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GENERATIONAL DIFFERENCES IN THE SUSTAINABILITY OF MAIZE PRODUCTION UNDER EXTENDED LAND CONTRACTS IN NORTHEAST CHINA

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Abstract

The major maize-producing region of Northeast China faces dual pressures from an aging rural population and the implementation of an extended land contract policy, potentially leading to significant divergence in production sustainability across farmer generations. To investigate this, a study was conducted from 2024 to 2025 in typical agricultural areas of Heilongjiang and Liaoning provinces. 72 maize-growing households were categorized into three groups based on the household head's age: Young Adults (YA), Middle-aged Adults (MA), and Old Adults (OA). Using the Sustainable Intensification Assessment Framework (SIAF), the sustainability of their production systems was systematically evaluated across five dimensions: productivity, economy, environment, human, and social. The results indicated that the YA group significantly outperformed others in maize grain yield, net income, and labor productivity. They also exhibited lower soil bulk density (BD), higher soil water content, and significantly better partial factor productivity of fertilizer (PFP). While the OA group maintained higher soil organic matter (SOM), they scored the lowest in technology adoption index and willingness of youth to engage in farming, showed poor system coordination, and had the lowest comprehensive sustainability score (CS). This study found that the YA group has developed a more resilient and coordinated sustainable intensification model by integrating scale management, mechanization, precision fertilization (e.g., soil testing-based formula fertilization), and conservation tillage. The study suggests that implementing the extended land contract policy should account for generational differences. It recommends promoting a youth-oriented agronomic system centered on the synergy of "scale-technology-market" and fostering the integration of traditional soil fertility management experience with modern precision agriculture to enhance the systemic sustainability of regional maize production.

Introduction

The sustainable development of agriculture is crucial for national food security and rural social stability. Northeast China, serving as the country's most important commercial grain production base, contributes approximately 40% of the national maize output, playing a "ballast" role in ensuring national food supply. However, the region is confronting a series of severe challenges: intensifying rural population aging, continuous outflow of young labor, and increasingly tight constraints on cultivated land resources and the environment. Against this backdrop, the Chinese government's policy to extend the second round of rural land contracts by another thirty years upon expiration aims to stabilize farmers' expectations and promote long-term agricultural investment (Peng *et al*. 2022). Yet, how this policy coordinates the interests and behaviors of different generational groups of farmers during implementation, and thereby influences the sustainability of agricultural systems, has become a critical issue requiring urgent exploration.

Generational difference is a core perspective for understanding the evolution of agricultural systems (Boscardin *et al*. 2023). Existing research indicates systematic differences among farmers of different age groups in technology adoption, risk preferences, operational objectives, and

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resource allocation (White 2015). Young farmers are generally more inclined to adopt modern agricultural technologies, expand operational scale, and participate in land transfer; middle-aged farmers seek a balance between maintaining yield and avoiding risks; while older farmers rely more on traditional experience, hold deep affection for the land, but often face dual challenges of efficiency and succession in their production methods. These differences may lead to significant divergence in productivity, economic benefits, environmental effects, and social sustainability of production systems among different generational groups under the same policy environment. While Chiswell (2018) focused on the process of farm transfer between generations, less is known about how established farmers of different ages currently operating under a stable long-term land lease policy diverge in their production sustainability. However, most existing studies focus on comparisons of single technologies or purely economic performance, lacking empirical exploration that integrates land contract extension, generational differences, and multidimensional sustainability into a unified analytical framework from a systemic perspective.

The Sustainable Intensification Assessment Framework (SIAF) provides robust methodological support for the systematic evaluation of agricultural systems (Abdul *et al*. 2024). This framework emphasizes a comprehensive assessment of agricultural technology sustainability across multiple dimensions-productivity, economy, environment, human, and social-and has yielded positive results in evaluations of smallholder systems in regions such as Africa. Nevertheless, the application of this framework within China, particularly against the backdrop of land institution transformation, remains largely unexplored (Lou *et al*. 2025). Introducing it to assess maize production systems in Northeast China can not only address the gaps in existing research but also provide a scientific basis for the precise adjustment of the land contract extension policy.

