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From growth to decline: The dynamic effects of maize-based cropping systems on soil organic carbon storage in Northeast China

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ABSTRACT

Continuous maize cultivation in Northeast China has resulted in soil degradation and a decline in soil organic carbon (SOC) storage. Diversified maize-based cropping systems offer a promising strategy for restoring soil health and enhancing SOC sequestration. However, their long-term impacts, the key driving factors influencing SOC dynamics, and the spatial variability in SOC responses remain insufficiently understood. In this study, we employed a Genetic Algorithm-Random Forest (GA-RF) model to identify the key factors affecting SOC storage under maize-based diversified cropping systems. Focusing on the prevailing maize-based cropping patterns in Northeast China, we examined the spatiotemporal effects of maize-based rotation systems on SOC storage. The results indicated that the SOC storage under maize-based rotations was influenced by management practices (e.g., duration and intensity of crop rotation), meteorological factors (such as mean annual precipitation), and initial soil conditions including bulk density and total nitrogen content. The greatest potential for enhancing SOC storage was observed in regions with high initial soil fertility and abundant rainfall. Maize-based rotations implemented between 2010 and 2018 in Northeast China increased SOC storage in the 0–20 cm soil layer by 0.53 % (≈15.86 Tg). In comparison, optimized maize-soybean rotation scenarios have the potential to raise SOC storage by 1.48–3.21 % (≈33.44–72.53 Tg). As the intensity of maize-based diversified rotation increased, SOC storage underwent phases of rapid increase, gradual growth, stagnation, and decline. Consequently, implementing an annually alternating maize-soybean rotation over five consecutive years was found to be the most effective strategy for enhancing SOC storage and providing practical insights for improving soil quality and promoting the sustainable development of maize-based agriculture in Northeast China.

1. Introduction

Soil organic carbon (SOC) forms the foundation of agricultural soil fertility, which is crucial for ensuring crop production and food security (Amelung et al., 2020). In recent decades, SOC sequestration in cropland is considered a "win-win" option because it involves fewer trade-offs and can achieve multiple benefits (IPCC, 2021). Indeed, agronomists have long advocated agricultural measures to enhance SOC sequestration to improve soil function and promote it as a national agricultural strategy to achieve the sustainable development goals (SDGs, e.g., SDGs #2: Zero Hunger; SDGs #13: Climate Action) (Smith et al., 2019; Lal, 2020). However, the current global agricultural system faces significant challenges in balancing SOC sequestration and crop yield improvement to adapt to climate change (Qiao et al., 2022). Therefore, enhancing SOC sequestration from an agroecological perspective is essential to address "wicked problems" such as climate change and food security (Smith, 2012; Giller, 2020; Lal, 2024).

Intensive agricultural management has enabled China to feed 22 % of the world's population with only 7 % of the world's arable land. However, this has exacerbated the risk of soil fertility decline in cropland, making it more vulnerable to the impacts of climate change (Piao et al., 2010; Zhao et al., 2018; Iqbal et al., 2024). Data from the Second

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National Soil Survey conducted in 1980 indicates that the overall growth rate of SOC sequestration in primary agricultural regions in China is relatively slow, and has even showed a downward trend some areas, such as the Northeast China (Zhao et al., 2018). As a crucial region for national food security, human activities have exacerbated the ecological vulnerability in Northeast China (Mao et al., 2019). In recent years, the decline in soil organic carbon (SOC) storage in the Northeastern black soil region has garnered widespread attention from the Chinese government and various sectors of society (Wang et al., 2024). Improving the sequestration capacity of cropland SOC in Northeast China has thus become a key challenges in the agricultural field (Berhane et al., 2020).

Long-term continuous maize cropping in Northeast China has been associated with soil degradation, including the loss of SOC and nutrient depletion (Zhang et al., 2018). In response to these negative effects, diversified maize-based cropping systems have been increasingly adopted to sustain soil quality and productivity (Snapp et al., 2010). Specifically, intercropping and crop rotation systems have been shown to enhance key ecosystem functions such as nutrient cycling, root biomass input, and microbial activity, thereby contributing to increased SOC storage and improved soil fertility (Beillouin et al., 2021; Ditzler et al., 2021; Yin et al., 2024). In Northeast China, diversified cropping practices centered on maize are primarily implemented as rotation systems, most commonly involving maize-legume sequences. These rotations have been shown to significantly enhance SOC storage, particularly in the topsoil, due to increased nitrogen fixation and greater organic matter input from legumes (Yan et al., 2023). A long-term field experiment in Heilongjiang Province showed that maize-soybean rotations improved surface-layer SOC and altered its distribution among soil aggregates; however, the total SOC increase was lower than that achieved under continuous maize with organic amendments (Kou et al., 2012). Similarly, an eight-year trial in Northeast China reported that both maize-soybean and maize-maize-soybean rotations improved soil quality indices and increased SOC storage by 9.3–29.4 % compared to monoculture systems (Luo et al., 2024). Long-term experiments in Northern China also demonstrated that maize-based rotations combined with organic inputs can raise SOC levels by up to 36 % (Zhu et al., 2012).

However, SOC gains are highly dependent the specific management practices accompanying the maize–soybean rotation. For example, Kou et al. (2012) reported enhanced SOC within soil aggregates, no significant increase was observed in deeper soil layers. Zhang et al. (2018) found that under conventional tillage, the absence of straw return substantially limited SOC accumulation relative to no-tillage systems. An eight-year field study further demonstrated that SOC improvements were achieved only when soybean frequency was optimized and both residue and nutrient inputs were adequate, whereas suboptimal management practices yielded minimal benefits (Luo et al., 2024). Moreover, although maize-soybean rotations have been shown to enhance microbial activity (Cui et al., 2021) and redistribute SOC within the soil profile (Qiao et al., 2018), their overall contribution to net SOC storage remains limited without sufficient phosphorus or organic matter inputs.

These differences often arise from an oversight of the complexity of how maize-based diversified rotation affects SOC storage, including the combined effects of environmental and management factors (Kou et al., 2012; Cui et al., 2021). Studies focusing on specific cropping systems, specific locations, or small-scale experiments, share similar limitations and exhibit considerable variability (Kou et al., 2012; Qiao et al., 2018; Zhang et al., 2018; Luo et al., 2024). Therefore, additional factors, such as environmental meteorological factors, cropping management, and initial soil physical and chemical properties, are critically needed to explain why SOC sequestration responds differently to maize-based diversified cropping systems.

