{\text{Amine}} = E2, G4, H4 \end{cases}$$

Among them, W represents the cumulative utilization intensity of microorganisms for this type of carbon source.

2.4.5. Straw Decomposition Rate Calculation

After removing the straw (still in the mesh bag) from the soil, it was placed into a sterile bag and stored at 4 °C until transportation to the laboratory. The mesh bags were then rinsed with deionized water to remove any soil and plant roots. After rinsing, the bags were dried in a 60 °C constant temperature oven to remove moisture, and the dry weight was recorded. The dry weight of the straw at each sampling time point was measured, and the decomposition rate was calculated using the following formula:

Straw decomposition rate

$$G^T = (m_0 - m_T)/m_0 \times 100\%$$

In the formula, m_0 is the dry weight of straw before returning to the field, g; m_T is the dry weight of straw after T days of decomposition in the field, g.

2.5. Data Analysis

2.5.1. Path Analysis Model

The path analysis model was used to investigate the direct and indirect effects of independent variables on a dependent variable by decomposing the correlation coefficients between them. In this study, soil nutrients, soil enzyme activity, soil carbon pool, and microbial community carbon source utilization intensity were treated as independent variables: G_x, while straw decomposition rate was set as the dependent variable: ${G^T}_y$. $R_{\alpha\beta}$ represents the simple correlation coefficient between $G_{x\text{-}\alpha}$ and $G_{x\text{-}\beta}$. Among them, α and β represent different indicators; $R_{\alpha\varphi}$ represents the correlation coefficient between G_x and ${G^T}_y$; $P_{\alpha\varphi}$ is the direct path coefficient, which represents the magnitude of $G_{x\text{-}\alpha}$ directly acting on ${G^T}_y$ when other variables are fixed. $R_{\alpha\varphi}$ can be decomposed into the following system of equations:

$$\begin{cases} P_{1\varphi} + r_{12}P_{2\varphi} + r_{13}P_{3\varphi} + \cdots + r_{1k}P_{k\varphi} = r_{1\varphi} \\ r_{21}P_{1\varphi} + P_{2\varphi} + r_{23}P_{3\varphi} + \cdots + r_{2k}P_{k\varphi} = r_{2\varphi} \\ r_{31}P_{1\varphi} + r_{32}P_{2\varphi} + P_{3\varphi} + \cdots + r_{3k}P_{k\varphi} = r_{3\varphi} \\ \cdots \\ r_{k1}P_{1\varphi} + r_{k2}P_{2\varphi} + r_{k3}P_{3\varphi} + \cdots + P_{k\varphi} = r_{k\varphi} \end{cases}$$

In this study, the absolute value of the path coefficient was used to compare the relative importance of straw decomposition on ecosystem effects. Specifically, the direct

path coefficient reflects the magnitude of the direct effect of the independent variables on the dependent variable. In contrast, the indirect path coefficient represents the magnitude of the indirect effects.

The indirect path of $G_{x\text{-}\alpha}$ to the dependent variable ${G^T}_y$ through other variables $G_{x\text{-}\beta}$ is $R_{\alpha\varphi}P_{\beta\varphi}$, and the coefficient of determination (C) of $G_{x\text{-}\alpha}$ to ${G^T}_y$ is:

$$C^2_{(\alpha)} = P^2_{\alpha\varphi} + 2\sum_{\alpha\neq\beta} P_{\alpha\varphi}R_{\alpha\beta}P_{\beta\varphi} = 2R_{\alpha\varphi}P_{\alpha\varphi} - P^2_{\alpha\varphi}$$

Secondly, the residual effect of the path is calculated $P_{R\varphi}$. If the residual effect is very small (typically less than 0.05), it suggests that the path analysis model has captured the primary influencing factors. If the residual effect is larger, additional variables should be considered to refine the model.

$$P_{R\varphi} = \sqrt{1 - \left(P_{1\varphi}R_{1\varphi} + P_{2\varphi}R_{2\varphi} + P_{3\varphi}R_{3\varphi} + \cdots + P_{k\varphi}R_{k\varphi}\right)}$$

To improve the model's credibility, the key ecological response indicator G_X was selected based on the criterion that the residual path coefficient was less than 2.00%.

2.5.2. Factor Analysis Model

The advantage of the factor analysis model lies in its ability to determine weights based on the inherent structural relationships between indicators derived from the data, without being influenced by external factors. This process enhances the objectivity and determinism of the analysis and evaluation results. In this study, important ecological response indicators extracted from the path analysis model were used as input data to construct a comprehensive soil ecological response index. The specific process is outlined as follows:

Firstly, a correlation coefficient matrix of the indicators was computed. Based on previous research [25,39], over 80% of the correlation coefficients were found to be greater than 0.1, indicating a strong correlation between the various indicators. This high correlation suggests that factor analysis is appropriate for studying the relationships among the indicators.

Secondly, the main factors were extracted. When the variance of the first i main factors F_1, F_2, …, F_i ($i < k$) and their proportion to the total variance satisfy $\xi \geq 0.70$, then the first i components are selected, which basically retain all the information of the original variables. λ_i is the largest eigenvalue. In this study, the extracted main factors were rechecked using $\lambda_i > 1$ as the standard. If the extracted factors did not meet this criterion, it was determined that the factor analysis model lacked scientific validity and could not proceed to further analysis.