Therefore, this study takes Heilongjiang and Liaoning provinces in the main maize-producing region of Northeast China as cases. By constructing a comprehensive research methodology that integrates the SIAF with generational difference analysis, it aims to achieve the following objectives: (1) Quantitatively analyze the performance differences of different generational farmer groups across the five dimensions of productivity, economy, environment, human, and social; (2) Assess and compare the comprehensive sustainability (CS) score and internal coordination of production systems among different generational farmer groups; (3) Identify key generational factors influencing system sustainability, providing an empirical foundation and policy insights for refining the land contract extension policy and balancing intergenerational equity and efficiency.

Materials and Methods

This study was conducted in Heilongjiang and Liaoning provinces, the maize production heartland of Northeast China (Fig. 1). The region has a temperate continental monsoon climate, a frost-free period of 130-150 days, and single-cropping spring maize.

Four counties/cities were selected to represent different agro-ecological zones: Huachuan County (high-yield plain) and Fangzheng County (hilly transition) in Heilongjiang; Xinmin City (suburban intensive) and Zhangwu County (windy-sandy arid) in Liaoning. Within each county, we collaborated with local Agricultural Technology Extension Centers and used stratified random sampling to select a total of eight administrative villages (Table 1). In each village, we obtained the latest land contract registry and identified maize-growing households. Households were preliminarily grouped by household head age: young (≤45 years), middle-aged (46-60 years), and old (>60 years), following standard classifications (Fan 2002). From each age group in each village, three households were randomly selected, resulting in 8 villages×3 groups×3 households = 72 households as the valid sample. This design ensured balanced representation across age groups and villages.

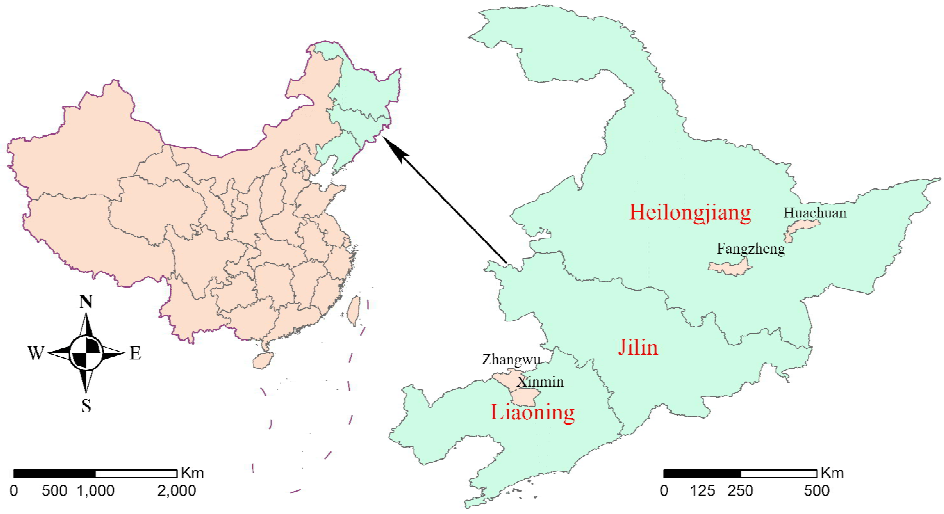


Fig. 1. Map of study sites in Northeast China.

Table 1. Sample administrative villages.

Province	County/City	Administrative village
Heilongjiang	Huachuan County	Xinghuo Village, Chuangye Village
	Fangzheng County	Demoli Village, Baoxing Village
Liaoning	Xinmin City	Xinglongbao Village, Damin Tun Village
	Zhangwu County	Zaolin Village, Qingshan Village

Data were collected during the 2024 and 2025 maize growing seasons through field measurements, farmer-recorded logs, and laboratory analyses, guided by the Sustainable Intensification Assessment Framework (SIAF).