In summary, the effects of maize-based diversified rotation on SOC sequestration vary with differences in management practices, environmental conditions, and experimental designs. This highlights the need for aligning such rotation strategies with site-specific conditions and field management practices (Lin, 2011). Therefore, a comprehensive assessment of the impact of maize-based diversified rotation on improving SOC potential in the Northeast China is particularly needed. Using quantitative methods such as meta-analysis and machine learning, it is crucial to explore key environmental and management factors and to clarify the spatial and temporal effects of maize-based diversified cropping on SOC sequestration in the Northeast China. These insights are critical for refining maize-based diversification strategies, improving soil quality and land productivity, addressing climate change, and ensuring food security.

This study aimed to assess the impact of maize-based diversified cropping on the SOC sequestration potential in Northeast China through meta-analysis and a Genetic Algorithm-Random Forest (GA-RF) prediction model. To this end, we addressed three key scientific issues: (1) to identify key environmental and management factors influencing changes in SOC storage under maize-based diversified cropping systems; (2) to assess the impact of existing maize-based cropping patterns on the spatial distribution of SOC storage across Northeast China; (3) to evaluate the potential of optimized maize-based rotation strategies to enhance SOC storage compared to historically observed patterns. To answer these questions, we constructed a spatial-temporal dataset of maize cultivation in Northeast China, analyzed the spatial heterogeneity of SOC storage under historical rotation scenarios, and simulated the potential outcomes of optimized maize-based diversification cropping strategies using the GA-RF model. To address these research questions, a spatiotemporal dataset was developed to capture the evolution of maize cultivation patterns across Northeast China (Liaoning, Jilin, and Heilongjiang provinces) from 2010 to 2018. This dataset was constructed by integrating multiple data sources, including climate variables and soil characteristics, to assess the spatial heterogeneity of SOC storage under maize-based diversified cropping systems during 2010–2018. Additionally. it served the foundation for simulating the SOC sequestration potential of optimized maize rotation strategies using the GA-RF modeling framework.

2. Materials and methods

The study followed a structured process for data collection, processing, simulation, and estimation. Initially, research data on the effects of maize-based diversified cropping systems on SOC in Northeast China were systematically complied and rigorously evaluated using meta-analysis. Subsequently, a Genetic Algorithm-Random Forest (GA-RF) prediction model was developed to determine the key environmental and management factors influencing SOC storage enhancement. Finally, with inputted data on management strategies and environmental conditions in the northeastern maize cultivation area, changes in SOC storage under diversified cropping patterns were both simulated and predicted.

2.1. Data collection

A comprehensive search was conducted on the China National Knowledge Infrastructure (CNKI: http://www.cnki.net) and Web of Science (http://apps.webofknowledge.com/) for peer-reviewed journal articles published before December 31, 2023. The search terms included "(China) and Northeast OR Jilin Province OR Liaoning Province OR Heilongjiang Province", and (Intercropping OR Relay Intercropping OR green manure OR Compound Planting OR Rotation OR Cover Crop)". Subsequently, the compiled databases were refined based on the following criteria: (a) intercropping systems involving crop strip exchange were simultaneously assigned to both the intercropping and rotation subgroups; (b) experiments conducted in the laboratory or pot and model simulation studies were excluded. Only field-designed side-by-side studies were included; (c) the control treatment involved monocropping or continuous cropping; (d) observations were conducted under a repeated experimental design (minimum of three) with reported data on SOC or SOC storage or SOC stock or soil organic matter; (e) clear and detailed information about field management and site locations was required (more details are presented in the supplementary information (SI) method 1). The process of dataset construction and methods for supplementing missing data are provided in SI method 2.

2.2. Data processing

For studies that reported the SOC content (g kg^{-1}), the SOC storage (Mg ha^{-1}) was converted from SOC content using the following equation (Jian et al., 2020):

$$SOC\ storage = BD \times SOC \times h \quad (1)$$

Where *SOC storage* and *SOC* represent SOC storage (Mg C ha^{-1}) and SOC concentration (g C kg^{-1}). h represented the corresponding soil depth (dm), and BD is soil bulk density (g cm^{-3}). If the value of BD was missing, it was estimated using the following equation (Wang et al., 2023):

$$BD = 1.377e^{-0.0048SOC} \quad (2)$$

To explore the impact of maize-based diversified cropping on SOC storage, we employed a random effects model of meta-analysis (Hedges et al., 1999). The natural logarithm of response ratio (lnR) was defined as "effect size" to quantify the change in the soil carbon pool as described by Eq. (3):

$$\ln R = \ln\left(\frac{\overline{X}_d}{\overline{X}_c}\right) = \ln\overline{X}_d - \ln\overline{X}_c \quad (3)$$

Where $\overline{X}_d$ and $\overline{X}_c$ represent the mean SOC storage value of treatment and control, respectively, in different maize-based diversified cropping systems. The detailed methodology, including the random effects model of meta-analysis, weighting methods, statistical analysis, and categorization of variables, is presented in SI method 3.

2.3. Diversified cropping intensity

Diversified cropping intensity (DCI) is used to describe the spatial and temporal intensity of maize-based diversified cropping systems. The calculation procedure and corresponding formula are detailed are outlined as follows.

(1) In crop rotation scenarios, alternating crop types across two consecutive years on the same plot increments the DCI by + 1; maintaining the same crop type over two years results in no change in DCI (+0).

(2) In the case of intercropping and relay intercropping, DCI equals the number of crop species planted simultaneously on the same plot.

(3) The initial DCI for the evaluated farmland is defined as 0, meaning that the DCI for single cropping is set to 0.

It was estimated using the following Eqs. 3 to 5, and the distribution map of DCI with maize as the main crop within the study area in Northeast China is shown in Fig. 1.

$$DCI_{total} = DCI_{rotation} + \sum\nolimits_{1}^{y} DCI_{intercorp} \quad (4)$$

$$DCI_{rotation} = \sum\nolimits_{i=2}^{y} \delta_i \quad (5)$$

$$DCI_{intercorp} = n \quad (6)$$

Where DCI_{total} signifies the aggregate DCI for a specified plot over a period, accounting for the simultaneous implementation of crop rotation and intercropping. $DCI_{rotation}$ is the DCI due to crop rotation, and $DCI_{intercrop}$ is the DCI due to intercropping; y denotes the duration of maize-based diversified cropping (DCD), measured in year. If the crop type in $year_i$ distinct from that in $year_{i-1}$, δ_i is set to 1, otherwise, δ_i is set to 0. The variable n indicates the number of different crops intercropped within the same year.