Thirdly, the factor loadings were calculated. Factor load l reflects the correlation between indicator G_X and the main factor. The larger $|l_i|$, the stronger the relationship between the indicator and the main factor F_i. The main factor to which G_X belongs is denoted as F_i.

Fourth, the commonality ψ was verified. The commonality value represents the degree to which the extracted main factor F_i. can explain the indicator G_X. A commonality value closer to 1 indicates a better fit (the maximum value is 1) [39]. If ψ is lower than 0.5, it suggests that there is a deviation in the factor extraction process, and the factor loading values should be carefully reviewed. The biological significance of each indicator should be used to verify its association with the main factor.

Finally, a comprehensive response index Q for soil ecology was constructed. The weight w of each indicator was calculated based on its contribution rate ξ and commonality ψ, which were rotated by the principal factor, and then Q was constructed.

$$Q = \sum_{i=1}^{k} (\psi_i / \xi_i)$$

3. Results

3.1. Response of Soil Ecosystem After Straw Return

As shown in Figure 2, during the six sampling periods after straw return, 13 indicators were included in the path analysis model. Among these, the residual path coefficient during the t−2 period (45 days after straw return) was the highest at 1.8% (with $p < 0.01$), which met the analysis criteria of the path analysis model, indicating the reliability of the results. In Figure 2, after 30 days of straw return, indicator *X*16 exhibited the highest positive direct path coefficient of 0.654, suggesting its direct impact on straw decomposition. However, due to its indirect effect (−0.563) through *X*2, the total effect of *X*16 on straw decomposition was relatively low, with a total effect coefficient of only 0.134. In contrast, *X*22 and *X*6 ranked highest in terms of positive total effects, with coefficients of 0.491 and 0.455, respectively. Both had significant direct effects (0.431 and 0.323, respectively) and positive total indirect effects (0.059 and 0.132, respectively), highlighting their crucial roles in promoting straw decomposition.

After 45 days of straw return, the direct positive effect of *X*22 reached its maximum (1.059), but this was offset by a negative total indirect effect (−0.442). Despite this, *X*22 still showed the highest total effect, with a coefficient of 0.617, indicating its significant role in the soil ecosystem after 45 days of straw return. By 60 days, *X*19 exhibited the largest positive direct path effect (3.271) but also the largest negative total indirect path effect (−3.239), resulting in a near zero total effect (0.032) on straw decomposition. As shown in Figure 2, *X*19 negatively impacted straw decomposition through *X*11, contributing to this outcome. Furthermore, *X*11 displayed a large negative direct effect (−2.700), but its positive indirect effect via *X*19 (2.538) moderated this, leading to a net negative total effect of −0.043 for *X*11. This indicates an antagonistic relationship between *X*19 and *X*11.

After 75 days of straw return, *X*20 exhibited the largest negative direct effect (−1.259). However, this negative effect was mitigated by the positive indirect effects of *X*4 (0.257) and *X*5 (0.133), leading to a lower total effect (−0.448) on straw decomposition compared to *X*4 (−0.463), which ranked second in terms of negative effects. After 90 days of straw return, the negative direct effect of *X*20 (−0.207) was offset by a positive indirect effect (0.554), resulting in a positive total effect (0.347) on straw decomposition, positioning *X*20 as the second most influential factor, just below *X*17 (0.372).

In the final stage of the straw return experiment (105 days), *X*7 was the only factor showing positive direct (0.142), total indirect (0.116), and total (0.258) effects simultaneously. Its indirect effect through *X*22 was the largest positive indirect effect, with a value of 0.576. Meanwhile, *X*11 ranked second in terms of indirect effect, with a value of 0.563. As shown in Figure 2, the negative maximum direct effect of *X*11 (−0.629) was counterbalanced by its positive maximum total indirect effect (1.166), resulting in a total effect of 0.537 for *X*11, second only to *X*16 (0.649). In contrast, *X*22 showed a positive maximum direct effect (1.074) that was offset by its large negative total indirect effect (−0.871), leading to a modest total effect of 0.204 for *X*22. This suggests that, by this stage, the response of the soil ecosystem had become more complex and integrated, with multiple factors interacting to influence straw decomposition.