In the productivity domain, maize grain yield was measured at physiological maturity from a 10 m² central area per field, oven-dried at 65°C to constant weight, and converted to standard moisture content (Kenney *et al.* 2015). Weed biomass was sampled at the bell stage using three 1 m² quadrats per field (Darfour and Rosentrater 2022). Land output rate was calculated as total maize output value per unit area.

For the economic domain, a detailed input-output account was constructed. Total revenue came from grain yield × local farm-gate price. Total costs included variable inputs (seed, fertilizer, pesticide, irrigation, machinery) and labor (family and hired, valued at local wage rate). Net income per hectare and cost-benefit ratio were derived.

In the environment domain, at tasseling and after harvest, soil bulk density (BD) was determined by the core method (0-20 cm depth) (Ataullah *et al.* 2017, Propa *et al.* 2021). Soil temperature was measured with a portable thermometer, and volumetric water content gravimetrically. Top soil (plow layer) samples were collected post-harvest; soil organic matter (SOM) and total nitrogen (TN) were analyzed by standard methods (Alam *et al.* 2024, 2026a, 2026b), and available phosphorus (AP) by sodium bicarbonate extraction (Soulaimani *et al.* 2025, Rahman *et al.* 2025). Partial factor productivity of fertilizer (PFP) was calculated as grain yield/pure nutrient input (Wierzbowska *et al.* 2022).

In the human domain, a structured questionnaire assessed adoption of five sustainable technologies (e.g., soil testing, formula fertilization, straw return, conservation tillage). A composite green technology adoption index was calculated. Willingness of youth to farm was measured by asking respondents about the likelihood of young relatives taking over the farm.

Finally, in the social domain, Focus group discussions (separate for male and female farmers) explored farmers' intentions regarding long-term land investment and intergenerational transfer of land rights (Liu *et al.* 2022). Through the questionnaire, farmers reported land transfer participation (inflow/outflow) over the previous three years.

Based on SIAF and the context of Northeast China, an assessment system with 5 domains and 15 core indicators was established (Table 2). Domain weights were determined by consulting 20 experts using the Analytic Hierarchy Process (AHP): productivity (0.25), economy (0.25), environment (0.20), human (0.15), social (0.15). Sub-indicator weights were assigned similarly. All raw indicators were normalized to 0-1 using min-max method (Mazziotta and Pareto 2022).

Table 2. Sustainability assessment indicator system and weights.

Dimension	Total Weight	Core indicators	Sub-indicator Weight
Productivity (P)	0.25	Maize grain yield	0.10
		Weed biomass	0.05
		Land output rate	0.10
Economic (Ec)	0.25	Net income	0.10
		Labor productivity	0.08
		Cost-benefit ratio	0.07
Environment (En)	0.20	Soil temperature	0.03
		Soil water content	0.03
		SOM	0.05
		BD	0.03
		PFP	0.06
Human (H)	0.15	Technology adoption index	0.09
		Willingness of youth to farm	0.06
Social (S)	0.15	Long-term land investment willingness	0.08
		Land transfer participation rate	0.07

Based on the normalized indicator scores, the CS for each farmer's production system was calculated using the weighted sum method:

$$CS = 0.25P + 0.25Ec + 0.20En + 0.15H + 0.15S$$

Where P, Ec, En, H, and S represent the standardized scores for the Productivity, Economic, Environment, Human, and Social domains, respectively.

To assess the balance of development among the five dimensions within a system, a System Coordination (D) index was introduced. The five domain scores were visualized on a radar chart and treated as five points in a polar coordinate system. The score r_i for each point at a fixed angle $\theta_i = \frac{2\pi}{5}(i-1),\ \ (i = 1,2,3,4,5)$was converted to Cartesian coordinates (x_i, y_i):

$$x_i = r_i cos\theta_i,\ \ y_i = r_i sin\theta_i$$

The geometric centroid (G_x, G_y) of these five points was calculated, and its Euclidean distance from the origin defined the D value:

$$D = \sqrt{G_{x^2} + G_{y^2}}$$

Where $G_x = \frac{1}{5}\sum x_i\ \ G_y = \frac{1}{5}\sum y_i$.