2.4. Genetic algorithm- random forest model

The Random Forest (RF) model is a machine learning algorithm

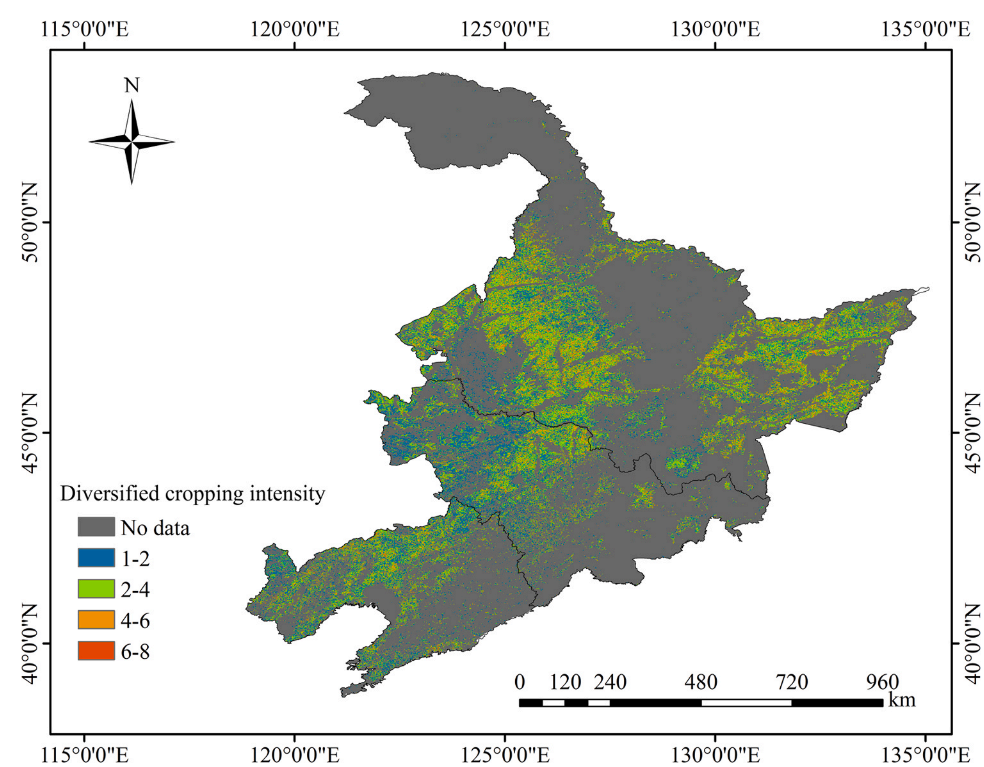

Fig. 1. Spatial distribution of DCI in the Northeast region from 2010 to 2018.

renowned for its fast computation speed, high precision, and strong resistance to overfitting, making it widely used in estimating ecological indicators. In RF model, the predicted values for observations are calculated by averaging across all trees. The Genetic Algorithm (GA) is an optimization search method based on the principles of natural selection and genetics (Wesemeyer et al., 2023). GA iteratively refines solutions to find optimal or near-optimal outcomes by mimicking natural evolution, using processes like fitness evaluation, selection, crossover (Alaoui et al., 2020). In this study, the GA was used to optimize parameters within the RF model, with the coefficient of determination and mean square error as optimization objectives, thereby enhancing model performance. SI Method 4 provided detailed methods for the Genetic Algorithm- Random Forest (GA-RF) model. The algebraic evolution of fitness and parameter distribution of the GA-RF model is shown in Fig. S4.

Using the well-trained Genetic Algorithm -Random Forest (GA-RF) model, the primary drivers of SOC storage changes under maize-based diversified cropping systems were identified from a set of 16 parameters, including soil properties, meteorological conditions, and management practices. Subsequently, multi-source grid datasets (including soil properties, climate conditions, crop management practices) were used to predict the relative changes (%) in 0–20 cm SOC storage at a 1 km grid level in maize planting areas. The prediction model requires multiple data inputs, including climate conditions, soil properties, crop types, and agronomic management. Details of the data sources are provided in Supplementary Table S3. To ensure consistency and accuracy, all environmental and management data including national crop classification data, 1 km resolution soil property grids, monthly average temperature and precipitation, and nitrogen fertilizer application intensity, were clipped to the Northeast China region and standardized in terms of formatting and spatial alignment. The unification of spatial resolution, projection information, and spatial reference systems of multi-source images, as well as the generation of spatial maps, was performed using ArcGIS 10.8 software (ESRI, 2017).

3. Results

3.1. Response of SOC storage to diversified maize cropping systems under varying conditions

Overall, the lnRs for maize-based diversified cropping shows significant variability compared to continuous single cropping, with the range of SOC storage spanning from −0.25–0.46. This is derived from a dataset of 218 observations across 17 independent sites in the Northeast region (Figs. S1 and S2). The lnRs of SOC storage follow a Gaussian normal distribution ($R^2 = 0.95$, $P < 0.01$) with a fitted mean of 0.02. Given the variability in lnRs of SOC storage, the weighted overall effect size was calculated to be 0.03 ± 0.02 ($\ln R_{++} \pm 95$ % CI), indicating that diversified cropping significantly increases SOC storage by 3.00 ± 2.17 % compared to continuous monocropping.

The results of categorical meta-analysis confirmed the importance of initial soil physicochemical properties: BD ($P < 0.05$), SOC ($P < 0.05$), total nitrogen (TN, $P < 0.05$), total soil phosphorus (TP, $P < 0.01$), and total soil potassium (TK, $P < 0.05$), as well as management practices: DCD ($P < 0.01$), DCI ($P < 0.01$), and average annual nitrogen application ($P < 0.05$), and meteorological conditions: mean annual temperature (MAT, $P < 0.01$) and precipitation (MAP, $P < 0.01$) on the lnRs of SOC storage. These factors were associated with significant heterogeneity among sub-groups (Q_b, Table S1; methodological details in SI Method 3). Furthermore, significant Q_b values were observed for additional soil factors, including soil initial alkali-hydrolyzable nitrogen (AN, $P < 0.05$), available phosphorus (AP, $P < 0.01$), available potassium (AK, $P < 0.01$), pH ($P < 0.05$), and cation exchange capacity (CEC, $P < 0.01$) among sub-groups. This trend suggests that significant changes in SOC storage may be observed when transitioning from traditional continuous monocropping to diversified cropping under varying conditions.