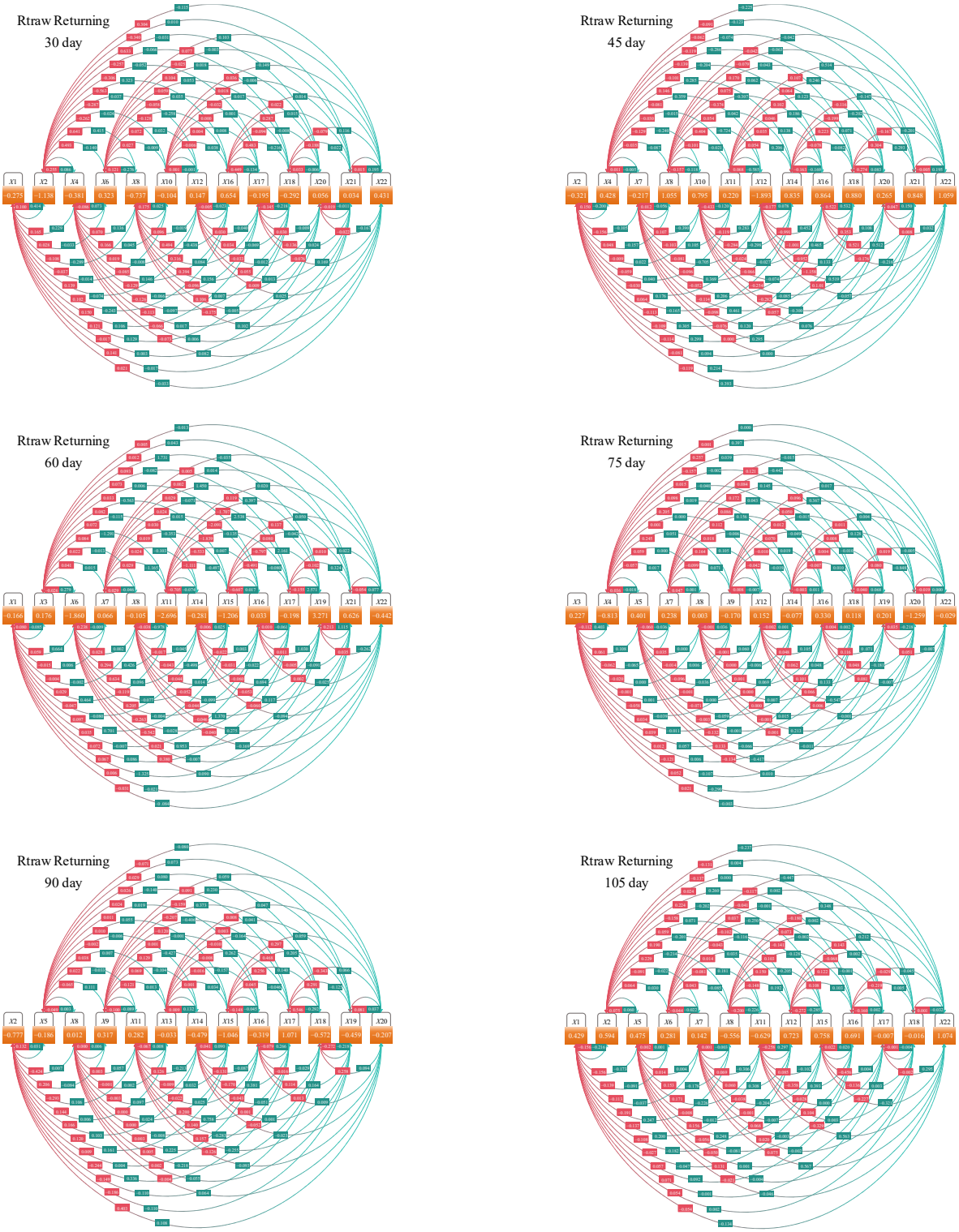


Figure 2. Path analysis diagram ($p < 0.01$).

3.2. Impact of Straw Returning Factors on Soil Ecosystems

Construct a comprehensive soil ecological response index using factor analysis models (see Supplementary Materials for the model validation process). Based on this response index, the response surface analysis was conducted on the factors affecting straw returning. The results of the model construction are shown in Table 3.

Table 3. Response surface model and the variance analysis.

Straw Returning Time (Day)	Polynomial	Regression Equation		Variance Analysis			
		Coefficients	Type	Sum of Squares	df	*F* Value	*p* Value
30	*A*	−3.51	Cubic Model	168.09	1	0.25	0.6284
	B	4.29		103.88	1	0.15	0.7030
	C	−9.94		1348.80	1	1.99	0.1861
	BC	−11.36		1031.98	1	1.52	0.2431
	A^2	13.10		2499.61	1	3.69	0.0812
	C^2	−11.99		2093.04	1	3.09	0.1067
	ABC	27.16		5900.25	1	8.70	0.0132
	A^2B	13.12		570.10	1	0.84	0.3789
	Constant	525.47					
	Model			16,022.64	8	2.95	0.0497
	Lack of Fit			4190.61	6	1.07	0.4812
45	*A*	11.00	Quadratic Model	1653.20	1	2.83	0.1206
	B	11.83		1912.06	1	3.28	0.0977
	C	−14.49		2867.58	1	4.91	0.0487
	AB	16.75		2244.67	1	3.84	0.0757
	BC	13.27		1409.28	1	2.41	0.1485
	A^2	14.82		3166.21	1	5.42	0.0400
	B^2	12.42		2223.73	1	3.81	0.0769
	C^2	6.74		654.19	1	1.12	0.3125
	Constant	367.98					
	Model			15,266.61	8	3.27	0.0363
	Lack of Fit			5128.64	6	3.30	0.1053
60	*A*	−27.12	Quadratic Model	10,042.46	1	12.16	0.0059
	B	0.72		7.14	1	0.00	0.9278
	C	−16.98		3938.61	1	4.77	0.0539
	AB	−7.61		462.95	1	0.56	0.4713
	AC	12.78		1305.98	1	1.58	0.2372
	BC	3.30		87.33	1	0.11	0.7518
	A^2	−22.46		7270.07	1	8.80	0.0141
	B^2	−18.60		4987.37	1	6.04	0.0338
	C^2	−16.58		3959.81	1	4.79	0.0534
	Constant	390.34					
	Model			29,445.81	9	3.96	0.0214
	Lack of Fit			6450.34	5	3.56	0.0948
75	*A*	−3.58	Quadratic Model	174.93	1	0.40	0.5397
	B	−5.24		375.04	1	0.86	0.3744
	C	−10.83		1601.80	1	3.69	0.0836
	AB	9.18		674.50	1	1.55	0.2409
	AC	5.43		236.16	1	0.54	0.4776
	BC	−15.30		1871.96	1	4.31	0.0645
	A^2	−13.75		2726.36	1	6.28	0.0311
	B^2	−18.37		4860.69	1	11.20	0.0074
	C^2	−1.60		36.99	1	0.09	0.7763
	Constant	462.39					
	Model			11,891.64	9	3.05	0.0488
	Lack of Fit			1796.97	5	0.71	0.6435