D value approaching 0 indicates balanced development and high system coordination, while an increasing D value suggests the presence of significant weak domains and system imbalance.

To examine the effect of generational differences on system sustainability, the following statistical methods were employed. Linear mixed models were constructed with generational group as a fixed effect and village as a random effect to test for generational differences in the CS score and D index. If the main effect of generation was significant ($p < 0.05$), post hoc multiple comparisons were conducted using Fisher's Least Significant Difference (LSD) test. Furthermore, multivariate analysis of variance (MANOVA) was performed to test the overall effect of generational grouping on the scores of the five SIAF domains (Productivity, Economic, Environment, Human, Social).

Results and Discussion

The assessment of the five SIAF dimensions revealed significant and consistent generational differences across all indicators as shown in Tables 3 and 4. The Young Adult group outperformed the Middle-aged and Old Adult groups in yield, net income, labor productivity, and fertilizer efficiency, while the Old Adult group maintained higher soil organic matter but scored lowest in technology adoption, investment willingness, and land transfer participation.

YA farmers achieved the highest yields, 8-10% above MA and 13-17% above OA, with the lowest weed biomass at 145.8-168.9 g m^{-2} versus 228.4-255.1 g m^{-2} for MA and 310.2-345.8 g m^{-2} for OA. Their productivity advantage reflects systematic adoption of precision practices including optimal density, soil-test-based fertilization, and integrated weed control, whereas older farmers relying on traditional experience left yield potential unrealized. YA net income ranged from 11.5 to 13.5 k¥ ha-1 and labor productivity from 265.4 to 310.2 ¥ $workday^{-1}$, both substantially exceeding the other groups. Environmentally, YA fields showed lower bulk density of 1.23-1.28 g cm^{-3} versus 1.35-1.41 g cm^{-3} for OA, higher soil water content at 0.201-0.225 cm^3 cm^{-3} versus 0.168-0.189 cm^3 cm^{-3} for OA, and greater fertilizer efficiency with PFP of 33.5-36.5 kg kg^{-1} versus 27.1-29.5 kg kg^{-1} for OA. OA soils retained more organic matter at 28.0-29.2 g kg^{-1} versus 25.8-26.8 g kg^{-1} for YA, but used nutrients less efficiently, a trade-off between traditional fertility maintenance and modern nutrient optimization also observed in other smallholder systems (Abdul *et al.* 2024).

YA farmers also led in technology adoption, succession willingness, long-term land investment, and land transfer participation. Generational rankings remained stable across provinces and years, confirming that age-cohort characteristics including knowledge structures, professional perspectives, and future expectations drive differentiation more than regional or annual fluctuations (White 2015).

Notably, yields in Heilongjiang exceeded those in Liaoning across all groups despite the latter's warmer coastal location and higher provincial average yields in some recent years. This seemingly counterintuitive result arises from two considerations. First, our Liaoning sites included Zhangwu County with sandy, low-fertility soils that suffer from poor water and nutrient retention, whereas Heilongjiang sites are located on deep, fertile Mollisols with inherently higher productivity. Second, management intensity can override natural endowments: Heilongjiang farmers, especially the YA group, showed greater land transfer participation and long-term investment, enabling scaled mechanization and precision technologies that compensated for climatic disadvantages. This aligns with the view that institutional environments favoring land concentration and long-term investment are critical for sustainable intensification (Grubbström and Eriksson 2018), and supports the principle that coordinated multidimensional progress outperforms single-objective gains (Adams *et al.* 2025).

Table 3. Performance of maize cultivation sustainability indicators in 2024.