Specifically, among sub-groups of soil depth, diversified cropping practices almost universally demonstrated a significant enhancement in SOC storage, ranging from 4.40 % to 8.04 %, with over 75 % of observations occurring within the 0–20 cm soil layer (Fig. 2a). According to soil physical properties, sub-groups differentiated by initial soil BD also exhibited significant variations in the RC of SOC storage (Table S1, Fig. 2a). Sub-groups with soil BD < 1.34 g cm^{-3} showed a notable increase in SOC storage by 4.13–5.36 %. Among all observations, the categorization based on soil texture primarily focused on the sub-groups of clay loam and loam, with only the loam sub-group witnessing a significant increase in SOC storage (Fig. S5). Furthermore, in classifications based on soil chemical parameters, diversified cropping practices were observed to significantly increase SOC storage by 5.41 %, 11.43 %, 10.30 %, and 8.03 % in sub-groups with initial SOC content < 14.00 g kg^{-1}, TN content between 1.50 and 2.00 g kg^{-1}, TP content > 0.80 g kg^{-1}, and TK content < 22.00 g kg^{-1}, respectively (Fig. 2a). The initial soil effective nutrients (AN, AP, AK) and chemical properties (pH and CEC) showed significant differences in RC between sub-groups. The RC of SOC storage ranged from 3.31 % to 14.66 % when diversified cropping soils had initial AN < 1.24 mg kg^{-1} , AP > 14.00 mg kg^{-1} , AK < 20.00 mg kg^{-1} , CEC < 23.00 cmol kg^{-1} , and pH > 7.50 (Table S1, Fig. 2a and S5).

Moreover, categorization based on management practices revealed that diversified cropping methods, including intercropping and crop rotation, significantly increased SOC storage by 4.03–4.75 %. Notably, over short-term periods (DCD <10 years), 103 observations demonstrated that diversified cropping significantly enhanced SOC storage compared to continuous monoculture (Fig. 2b). However, no significant enhancement effect was observed in the medium-term (DCD within 10–20 years) and long-term (>20 years), with some instances even indicating inhibitory effects. The DCI significantly influenced the SOC storage response to diversified cropping; sub-groups with low DCI (≤5) experienced a 7.34 % increase in SOC storage (Fig. 2b). In contrast, no significant effects were observed in the sub-groups with medium (5−15) and high DCI (≥15).

In terms of climate factors, for areas with MAT ≤ 4.2 ℃ (63 observations) and > 5.2 ℃ (39 observations), diversified cropping led to an increase in SOC storage by 4.51 % and 6.50 %, respectively. However, in the sub-group within the 4.2–5.2 ℃ range (116 observations), a 2.65 % reduction in SOC storage was observed (Fig. 2b). Diversified cropping significantly increased SOC storage by 5.10 % in regions with annual precipitation greater than 620 mm, whereas no significant effects were observed in the other two sub-groups with less than 620 mm of precipitation (Fig. 2b).

3.2. Factors affecting changes in SOC storage in diversified maize cropping systems

The GA-RF model demonstrated that meteorological conditions (MAT and MAP), initial soil properties, and management measures (DCI, DCD and N application) collectively influence SOC storage during periods of diversified cropping (Fig. 3). In the rotation system, all ten inputted initial soil properties significantly impact SOC storage ($P < 0.05$), with initial BD exerting the greatest influence on SOC storage among other soil properties, accounting for 12.29 % (Fig. 3a). In terms of management measures, the annual average diversified cropping intensity (ADCI, calculated as the ratio of DCI to DCD) and the N application in the rotation system showed no significant effect on the SOC storage response model ($P > 0.05$). However, the DCD and DCI had the most significant impact on SOC storage, with their relative importance at 15.38 % and 15.21 %, respectively. Among the climatic conditions, 77.36 % of the MAP inputted into the model is concentrated between 500 and 530 mm, with no significant impact identified. The MAT has a significant effect on SOC storage ($P < 0.01$), with a relative importance of 6.08 %. Notably, in the rotation system, BD, DCD, and

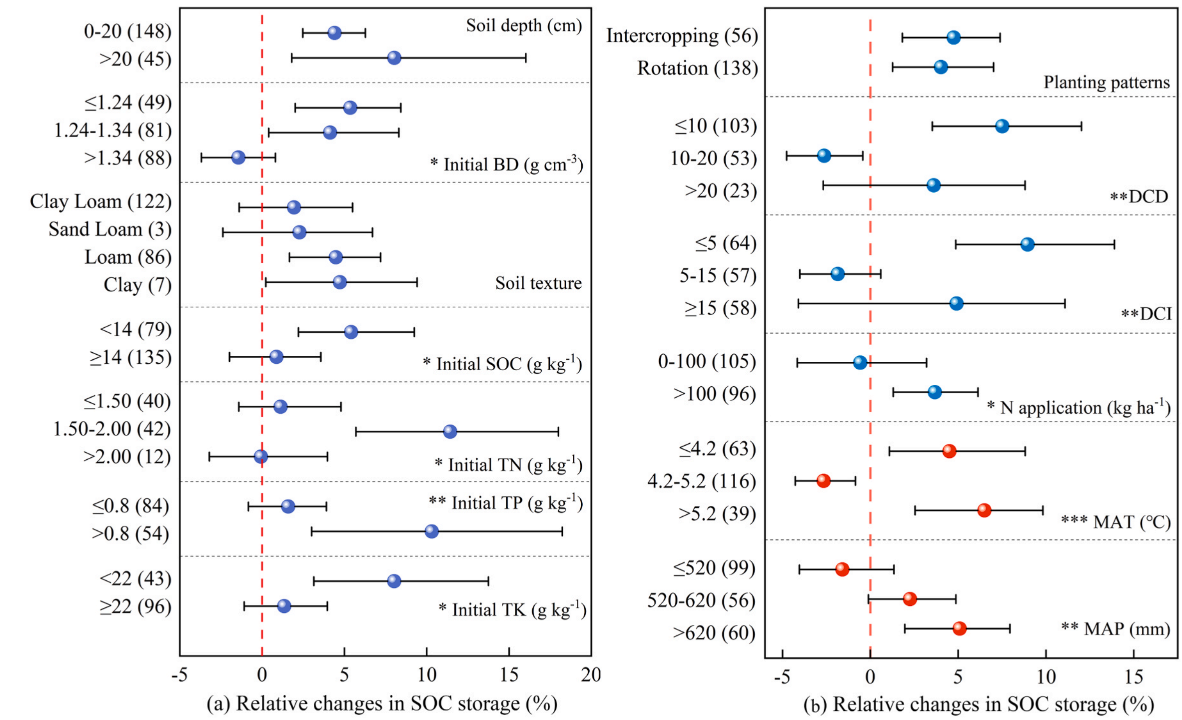

Fig. 2. The response of SOC storage to diversified cropping is influenced by various soil properties, management measures, and meteorological conditions. The numbers represent the observations. The error bars were 95 % confidence intervals and indicate significant if there is no overlap with zero. *P < 0.05, **P < 0.01 and ***P < 0.001 represent significant differences among subgroups. BD: soil bulk density; TN: soil total nitrogen content; TP: soil total phosphorus content; TK: soil total potassium content; DCD: diversified cropping duration; DCI: diversified cropping intensity; N application: average annual nitrogen application in diversified cropping systems; MAT: mean annual temperature and MAP: mean annual precipitation.