Table 3. *Cont.*

Straw Returning Time (Day)	Polynomial	Regression Equation		Variance Analysis			
		Coefficients	Type	Sum of Squares	df	*F* Value	*p* Value
90	*A*	−35.36	Cubic Model	7071.86	1	12.23	0.0129
	B	0.94		5.05	1	0.00	0.9286
	C	36.50		7538.23	1	13.04	0.0112
	AB	1.01		8.19	1	0.01	0.9091
	AC	23.61		4458.34	1	7.71	0.0321
	BC	−10.67		910.72	1	1.57	0.2562
	A^2	−16.61		3976.47	1	6.88	0.0395
	B^2	−13.21		2514.22	1	4.35	0.0821
	C^2	17.91		4623.66	1	8.00	0.0300
	ABC	21.83		3813.21	1	6.59	0.0425
	A^2B	10.95		397.50	1	0.69	0.4388
	A^2C	−58.02		11,154.31	1	19.29	0.0046
	AB^2	48.90		7923.15	1	13.70	0.0101
	Constant	429.64					
	Model			42,259.12	13	5.62	0.0219
	Lack of Fit			1277.19	1	2.91	0.1486
105	*A*	27.34	Quadratic Model	10,211.47	1	16.10	0.0025
	B	14.87		3018.61	1	4.76	0.0541
	C	−15.05		3093.54	1	4.88	0.0517
	AB	15.98		2042.84	1	3.22	0.1029
	AC	−6.49		337.48	1	0.53	0.4825
	BC	−44.84		16,082.44	1	25.36	0.0005
	A^2	−3.12		140.15	1	0.22	0.6484
	B^2	4.25		259.82	1	0.41	0.5365
	C^2	17.44		4381.65	1	6.91	0.0252
	Constant	431.46					
	Model			39,638.32	9	6.94	0.0028
	Lack of Fit			4133.34	5	1.87	0.2541

Note: A is the straw length; B is the straw amount; C is the straw burial depth.

According to the table, the Prob > *F* values for the models constructed for each treatment group were all less than 0.05, indicating that the models are statistically significant. Additionally, the term "Lack of Fit" is not significant, further supporting the validity of the regression models. These equations demonstrated scientific rigor and effectively captured the impact of various factors on the soil ecosystem following straw return. Specifically, after 30 and 90 days of straw return, cubic models were used to represent the comprehensive response of the soil ecosystem to the factors associated with straw return. The interaction term (*ABC*) in the cubic equation was found to be significant, indicating that the interaction between straw burial depth, straw length, and straw return amount has a notable effect on the soil ecosystem. At 90 days of straw return, the linear terms *A* (straw amount) and *C* (burial depth), as well as the interaction term *AC*, were also found to significantly influence the soil ecology. And the degree of impact on soil ecological effects is $C > A > AC$. As shown in Figure 3, when the straw return amount (*B*) was set to its baseline (zero coding value), the soil's comprehensive ecological response reached its maximum with the minimum straw length and burial depth. As the straw burial depth increased, however, the comprehensive response of the soil ecology followed an "inverted U" shape with increasing straw length. In contrast, when the straw burial depth was at its minimum, the soil's comprehensive ecological response followed a "U" shape as the straw length increased.