Dimension	Indicator	Heilongjiang province					Liaoning province				
		YA	MA	OA	SEM	P	YA	MA	OA	SEM	P
Productivity	Maize grain yield (kg ha^{-1})	10120.2 a	9355.5 b	8760.3 c	185.4	***	9245.7 a	8525.4 b	7980.9 c	201.7	***
	Weed biomass (g m^{-2})	152.3 c	235.7 b	321.5 a	18.6	***	168.9 c	255.1 b	345.8 a	20.4	***
	Land output rate (score)	0.86 a	0.73 b	0.66 c	0.03	***	0.81 a	0.69 b	0.62 c	0.03	***
Economic	Net income (k¥ ha^{-1})	12.8 a	11.1 b	9.2 c	0.4	***	11.5 a	9.8 b	7.9 c	0.4	***
	Labor productivity (¥ workday^{-1})	295.1 a	235.7 b	208.6 c	10.5	***	265.4 a	210.2 b	185.8 c	11.2	***
	Cost-benefit ratio	2.2 a	1.9 b	1.7 c	0.07	**	2.1 a	1.8 b	1.6 c	0.08	**
Environment	Soil temperature (°C)	26.8 b	27.5 a	27.7 a	0.2	*	27.2 b	28.1 a	28.3 a	0.2	*
	Soil water content (cm^3 cm^{-3})	0.218 a	0.195 b	0.183 c	0.007	***	0.201 a	0.179 b	0.168 c	0.008	***
	SOM (g kg^{-1})	26.5 b	27.4 b	28.9 a	0.5	*	25.8 b	26.7 b	28.0 a	0.6	*
	BD (g cm^{-3})	1.24 c	1.30 b	1.36 a	0.02	***	1.28 c	1.35 b	1.41 a	0.02	***
	PFP (kg kg^{-1})	35.8 a	32.1 b	28.9 c	1.1	***	33.5 a	30.2 b	27.1 c	1.2	***
Human	Technology adoption index (0-1)	0.79 a	0.62 b	0.45 c	0.04	***	0.76 a	0.60 b	0.42 c	0.05	***
	Willingness of youth to farm (%)	70.1 a	46.3 b	25.8 c	4.2	***	65.5 a	42.9 b	23.1 c	4.8	***
Social	Long-term land investment willingness (%)	83.5 a	66.7 b	49.3 c	5.1	***	80.2 a	63.1 b	46.5 c	5.6	***
	Land transfer participation rate (%)	76.8 a	58.3 b	35.2 c	5.3	***	72.9 a	55.4 b	33.7 c	5.9	***

Notes: Different lowercase letters within a row and province indicate significant differences among generational groups (LSD, $p < 0.05$). Significance levels: *$p < 0.05$; **$p < 0.01$; ***$p < 0.001$.

Table 4. Performance of maize cultivation sustainability indicators in 2025.

Dimension	Indicator	Heilongjiang province					Liaoning province				
		YA	MA	OA	SEM	P	YA	MA	OA	SEM	P
Productivity	Maize grain yield (kg ha^{-1})	10450.3 a	9680.8 b	9020.4 c	190.1	***	9520.1 a	8790.7 b	8210.6 c	205.3	***
	Weed biomass (g m^{-2})	145.8 c	228.4 b	310.2 a	17.9	***	162.1 c	247.6 b	334.5 a	19.8	***
	Land output rate (score)	0.88 a	0.75 b	0.68 c	0.03	***	0.83 a	0.71 b	0.64 c	0.03	***
Economic	Net income (k¥ ha^{-1})	13.5 a	11.7 b	9.6 c	0.4	***	12.1 a	10.3 b	8.3 c	0.4	***
	Labor productivity (¥ workday^{-1})	310.2 a	248.5 b	218.3 c	10.8	***	278.8 a	222.2 b	195.1 c	11.5	***
	Cost-benefit ratio	2.3 a	2.0 b	1.7 c	0.07	**	2.1 a	1.9 b	1.6 c	0.08	**
Environment	Soil temperature (°C)	26.6 b	27.4 a	27.6 a	0.2	*	27.0 b	27.9 a	28.1 a	0.2	*
	Soil water content (cm^3 cm^{-3})	0.225 a	0.202 b	0.189 c	0.007	***	0.208 a	0.185 b	0.174 c	0.008	***
	SOM (g kg^{-1})	26.8 b	27.6 b	29.2 a	0.5	*	26.1 b	27.0 b	28.3 a	0.6	*
	BD (g cm^{-3})	1.23 c	1.29 b	1.35 a	0.02	***	1.27 c	1.34 b	1.40 a	0.02	***
	PFP (kg kg^{-1})	36.5 a	32.8 b	29.5 c	1.1	***	34.2 a	30.8 b	27.6 c	1.2	***
Human	Technology adoption index (0-1)	0.81 a	0.64 b	0.47 c	0.04	***	0.78 a	0.62 b	0.44 c	0.05	***
	Willingness of youth to farm (%)	71.5 a	47.6 b	26.4 c	4.3	***	66.8 a	44.2 b	23.8 c	4.9	***
Social	Long-term land investment willingness (%)	84.2 a	67.8 b	50.1 c	5.2	***	81.0 a	64.3 b	47.2 c	5.7	***
	Land transfer participation rate (%)	78.3 a	59.8 b	36.5 c	5.4	***	74.1 a	56.7 b	34.3 c	6.0	***

