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Sustainable Intensification of Cultivated Land Use and Its Influencing Factors at the Farming Household Scale: A Case Study of Shandong Province, China

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Abstract: Promoting the sustainable intensification of cultivated land use (SICL) has become crucial for ensuring a sufficient supply of grain and important agricultural products, as well as for the sustainable use of resources. Taking widely used areas of Shandong Province in China as examples, an analytical scale and level framework for SICL is constructed in this study. It measures the level of SICL through material flow analysis, constructs Tobit models to analyze the influencing factors of SICL at the farming household scale, and analyzes the transition mechanisms of SICL. The results show that the overall level of SICL in Shandong Province is low, and the spatial distribution is uneven. There are relatively more farmers participating in unsustainable intensification than in medium or low levels of SICL, with farmers working at a high level of SICL making up the smallest proportion. The factors that determine the level of SICL at which farmers work vary significantly. More male farmers operate at a low SICL level than female farmers, while females outnumber males at a high SICL level. This is mainly related to the regional distribution of age and population. Meanwhile, with larger cultivated land areas, there is a lower degree of land fragmentation, with a higher level of SICL corresponding to a smaller distance to the nearest town closer within 1–5 km from the town center. We can see the level of SICL and its processes themselves are closely related to time and space scales. Based on the above analysis, it is necessary to clarify the standard processes of SICL to adapt them to local conditions. This includes instructing managers on how to improve resource utilization, increase the sustainable development of cultivated land and establish a comprehensively efficient and functional SICL mechanism. The sustainable intensification of cultivated land use and its specific application in the new era are conducive to enriching the frontier theories and methodology of sustainable development, and are of great significance to the advancement of green agriculture and the decision-making of rural high-quality development.

Keywords: cultivated land use; sustainable intensification; farming household scale; material flow analysis

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1 Introduction

The United Nations: World Population Prospects 2019 shows that there will be approximately nine billion humans to feed by 2050. However, the estimated annual loss of agricultural area globally is approximately 20 000 km^2 (Huang et al., 2015), which poses a challenge for the world with regard to sufficient food production (Foley et al., 2007). Under the current climate, the continuous decline in cultivated land area and con-

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tinuous rise in population, the intensification of cultivated land use has become necessary for increasing agricultural production levels (Riwthong et al., 2015; Robinson et al., 2015; Mahon et al., 2018; Scherer et al., 2018; Snapp et al., 2018). The potential for agricultural scale expansion is very limited; thus, higher food demand in the future will often need to be realized through the intensification of production (Herrero et al., 2010; Jules, 2018). However, the over-intensification of cultivated land use results in an overloaded ecosystem and increased pressure on the environment (Marrero et al., 2014; Newbold et al., 2015; Areal et al., 2018). Therefore, it is necessary to seek a solution that will simultaneously ensure food security and ecological environmental protection. Theoretical research and the practical exploration of sustainable intensification face great challenges; consequently, promoting sustainability of cultivated land intensive use is critical for securing a sufficient supply of grain and agricultural products, along with the sustainable utilization of resources (Wang et al., 2014; Wezel et al., 2015; Niu et al., 2018; Scherer et al., 2018). China uses less than 9% of the world's cultivated land to feed nearly 20% of the world's population①. However, long-term, high-intensity, and high-load utilization has also caused serious ecological problems, restricting the sustainable use of cultivated land (Xie et al., 2020). The transformation of cultivated land utilization and protection of the quantity, quality, and ecology (Niu and Fang, 2019) has become an inevitable requirement for the construction of ecological civilization. Under the contexts of climate change, scientific and technological change, and economic and social transformation, China practices the strictest farmland protection system and a strategy of sustainable farmland use and innovative application of agricultural technology to increase farmland productivity. As such, it is imperative for China to optimize the processes of cultivated land use and change current methods of agricultural development. Such a task depends on maintaining balances between the extension and conversion of cultivated land and between the amounts of land allocated for urban and rural construction.

In recent years, with an increase in environmental impact research, the concept of sustainable intensification (SI) has emerged. SI can be traced back to 1983, when the Agroecosystem Research Group on Tidal Wetlands in Indonesia used SI for environmental assessment and coastal resource management. At that time, it was primarily aimed at promoting the sustainable use of aquatic natural resources; however, its definition and principles have not been clarified (Wezel et al., 2015). The first definition of SI was the 'substantial growth of yields in currently unimproved or degraded areas, while protecting or even regenerating natural resources' (Pretty, 1997). Until now, some research has focused on conceptual ideas, empirical evaluations, and impact mechanisms of SI. Based on differing scales and perspectives, SI has been implemented with empirical analysis in France, Canada, and Nepal, among other countries (FAO, 2009; Wezel et al., 2015; Martin-guay et al., 2018; Mutyasira et al., 2018). SI is a dynamic process, rather than a condition (Firbank et al., 2013). That is, land, labor, capital, and other factors per unit area are put into the production of additional grain, fodder, and fuel to protect the ecosystem and promote biodiversity (Petersen and Snapp, 2015). Thus, the land can withstand external pressures, such as climate change, and play an important role in maintaining global food security. The input and output production systems are designed to enhance land productivity and product quality while maintaining the integrity of the ecosystem. The long-term stability of the surrounding environment must also be maintained to meet the needs of both present and future generations of humans (Yami and Van Asten, 2017). SI assessment is mainly based on farming scale (Ruben et al., 2010; Firbank et al., 2013; Willy et al., 2019), building productivity (Altieri, 1999; Kassie et al., 2015), the sustainable development of the economy (Snapp et al., 2010), environment (Phalan et al., 2011; Vanlauwe et al., 2014; Demessie et al., 2015), society (Owenya et al., 2012), and human health (Kamanga et al., 2014). A model of the ecological efficiency index from data envelopment analysis (Gadanakis et al., 2015), comparative analysis of changes in agricultural production and environmental variables (Firbank et al., 2013), and the multivariate probability (MVP) model (Kassie et al., 2015) have been widely utilized to evaluate the level of SI. However, a unified research system