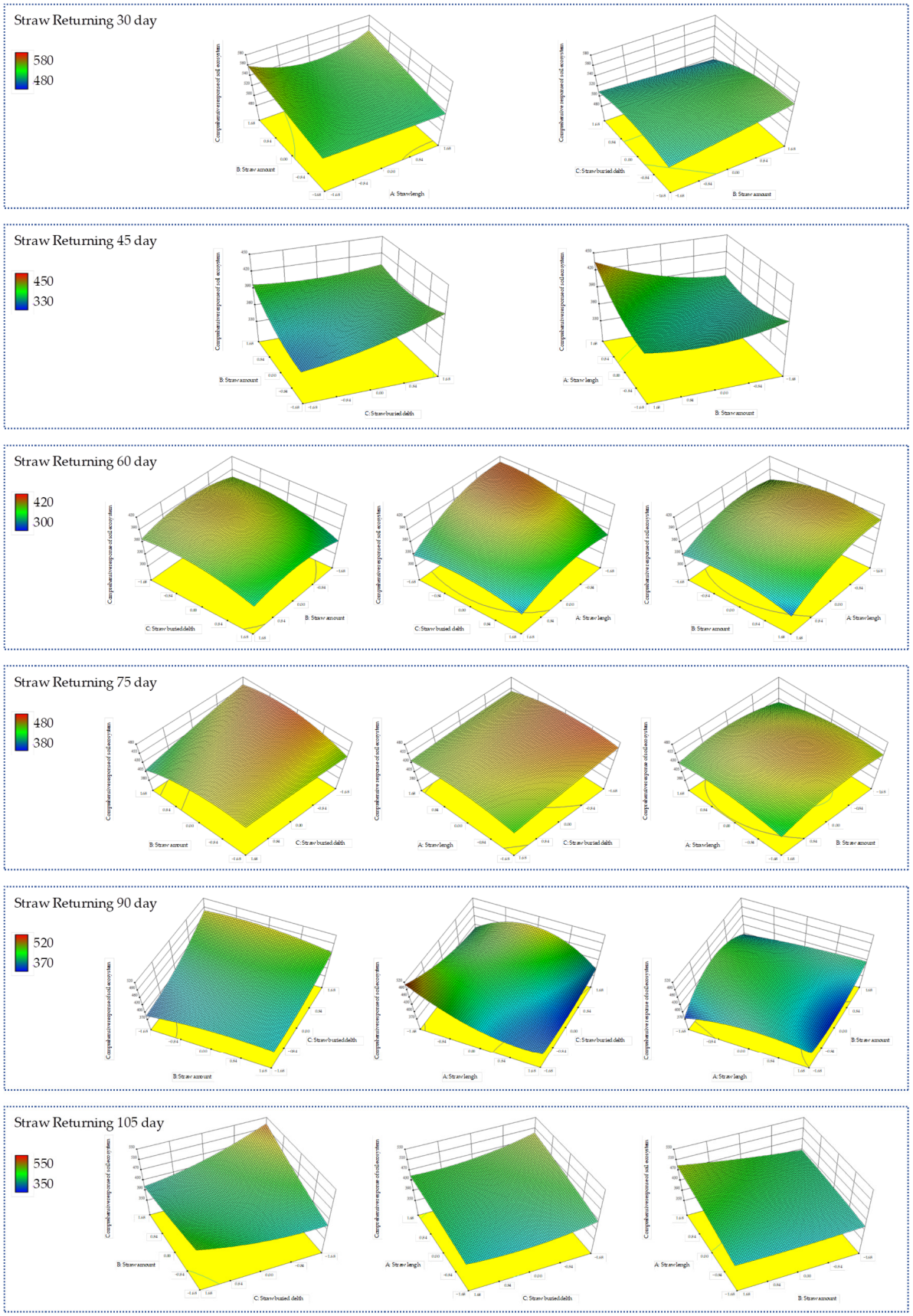


Figure 3. Response surface analysis of the impact of straw returning factors on soil ecosystems (only show the interaction terms where the coupling effect of straw returning factors reaches a significant level).

On days 60 and 105 after the straw return, quadratic models were applied to the comprehensive ecological response of the soil to the returning factors. In both cases, the linear term *A* (straw amount) showed a highly significant effect. However, on day 105, the interaction term *BC* also demonstrated a significant correlation with the comprehensive response of the soil ecosystem. Moreover, *BC* has a greater impact than *A*. After 75 days of straw return, while the model was successfully constructed, only the quadratic term in the regression equation showed a significant correlation with the soil's ecological response.

4. Discussion

Based on Figure 2 and Table S2 (see Supplementary Materials), the results of the path analysis model were reliable, and the factor analysis model met the criteria for factor extraction. This indicates that the composite model is suitable for studying the impact of straw return on haplic phaeozem ecosystems.

According to Figure 2, after 30 days of straw return, several key soil enzymes, namely FDA hydrolase, dehydrogenase, urease, sucrase, and catalase, were incorporated into the path analysis model, with all showing positive total effects. Furthermore, the interaction between straw burial depth, straw length, and straw return amount significantly influenced the soil ecological response (Table 3). This could be attributed to the decomposition of organic matter, which provides essential nutrients and energy for soil microorganisms, leading to rapid microbial proliferation [12,40]. The increase in microbial activity raises the availability of substrates for soil enzymatic reactions, thereby enhancing soil enzyme activity [41]. However, as the straw decomposition process continues over time, the easily decomposable cellulose and hemicellulose in the straw are fully broken down. This causes the decomposition rate to slow, eventually reaching a stagnation phase [42]. With the depletion of energy rich components such as cellulose, soil microorganisms begin to die in large numbers, resulting in a significant decrease in soil enzyme activity [43]. Therefore, after 105 days of straw return, only FDA hydrolase, dehydrogenase, and catalase were retained in the path analysis model, with catalase showing a positive total effect. This suggests a synergistic relationship between the soil enzyme system and straw decomposition.