Note: Same note as in Table 3.

Analysis of CS and coordination degree shown in Table 5 confirmed YA systems achieved the highest CS values from 0.855 to 0.954 with the lowest D values from 0.138 to 0.151, representing high sustainability with high balance across all dimensions. MA systems scored intermediate CS from 0.463 to 0.576, while OA systems had the lowest CS from 0.150 to 0.243 and the highest D values above 0.30, reflecting serious imbalances in economic, human, and social dimensions.

Table 5. CS and coordination degree (D) of maize production systems.

Province	Year	CS			D		
		YA	MA	OA	YA	MA	OA
Heilongjiang	2024	0.948	0.548	0.221	0.142	0.228	0.305
	2025	0.954	0.576	0.243	0.138	0.225	0.301
Liaoning	2024	0.855	0.463	0.150	0.151	0.241	0.321
	2025	0.869	0.491	0.169	0.148	0.238	0.318

CS: weighted comprehensive score (range 0-1). D: system coordination degree.

Figure 2 shows radar charts of dimension scores by generation. YA shows a nearly full and symmetrical shape, with no single dimension lagging behind. OA is distinctly contracted in economic, human, and social dimensions. This pattern aligns with D: YA has D from 0.138 to 0.151, indicating high sustainability and balance, while OA above 0.30 indicates uneven development.

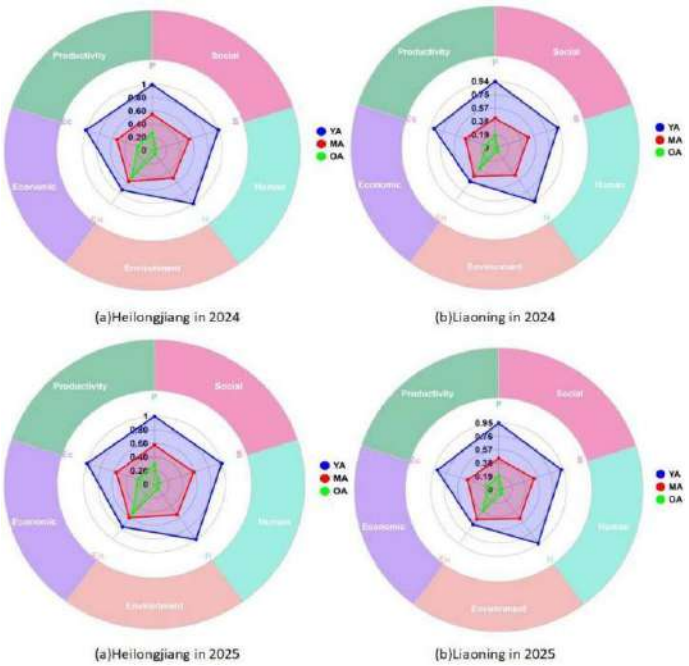


Fig. 2. Radar charts of sustainability dimension scores by generational group (YA, MA, OA).

Fig. 3 compares CS by generation. YA scored highest, 0.855-0.954; MA intermediate, 0.463-0.576; OA lowest, 0.150-0.243. All differences were significant, confirming that farmers operate more sustainable systems.