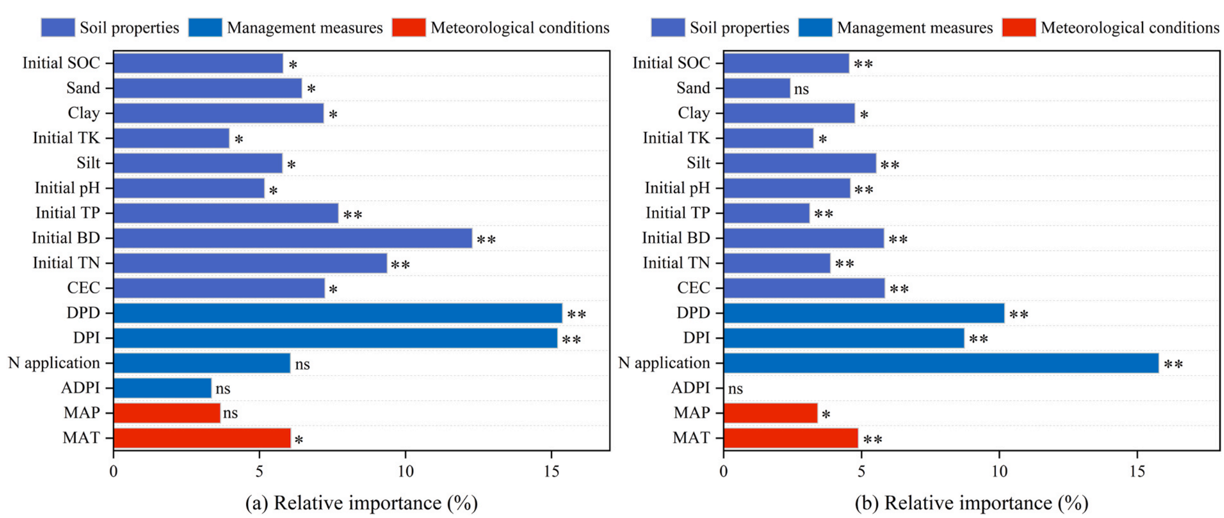

Fig. 3. Assessment of the relative importance of model moderating variables on SOC storage under diversified cropping using the GA-RF model. (a) represents rotation; (b) represents intercropping. * indicates $P < 0.05$, ** indicates $P < 0.01$, and ns indicates not significant.

DCI rank as the top three factors of relative importance ($P < 0.01$), contributing to 42.88 % of the total impact.

However, the response model for SOC storage under the intercropping system displayed a different performance (Fig. 3a and b), where the soil sand content and ADCI had no significant impact on SOC storage (Fig. 3b). The N application, DCD, and DCI rank as the top three factors of relative importance in the intercropping system, accounting for 33.64 % of the total contribution. Initial BD also significantly affects SOC storage in the intercropping system ($P < 0.01$), with its relative importance second only to DCI. In meteorological conditions, both MAT and MAP have significant impacts on the SOC storage response model ($P < 0.01$).

The GA-RF model demonstrated strong predictive capability for estimating SOC storage changes under both crop rotation ($y = 0.793x + 0.004$, MAE = 0.04, RMSE = 0.06, $R^2 = 0.80$) (Fig. 4a) and intercropping systems ($y = 0.744x + 0.007$, MAE = 0.04, RMSE = 0.05, $R^2 = 0.76$) (Fig. 4b). To enhance model robustness, 10-fold cross-validation was performed using both the RF and XGBoost algorithms (Details are presented in Table S4). The RF model exhibited strong generalization ability, with minimal variation across folds (R2 = 0.79–0.83, MAE = 0.03–0.04), yielding a mean R^2 of 0.81 and RMSE of 0.06. The XGBoost model produced nearly identical results (mean $R^2 = 0.81$), confirming

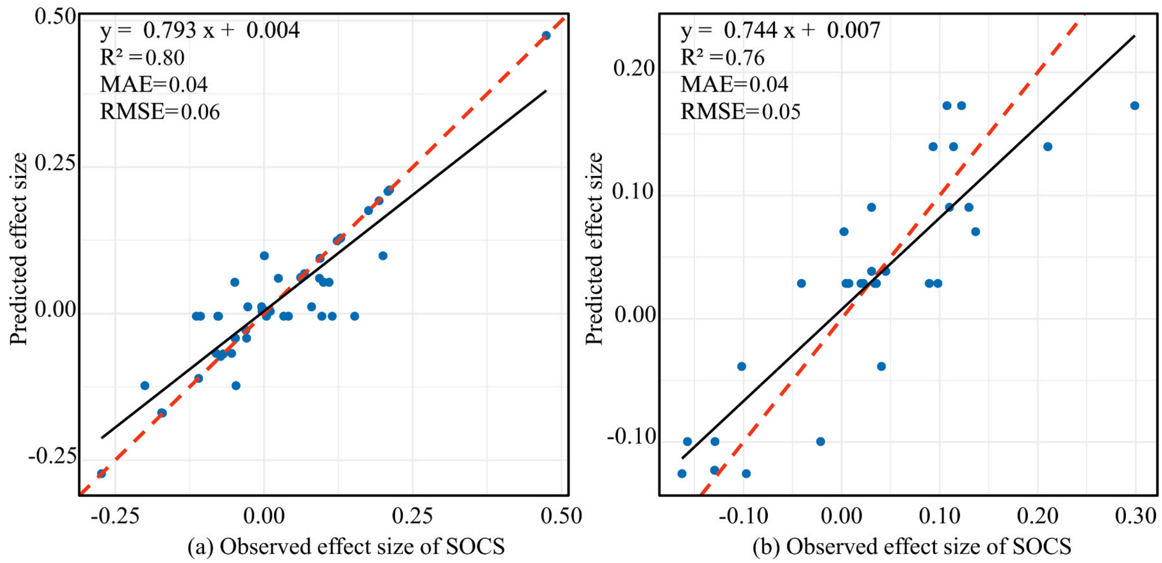

Fig. 4. GA-RF model performance evaluated by the correlation between the observed and predicted effect size. The model uses the 'leave-one-out cross-validation' method for evaluation, reserving 15 % of the data as a test set, with the remaining 85 % used for fitting predictions using the GA-RF. This process is repeated until each data point has been used once as part of the test set and its corresponding prediction has been obtained. The red line represents a one-to-one direct line relationship, while the green line represents the fit between the predicted values and observed values. (a) represents the crop rotation, and (b) represents the intercropping.