Furthermore, according to the model construction results shown in Table 3, after 105 days of straw return, the interaction between straw return amount and burial depth significantly influenced soil ecological effects, displaying a "polarization" phenomenon (Figure 3). When the coding values of straw returning amount are at (1.52, 1.63) and the coding values of straw burial depth are at (−1.47, −1.17), the soil ecosystem effect value is the highest; But when the coding value of straw returning amount is at (1.19, 1.30) and the coding value of straw burial depth is at (0.90, 1.19), the soil ecosystem effect value is the smallest. This was characterized by a maximum value on the opposite diagonal and a minimum value on the same diagonal. This pattern may be related to nitrogen dynamics in the soil. During the early stages of straw return, the high carbon-to-nitrogen ratio in the straw leads to competition between straw decomposition and the soil ecosystem for nitrogen [44]. However, in the later stages, nitrate nitrogen concentration increases while nitrogen leaching decreases [45,46]. During the first 45 days of straw return, only nitrate nitrogen entered the path analysis model, where its positive direct effects were offset by negative total indirect effects. After 105 days, both ammonium nitrogen and nitrate nitrogen were incorporated into the model, and the extent of cancellation between their positive direct and negative total indirect effects weakened, resulting in the maximum positive effect of nitrogen on straw decomposition during this period (Figure 2).

Soil urease, one of the most active hydrolytic enzymes in soil, plays a crucial role in nitrogen cycling within soil ecosystems. It catalyzes the hydrolysis of urea into NH_3, which can then be further converted into NH_3, reflecting the nitrogen supply capacity of the soil [47]. As shown in Figure 2, urease exhibited the largest negative direct effect after 75 days of straw return, suggesting that the reduced nitrogen supply capacity in the soil hindered straw decomposition. However, after 90 days, the negative direct effect of urease was offset by positive indirect effects, triggering a response process in the soil ecosystem (Figure 4) ("urease → amino acid microorganisms → FDA hydrolase"), resulting in urease's total effect being second only to that of FDA hydrolase. Soil FDA hydrolase, an important indicator of soil microbial biomass and microbial activity [48], exhibited the greatest positive direct and total effects after 90 days of straw return. In contrast, soil ammonium nitrogen showed the greatest negative direct and total effects during this period. These findings suggest that, as straw decomposes, the nitrogen required by microorganisms is insufficient, forcing them to absorb nitrogen sources from the soil ecosystem. To improve the effectiveness of straw return, nitrogen fertilizer could be applied alongside traditional straw returning practices [49]. On the one hand, in the early stage (0–45 days), nitrogen supplementation can help balance the high carbon-to-nitrogen ratio in the straw, promoting the activity of nitrogen solubilizing microorganisms [50]; On the other hand, in the later stage (75–90 days), appropriate nitrogen supplementation would help maintain the balance of soil ecosystem functions [51,52], enhance soil enzyme activity, and ensure the completion of straw decomposition.