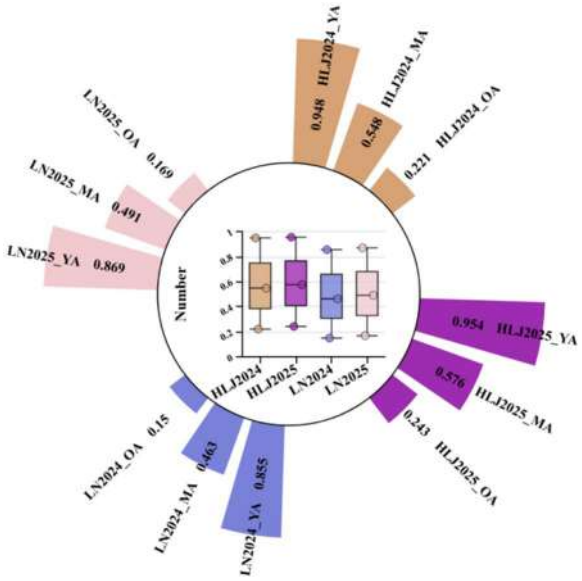


Fig. 3. Comprehensive sustainability (CS) scores by generational group, province, and year.

Figure 4 shows coordination degree D by generational group. A lower D value means more balanced development across the five dimensions. YA systems had the lowest D values, ranging from 0.14 to 0.15, indicating they are well coordinated. MA systems showed moderate D values around 0.23 to 0.24, while OA had the highest above 0.30, pointing to serious imbalances in economic, human, and social dimensions. This generational pattern was robust across both Heilongjiang and Liaoning provinces and across 2024 and 2025.

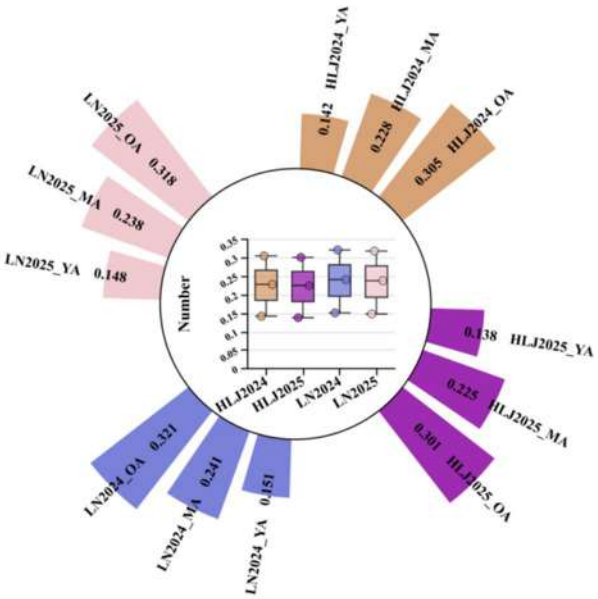


Fig. 4. Coordination degree (D) by generational group, province, and year.

This outcome reveals the systemic effects of different farming strategies. By integrating moderate scale, mechanization, precision technologies, market participation, and long-term investment, young farmers have constructed production systems that achieve synergistic improvement across productivity, profitability, resource conservation, and social adaptability. Promoting sustainable intensification should therefore focus on multidimensional optimization rather than single-objective gains alone (Adams *et al*. 2025).

This study applied the SIAF to evaluate maize production sustainability under extended land contracts in Northeast China. Generational differences significantly affected all dimensions. The YA group led in productivity, economic returns, and environmental efficiency, while the OA group, though maintaining higher SOM, lagged in human and social capital. Young farmers' systems achieved higher CS and better coordination through the integration of scale, mechanization, precision technology, and land transfer. Operational scale, technology adoption intensity, and land transfer participation are key drivers of generational divergence. Policies must account for these differences: support young farmers in scaling up and mechanizing, enhance older farmers' capacity through targeted training, and establish cross-generational platforms to blend traditional fertility management with modern precision technologies, thereby improving system-level productivity, efficiency, and long-term resilience.

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