the stability and transferability of the modeling framework. The consistent performance and lack of overfitting across folds underscore the reliability of the RF model in predicting SOC dynamics under maize-based diversified cropping systems.

3.3. *Effects of maize-based diversified rotation historical scenarios and optimization scenarios on SOC storage changes in Northeast China*

The study results indicate that from 2010 to 2018, the DCI for maize-based diversified rotation systems in Northeast China ranged from 1 to 4, with an average DCI of 2.83 (Fig. S1). The GA-RF model simulation results show that the diversified rotation system has a positive effect on the SOC storage of 0–20 cm soil in most farmland areas in Northeast China (Fig. 5a), increasing by 0.53 % (approximately 15.86 Tg) compared to the initial SOC storage. The spatial distribution of SOC storage changes under the historical evolution of diversified rotation exhibited significant regional differences. Large areas showed SOC storage change range of 0–8 %, whereas the southwestern part of Heilongjiang, western Jilin, and northwestern Liaoning displayed more heterogeneous SOC storage change patterns, with a substantial portion indicating a decrease in SOC storage.

Subgroup analysis of the impact of management practices on SOC storage indicates that when DCI ≤ 5, diversified cropping patterns have the most significant effect on increasing SOC storage (Fig. 2b). Based on this, three rotation scenarios for diversified cropping were set, ensuring that the shortest duration of DCD for a DCI of 5 years. Therefore, with DCD equal to 5, three diversified rotation scenarios were established: S1: maize → legume rotation, S2: maize → maize → legume rotation, S3: S1 → S2.

GA-RF simulation results show that under the S1, S2, and S3 scenarios (Fig. 5b, c, d), compared to monocropping, maize-legume rotations have the potential to increase SOC storage in Northeast China by 3.21 %, 1.48 %, and 1.52 % (72.53 Tg, 33.44 Tg, and 34.39 Tg), respectively. Certain areas in Heilongjiang Province showed significant increases in SOC storage (> 8 %), while western Jilin and northwestern Liaoning provinces exhibited heterogeneous SOC storage change patterns, with a substantial portion showing decreases in SOC storage. Compared to historical scenarios, the optimized rotation scenarios in Northeast China show an increased rate of SOC storage change, with a notable reduction in areas with decreased SOC storage.

3.4. *Response of SOC storage to crop DCI*

Figure S6 presents the relationship between crop DCI and SOC storage changes in Northeast China. The results indicate that SOC storage does not increase linearly with increasing DCI but rather exhibits a 'hump-shaped curve' pattern of growth, transition, and loss (Fig. 6). During the initial stage of diversification, soil nutrients are activated, leading to a rapid increase in SOC storage. However, as DCI increases, the growth rate of SOC storage slows down, entering a 'slow' phase. SOC storage continues to increase but at a slower rate. When DCI is further increased, SOC storage growth reaches a plateau and enters the 'transition' zone. Nutrients may become limiting at this stage but not to the extent of negatively impacting SOC storage. Further increase in DCI leads to a decline in SOC storage, entering the 'decline' phase. These results demonstrate that the impact of crop diversification on SOC storage exhibits distinct stage-dependent changes with varying diversification intensities. Initial diversification can significantly increase SOC storage, but excessive DCI can lead to a decrease in SOC storage.

4. Discussion

4.1. *Uncertainty analysis of diversification cropping on SOC storage*

Diversified cropping is considered an effective agricultural practice that can improve soil health and increase SOC sequestration, consistent with findings from other studies (Lange et al., 2015; Tiemann et al., 2015; Li et al., 2024). The meta-analysis in this study confirms that diversified cropping can significantly increase SOC sequestration, with an average increase of 3 %, aligning with the results of previous studies (McDaniel et al., 2014; Tiemann et al., 2015; Jian et al., 2020). However, based on limited observational data ($n = 218$), 45.87 % of the cases showed a decrease in SOC storage, with 69 % of these decreases occurring under maize-based diversified cropping systems with DCI > 6. The reason may be that a higher DCI means that maize is more frequently replaced by leguminous crops. Compared to grains, soybeans return less crop residue to the soil (Kou et al., 2012) and have a lower C:N ratio (Wright and Hons, 2004). Studies have shown that the rapid