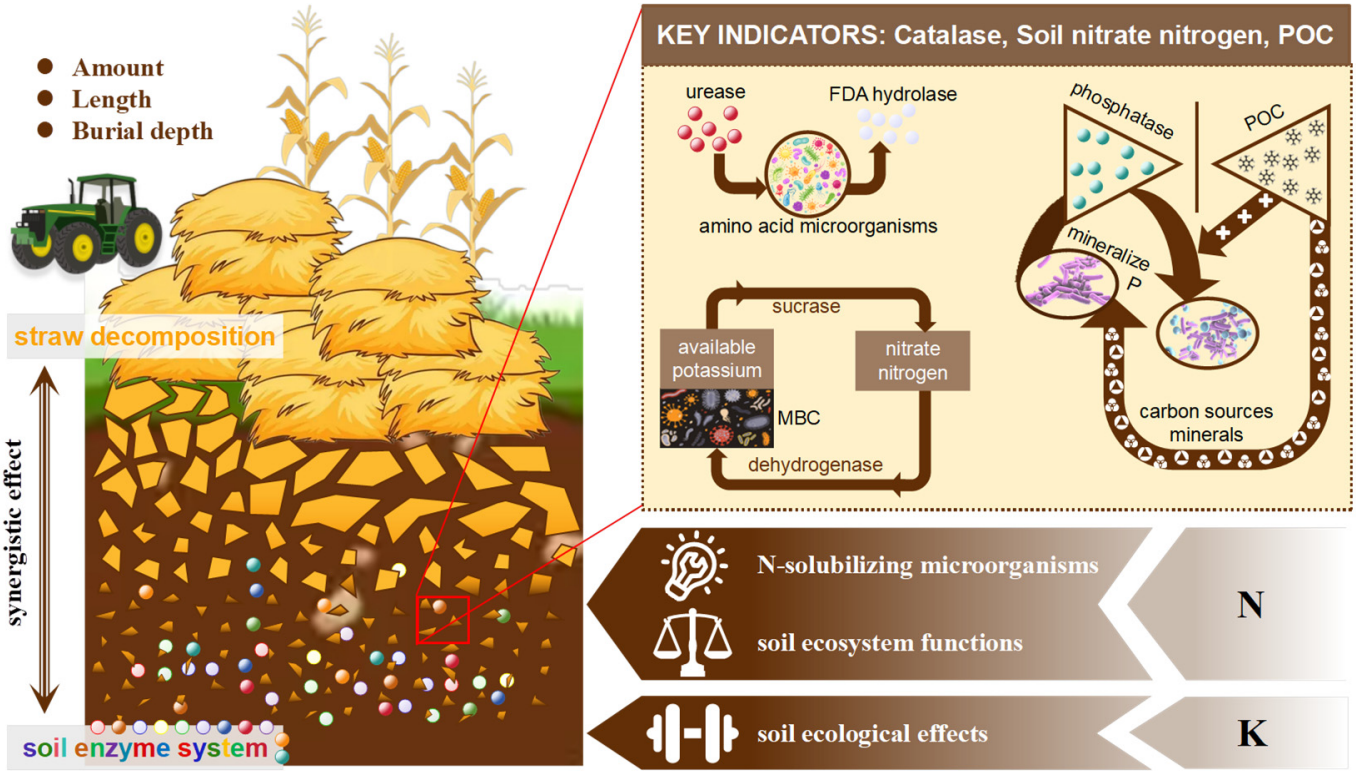


Figure 4. Key biological factors affecting the stability of haplic phaeozem ecosystems and their response mechanisms to straw return.

Catalase, a key indicator of soil humification and organic matter accumulation, was included in the path analysis model for all treatment groups except the 90-day straw return group. This suggests that catalase is an important response indicator for soil ecosystems following straw return. Catalase's spatial structure allows it to bind and catalyze amino acid

functional groups [53], which explains the significant indirect path effect of catalase through amino acid microorganisms during the early stages of straw return (30- and 45-day groups). However, amino acid microorganisms themselves show a significant negative direct effect on straw decomposition (Figure 2). Furthermore, catalase, as the primary oxidoreductase in soil, uses hydrogen peroxide as a substrate to quickly convert waste products from soil metabolism into harmless or less toxic substances, while also releasing oxygen [54]. In the short term, following straw return, substances that inhibit soil biochemical processes can accumulate, reducing catalase activity. This explains the negative direct effect of catalase observed in the middle stages of straw return (60- and 75-day groups). However, with long-term straw return, both the accumulation and activity of catalase in the soil increase, highlighting its positive effect. Moreover, long-term straw return optimizes soil physical properties and increases soil organic matter and nutrient content, directly or indirectly enhancing soil enzyme activity [55]. The direct effect of catalase on straw decomposition turned positive in the 105-day group, indicating that the detoxification capacity of soil catalase strengthens over time, helping to alleviate the toxic effects of hydrogen peroxide on soil and organisms.

After 60 days of straw return, phosphatase and POC emerged as "mirror" antagonistic indicators in the soil ecosystem under the influence of factors such as FDA hydrolase, sucrase, ammonium nitrogen, and amine microorganisms. Phosphatase exhibited the largest positive direct effect and the largest negative total indirect effect, while POC showed the largest negative direct effect and the largest positive total indirect effect. This antagonism may stem from the close relationship between the degradation of organic carbon and organic phosphorus compounds. Phosphorus solubilizing microorganisms secrete phosphatases to mineralize organic phosphorus (Figure 4), while the addition of organic materials provides carbon sources and minerals for microorganisms, enhancing microbial and phosphatase activity and promoting the conversion of organic phosphorus [56,57]. Spohn et al. [58] demonstrated in short-term experiments that the mineralization of organic phosphorus may occur as a side effect of microbial carbon acquisition, as the demand for carbon can drive the microbial mineralization of phosphorus in compounds such as glucose-6-phosphate. By 90 days of straw return, the antagonistic relationship between phosphatase and POC persisted, but their overall effect on straw decomposition shifted toward synergy. Concurrently, active organic carbon components such as MBC, ROC, and POC entered the path analysis model with positive direct effects. This may be attributable to the straw return method. Studies have shown that active organic carbon components, characterized by their small molecular weight and high turnover rate, are easily decomposed and utilized by microorganisms, absorbed by plants, and respond quickly to changes in soil surface cover conditions [59]. According to Table 3, at 90 days of straw return, straw burial depth and straw length had significant effects on the soil ecosystem, both individually and through their interaction. The degree of influence was ranked as follows: straw burial depth > straw length > interaction of straw burial depth × straw length. As indicated by the response surface (Figure 3), regardless of changes in straw length or straw return amount, the maximum soil ecosystem response occurred at the shallowest burial depth (coded as −1.682). This is likely because surface straw coverage reduces soil moisture evaporation, minimizes nutrient loss, regulates soil temperature, and improves the microenvironment for microbial activity within the soil [60–62].

After 105 days of straw return, phosphatase did not enter the path analysis model; however, POC had the largest positive total indirect effect (Figure 2). POC primarily originates from the organic carbon in plant residue decomposition products and serves as a transitional component in the conversion of fresh organic matter into humus. It is a

relatively easy-to-decompose and highly active component [63]. In the presence of sufficient soil nitrogen, POC is strongly correlated with soil organic carbon [64]. POC participates in the process of soil microbial chemical transformation, maintaining a dynamic equilibrium with organic carbon, and can mutually transform under certain conditions [65]. Therefore, at 105 days of straw return, TOC, MBC, ammonium nitrogen, and nitrate nitrogen were all included in the path analysis model, but only TOC exhibited both positive direct and total effects. This highlights the importance of nitrogen supplementation in the later stages of straw return.