① The State Council Information Office of the People's Republic of China, http://www.scio.gov.cn/video/gxsp/Document/1666242/1666242.htm relating to SI has not yet been formulated. Additionally, the influencing mechanisms of SI are diverse. Studies have found that the scale and scope of agricultural land management, land supply patterns, and policy regulations are important for SI assessment (Jules et al., 2011). From the spatial distribution, previous empirical studies of SI have primarily been conducted in the mountains of Europe, Africa, and the Americas, as well as in South Asia. Some scholars believe that both biological and intensification approaches are required to explore and realize the goals of SI (Sumberg, 2002), involving land sharing or sparing to protect the ecosystem (Garnett et al., 2013) and policy regulation.

The research and practice of SI have attracted attention in China. The goal of SI is to increase output through the intensive use of existing land while reducing the environmental pressure caused by the intensification process, minimizing the negative impacts on environment and ensuring that limited land can continue to provide for mankind (Zhu and Sun, 2014). Relevant studies in China focus mainly on the environmental effects and sustainability of cultivated land intensive use (Wang et al., 2012; Zhang et al., 2012; Song, 2013; Yin et al., 2015a), sustainable development of agriculture (Zhao, 2003; Cao, 2012; Luo et al., 2016), and efficiency of production in relation to social and economic factors (Liu and Zhang, 2012; Liu and Chen, 2013). Some domestic scholars have also been conducted on the sustainability of farmland ecosystems and eco-economic zones under highly intensive conditions (Yin et al., 2015b) and the environmental risks of resource input and pollution output in highly intensive agricultural areas (Zhao et al., 2014). Therefore, it is of great theoretical and practical significance to quantitatively evaluate the sustainability of intensification and the effects under different environmental conditions and spatial scales.

In view of the present research on SI at domestic and foreign, it is undeniable that the academic definition of SI remains ambiguous, even from the standpoint of goal orientation, function connotation, and system logic. Therefore, based on the above analysis, from the perspective of sustainable development and China's unique national conditions, a clear definition of the concept of sustainable intensification of cultivated land use (SICL) is provided in this paper. In particular, the SICL involves the strengthening of the sustainability of cultivated land intensive use. Based on the principle of ecological suitability, by improving agricultural productivity or intensive level, the synergistic coupling of efficient use and SICL productivity can be promoted to achieve a situation in which the combined effect is greater than the sum of its parts (Niu et al., 2018). In sustainable development view, SICL emphasizes the validity of production factors, improves the productivity of regional cultivated land, saves resources, reduces environmental pressures, and improves the natural capital and environmental service capacity of cultivated land resources, while realizing the intergenerational equity of resource utilization. Spatially, SICL requires differentiated regulation at a variety of regional and spatial scales. This is primarily due to the fact that land output and environmental effects differ in spatial scales. On time scales, it is a dynamic process that is adaptable to the construction of ecological civilization and the social and economic development of different regions in different periods, which reflecting the stage of sustainable intensification.

As the main subject of cultivated land use and management according to their agricultural production objectives under various constraints, farmers will eventually affect the land use change and its sustainability (Lian, 2005). Moreover, with the continuous development of new agricultural business entities, farmers are still an important force in the process of agricultural modernization. How can farmers understand SI? Facing the requirements of green development, will farmers' understanding and behavior regarding SICL conform to policy expectations? These are particular concerns that require further systematic study. Based on the material flow analysis method, the level of SICL is evaluated at the farming household scale, and the influencing factors and mechanism of SICL are analysed. Specifically, it comprises three aspects: 1) defining of the concept of SICL, which includes an analytical scale and hierarchical framework; 2) measuring the level of SICL and its influencing factors on the farmer scale; and 3) discussing the regulation and control route of SICL in relation to China. This paper puts forward optimized control measures aiming at the coordinated guarantee of food security and the implementation of ecological civilization strategy.