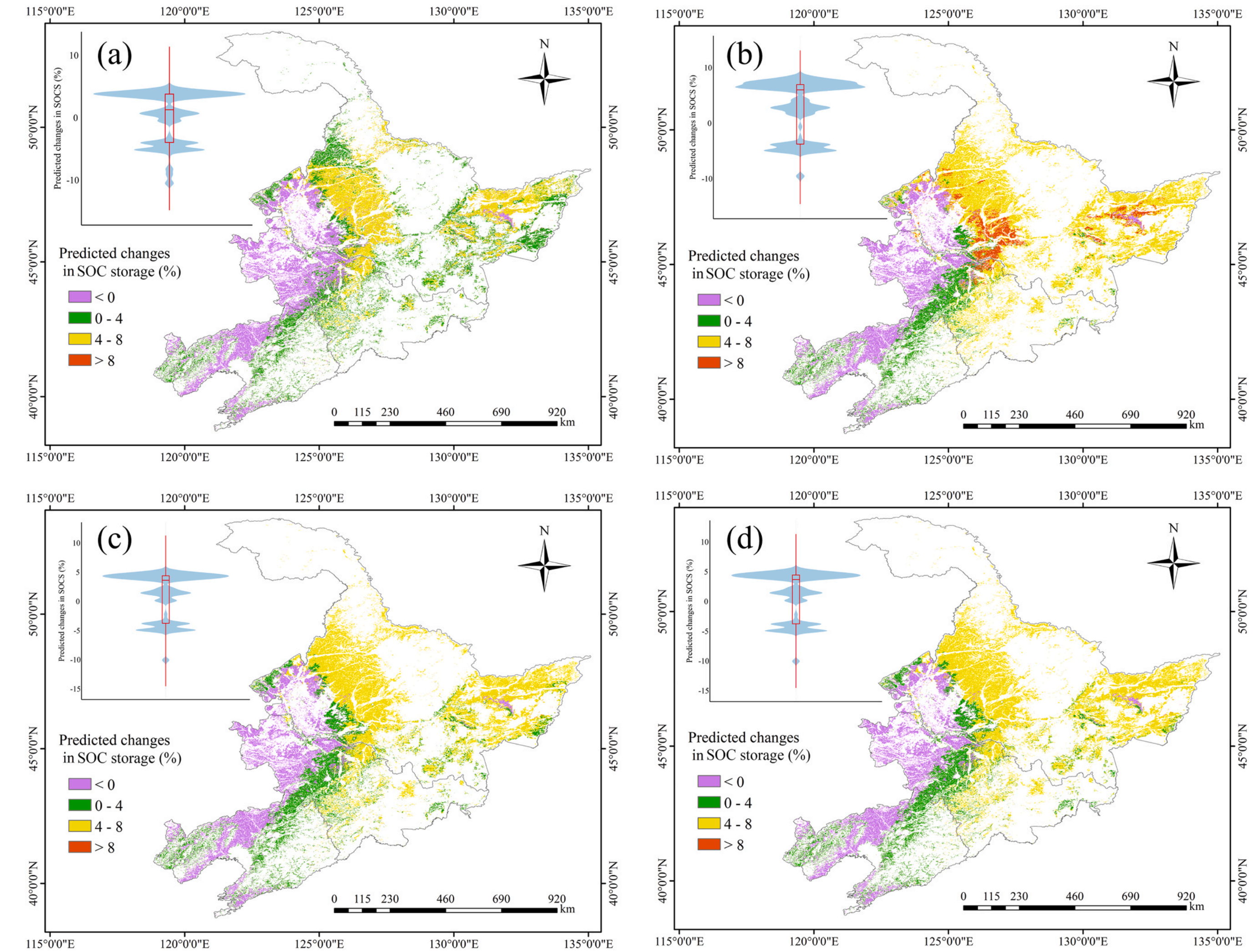

Fig. 5. Illustrates the predicted changes in SOC storage (0–20 cm) under different diversified cropping optimization scenarios. (a) represents the historical evolution scenario from 2010 to 2018; (b) represents the S1 scenario; (c) represents the S2 scenario; and (d) represents the S3 scenario (specific details of the 3 scenarios are given in Table S2). The predictions were made using the GA-RF model, considering 16 factors (MAT, MAP, Clay, Sand, Silt, Initial pH, Initial BD, Initial SOC, Initial TN, Initial TP, Initial TK, CEC, DCD, DCI, ADCI and annual nitrogen application) to predict the grid-scale spatial dataset. Detailed information on the data is described in the supplementary materials (Table S3).

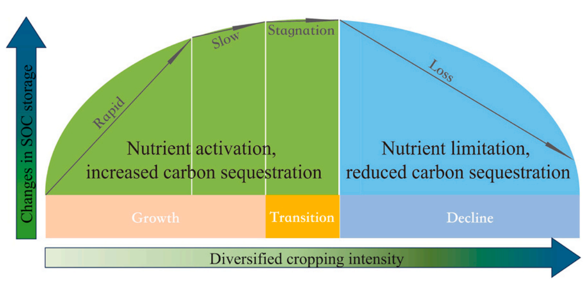

Fig. 6. Schematic diagram of the impact of increasing diversified cropping intensity on soil organic carbon storage (SOC storage) changes (%).

decomposition of soybean residues can increase susceptibility to erosion during fallow periods and the rate of SOC loss, especially in soils with a high frequency of soybean planting (Novelli et al., 2011). Simultaneously, the increase in soil nitrogen from the decomposition of increased legume residues may stimulate microbial growth and extracellular enzyme production, resulting in more localized carbon loss (Ramirez et al., 2010).

However, other studies have found that maize-soybean rotation can significantly increase large- and macro-sized fractions, and due to the physical protection of aggregates, the decomposition rate of SOC slows down, promoting SOC sequestration. Thus, the varying effects of maize-based diversified cropping on SOC sequestration can be reasonably attributed to differences in management practices, climate, and soil conditions. These factors likely influence crop productivity, planting patterns, and the biochemical composition of crop residues, all of which can affect microbial activity and the dynamics of soil organic matter (McDaniel et al., 2014).

The impact of maize-based diversified cropping on SOC sequestration exhibited significant regional variation across Northeast China, as demonstrated by spatial simulations based on cropping patterns from 2010 to 2018 (Fig. 5a). While most areas experienced moderate SOC gains (0–4 %), losses were observed in regions such as western Jilin, southwestern Heilongjiang, and northwestern Liaoning Provinces, suggesting that maize-based diversification does not universally enhance SOC storage. This spatial heterogeneity appears to be strongly linked to climatic and edaphic conditions. The meta-analysis revealed a significant positive correlation between SOC sequestration in the 0–20 cm soil layer and both mean annual temperature (MAT, $P < 0.001$) and mean annual precipitation (MAP, $P < 0.01$) (Fig. 2), which is consistent with previous studies (Wang et al., 2013; Li et al., 2023). Additionally, SOC losses were primarily concentrated in areas with low available nitrogen and phosphorus (Fig. S5), highlighting the pivotal role of soil fertility in regulating sequestration outcomes. This might be because nitrogen and phosphorus availability in the soil strongly controls microbial growth and respiration, and microbes need to maintain a balanced C to nutrient ratio in their cells (Manzoni et al., 2012). Nutrient limitation can lead to increased respiration overflow and/or carbon excretion, resulting in increased SOC mineralization and reduced sequestration capacity (Mehnaz et al., 2019). Therefore, in regions with relatively low precipitation and limited soil nutrient availability, adopting diversified cropping methods may increase the risk of SOC loss.