After 45 days of straw return, most of the indicators entering the path analysis model promoted straw decomposition through direct effects, while amino acid microorganisms, TOC, and available potassium relied more on indirect effects. Notably, only the total effect of soil available potassium was negative. Upon further investigation, it was found that while the soil ecosystem had initiated a response process (Figure 4) of "available potassium → sucrase → nitrate nitrogen → dehydrogenase → MBC," leading to the maximum positive indirect effect of available potassium, this was not sufficient to offset its direct negative effect. The potassium provided by straw return to the soil plays a crucial role in maintaining soil ecosystem functions [66], but it also indicates that in situ straw return cannot fully compensate for the potassium needs of crops, leading to a depletion of soil potassium [67]. As a result, during the final stage of straw return (105 days), the direct and indirect effects of available potassium on straw decomposition were relatively low. Although there was a positive total effect with straw decomposition, its effect size was smaller than that of nitrate nitrogen and POC. This suggests that straw return alone is not sufficient to fully mitigate soil potassium depletion [67,68].

By comparing the results of path analysis and response surface analysis, it was concluded that the impact of straw return amount on soil ecological effects was linked to whether soil available potassium was included in the path analysis model. In the 60-day and 90-day straw return groups, the F-value for straw return amount was extremely small, and it was not included in the path analysis model. However, in the other experimental groups, the straw return amount had a total effect of 0.080 with an F-value of 0.15 (30 days), a total effect of −0.142 with an F-value of 3.28 (45 days), a total effect of −0.09 with an F-value of 0.86 (75 days), and a total effect of 0.364 with an F-value of 4.76 (105 days). These results indicate that the amount of straw returned indeed influences the supplementation of soil potassium. Zhang et al. [69] also confirmed that, compared with in situ straw return, non-in situ straw return, which involves a greater input of straw, can significantly supplement soil potassium, leading to a surplus in soil apparent potassium balance. Therefore, to effectively supplement soil potassium, organic fertilizers rich in potassium can be combined with straw return [70]. In further research, different levels of potassium can be added externally to quantify the coupling effect between potassium and straw returning to the field, as well as its impact on soil ecosystems, effectively maintaining the material cycling process of the ecosystem.

The path analysis model developed in this study and the resulting optimization strategies are derived under specific conditions, including the climate and soil type of the cold Haplic Phaeozems region in northern China, as well as the large-scale and high-intensity mechanized farming model. It must be acknowledged that the direct quantitative results and specific parameter recommendations of these models may not possess universal applicability on a global scale. However, we believe the methodological framework adopted in this study holds broad referential value. This includes the use of multivariate statistics (such as factor analysis) to construct "comprehensive response indicators" of the soil ecosystem, thereby overcoming the one-sidedness of single-indicator evaluations; the application of path analysis to reveal the intrinsic causal relationships among soil

nutrients, microorganisms, enzyme activities, and organic carbon pools, moving beyond mere correlation analysis; and the research approach of employing multi-factor orthogonal experiments and response surface methodology to seek optimized solutions under the realistic constraints of large-scale machinery operations (such as the balance between energy consumption and work quality). This systematic approach to analyzing complex agroecological issues can provide important methodological references for other regions studying their own specific straw incorporation models or other agricultural management practices. The focus of future research should be to adopt the analytical framework of this study, combine it with local specific conditions, and conduct localized parameter calibration and validation, thereby developing optimal management practices suitable for respective regions.

5. Conclusions

This study constructed a path analysis model, integrating factor analysis and response surface methodology to systematically evaluate the comprehensive response of the soil ecosystem under straw incorporation and to elucidate the dynamic behavior of the system under multifactorial interactions.

The findings identified catalase, nitrate nitrogen, and POC as key indicators driving the soil's response to straw incorporation. Furthermore, the study revealed a dynamic "antagonistic-synergistic" transition mechanism: at the mid-term incorporation stage (approximately 60 days), phosphatase and POC exhibited a mirror antagonistic relationship, reflecting intrinsic nutrient competition tension within the system. By the late stage (90 days), this antagonistic relationship transitioned into an overall synergistic interaction, facilitating straw decomposition and improving the soil microenvironment, thereby contributing to the maintenance of healthy ecosystem functioning.

Based on the above mechanisms, temporally targeted management strategies are proposed: applying an appropriate amount of nitrogen during the early (0–45 days) and late (75–90 days) stages of incorporation to alleviate nitrogen immobilization induced by straw decomposition, combined with the application of potassium-rich organic fertilizers to sustain and enhance the efficiency of material cycling. This study elucidates that, within the context of large-scale agricultural machinery operations, regulating straw incorporation methods can optimize soil ecological processes, thereby achieving a synergy between "energy consumption control" and "incorporation benefits". It provides theoretical support and technical pathways for the sustainable development of agriculture in the cold haplic Phaeozem area.

Supplementary Materials: The following supporting information can be downloaded at https://www.mdpi.com/article/10.3390/agriculture15212195/s1, Section 1: Figure S1 Correlation coefficient matrix; Section 2: Table S1. Distribution of carbon sources in ECO plates; Section 3: Table S2. Factor analysis model results: Communality; Table S3. Factor analysis model results: Extraction of main factors; and Table S4. Factor analysis model results: Factor loading.

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Abbreviations

The following abbreviations are used in this manuscript:

POC	Particulate organic carbon
WDOC	Water-soluble organic carbon
ROC	Easily oxidizable organic carbon
TOC	Total organic carbon
MBC	Microbial biomass carbon

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