4.2. Dynamics response of SOC to changes in DCI

The analysis confirmed that both the duration and intensity of maize-based diversified cropping have a significant positive impact on changes in SOC (Fig. 3), particularly in rotation systems (Fig. 3a). The length of the planting period influences dynamic changes in carbon accumulation and nutrient cycling in the soil (Sun et al., 2025). While previous studies have suggested that maize-based diversified cropping may improve soil structure and organic matter inputs (Li et al., 2024), our findings specifically show that increasing DCD and DCI of maize-based cropping systems significantly enhance SOC storage. However, SOC reserves do not increase indefinitely with the continuous implementation of diversified cropping systems and are affected by multiple factors (Varvel, 2006). Our analysis of SOC changes and DCI at the 1 km grid level in Northeast China (Fig. S6) identified four main stages of SOC changes with increasing DCI: growth, deceleration, stagnation, and decline (Fig. 6).

Our analysis reveals a dynamic, phased pattern in SOC sequestration under maize-based diversified cropping systems. In the early stages of diversification, crop diversity increases rhizosphere carbon input, which enhances microbial activity and SOC storage, thus, stimulating microbial proliferation and activity (Lange et al., 2015). This is supported by our model results, which show that areas with higher cropping diversity and moderate nutrient availability exhibit the fastest SOC gains during the initial years (Fig. 2 and S5). The critical role of microbial stimulation at this stage has been well established (Gentsch et al., 2020; Chen et al., 2022). Our research provides spatially explicit evidence that these effects are most pronounced in regions with initially lower levels of SOC, AN, AK, and TK, where improvements in SOC are most substantial. (Fig. 2 and S5).

In the mid-term stage, SOC growth begins to plateau in many regions (Fig. S6), especially in soils with already elevated organic carbon levels and declining phosphorus availability (Fig. 2 and S5). This trend aligns with a saturation effect in the labile carbon pool, as observed in our simulations under medium-term rotation scenarios. These findings are consistent with the concept that carbon saturation limits SOC gains over time (McDaniel et al., 2014; Kan et al., 2022). Our results also highlight that in regions with initially low AP and TP levels (Fig. 2 and S5), SOC accumulation rates are markedly reduced, suggesting phosphorus limitation as a critical constraint. Studies indicate that diversified cropping systems, particularly those involving legumes, activate and efficiently utilize phosphorus and Fe, which are essential for SOC formation and stabilization (Kan et al., 2022). However, excessive consumption of phosphorus and Fe can limit organic carbon accumulation and accelerate mineralization (Singh et al., 2023). Consistent with our findings, sustained intensive diversified (DCI > 6) leads to diminishing returns on SOC storage and may even result in SOC losses (Fig. 6 and S6). This aligns with previous suggestions that nutrient mining by plants and microbes under prolonged diversification may inhibit SOC stabilization (Dhaliwal et al., 2019; Hicks et al., 2021). Our findings highlight that SOC sequestration under diversified cropping is not indefinitely linear, but is tightly constrained by nutrient dynamics, especially in high-yield diversified cropping systems.

4.3. Limitations and implication of this study

This study investigates the impact of maize-based diversified cropping systems on SOC sequestration in Northeast China. However, due to the complexity of intercropping systems and the absence of reliable classification data, we were unable to map spatial distribution of intercropping practices. Moreover, since intercropping is rarely adopted by local farmers, it was excluded from our scenario-based predictions. Therefore, our findings primarily reflect the rotation-based diversification.

While model incorporates key environmental and management variables, it omits several influential factors such as deep soil organic carbon, residue return, planting density, soil microbial communities, and enzyme activities due to data limitations. Previous studies have shown that these factors can significantly affect SOC accumulation and decomposition. For instance, residue return has been shown to increase topsoil SOC by over 10 % (Lin et al., 2023), and differences in planting density can influence root exudation, nutrient cycling, and microbial activity (Wardle et al., 2004; Lei et al., 2023).

Furthermore, the spatial datasets used in the analysis covering crop layout, soil properties, climate, and nitrogen inputs were sourced platforms with varying spatial and temporal resolutions (Table S3). Although we applied interpolation and normalization to standardized the data, this process inevitably introduced some uncertainty. Moreover, the nitrogen application rates were averaged across the cropping period and all crop types, potentially obscuring crop-specific nitrogen management effect. This study simulated only the net change in SOC storage before and after diversification, without capturing the dynamic accumulation process during the cropping period. This limitation may affect the interpretation of long-term SOC sequestration outcomes.

Nevertheless, despite these limitations, the study provides novel, region-specific insights into how maize-based diversified cropping influences SOC sequestration in Northeast China. It identifies key environmental constraints, particularly phosphorus availability and rainfall distribution, that shape the effectiveness of crop rotation strategies. By integrating meta-analysis with machine learning, the study presents a scalable framework for assessing carbon sequestration in complex agroecosystems. These findings offer practical guidance for promoting sustainable and climate-smart agriculture in maize-dominated regions.

5. Conclusions

Prolonged maize monoculture has led to soil degradation, limiting sustainable agricultural development in Northeast China. This study demonstrates that maize-based diversified cropping systems significantly enhance SOC storage, with an average increase of 3.00 ± 2.17 %, as confirmed by meta-analysis and GA-RF modeling. The extent of SOC improvement is strongly influenced by initial soil properties (BD, TN, TP), management practices (DCD, DCI), and climatic conditions (MAT, MAP). Notably, regions with sufficient initial soil nutrients and high rainfall exhibit highest SOC sequestration potential under maize-based diversified rotation. In contrast, areas with low SOC and limited precipitation may not achieve carbon gains without additional management intervention. SOC storage dynamics follow a non-linear trajectory with increasing DCI, passing through phases of growth, deceleration, stagnation, and decline. Optimized maize-soybean rotations could increase SOC storage in the 0–20 cm layer by up to 72.53 Tg, compared to 15.86 Tg under current practices. These findings provide practical guidance for maximizing SOC gains and promoting climate-resilient, resource-efficient agriculture in maize-dominated systems.

CRediT authorship contribution statement

Zhi-Heng Qin: Investigation. **Jia Cheng:** Investigation. **Yash Pal Dang:** Writing – review & editing. **Bai-Jian Lin:** Methodology, Conceptualization. **Xin Zhao:** Supervision, Project administration, Formal analysis. **Hai-Lin Zhang:** Writing – review & editing, Project administration. **Jin-Sai Chen:** Writing – original draft, Data curation, Conceptualization. **Zhuo Shi:** Investigation. **Yu-Gang Tian:** Investigation. **Hao-Ran Li:** Investigation. **Hong-Xuan Duan:** Investigation.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.agee.2025.109825.

Data availability

Data will be made available on request.

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