2 Materials and Methods

2.1 Study area

Shandong Province is located on China's eastern coast, downstream of the Yellow River at the latitudes of 34°20′N to 38°30′N and longitudes of 114°45′E to 122°45′E. It is situated in the north temperate zone, a semi-humid, monsoon climate that experiences four distinctive seasons and a large range of temperatures. With precipitation and heat over the same period, there were apparently seasonal changes in precipitation intensity, the average annual precipitation is 679.5 mm, and the average annual runoff depth is 126.5 mm. In 2015, the total area of land was 0.158×10^9 ha. Mountains and hills account for 34.9% of the total area, plains and basins make up 64.0%, and rivers and lakes constitute 1.1%. The cultivated area is 0.076×10^9 ha, accounting for 48.3% of the total land area of the province, with a per capita of 0.078 ha. Shandong Province, with a total area of sown crops of 11 026 600 ha at a multiple crop index of 160%, is one of China's major grain producing areas. The province now administers 17 prefecture-level cities with a total population of 98.47 million; this includes an agricultural population of 42.33 million, accounting for 42.99% of the total.

Rizhao City, Wulian County along the eastern coast, the Kenli District of Dongying City on the Yellow River Delta and Dongping County, and Tai'an City in the central, mountainous region of Shandong Province were selected as research areas (Fig. 1). They were chosen because they are evenly distributed in terms of the geographical space of Shandong Province. In terms of the gradient of regional development, Kenli District has a developed economy, whereas Dongping County and Wulian County are more focused on agricultural development. These areas can be used as a reference for the implementation of SICL in other countries.

2.2 Data sources

From June to August 2017, field surveys in Wulian County, Kenli District, and Dongping County were conducted. A random sampling was used to select townships that accounted for 30% of each county and randomly select two villages within each county or town for household surveys. Considering the geographical and spatial differences of the research area, including topography, hydrological characteristics, planting habits, and many other factors affecting the sustainable use of cultivated land, we formulated a questionnaire survey that meets scientific standards. In Wulian, 162 farming households from 19 villages in nine townships were investigated, and 162 valid questionnaires were retrieved. In Kenli, 110 farming households from 10 villages in five townships were investigated, and 110 valid questionnaires were retrieved. In Dongping, 121 farming households from 12 villages in six townships were investigated, and 121 valid questionnaires were retrieved. In total, the team visited 393 farming households from 41 villages in 20 townships, retrieving 393 questionnaires. After five questionnaires were determined to be invalid and removed and incorrectly filled and missing questionnaires were disposed of, 388 questionnaires remained, yielding a success rate of 98%.

Questionnaire data were primarily conducted based on a household's gender, age, education, total income, family size, number of land parcels, contracted land area, total business area, source of household income, and household income per capita (Table 1). In general,

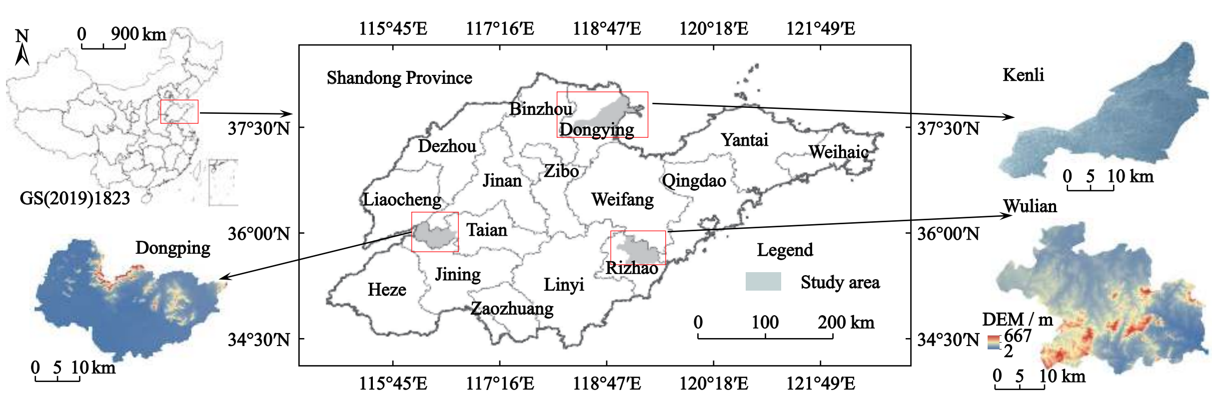

Fig. 1 Location of study area

Table 1 Characteristics of sample households

Item	Category	Number	Proportion / %	Item	Category	Number	Proportion / %
Gender	Male	254	65.40	Number of land parcels	< 3	102	26.29
	Female	134	34.50		[3, 10)	218	56.19
					≥ 10	68	17.53
Age / years-old	< 18	0	0	Contracted land area / ha	< 0.33	157	40.46
	[18, 30)	3	0.77		[0.33, 0.67)	137	35.31
	[30, 50)	76	19.59		[0.67, 1.00)	55	14.18
	[50, 70)	254	65.46		[1.00, 1.33)	12	3.09
	≥ 70	55	14.18		≥ 1.33	27	6.96
Degree of education	Illiteracy	88	22.68	Total operating area / ha	< 0.33	143	36.86
	Primary	116	29.90		[0.33, 0.67)	126	32.47
	Junior	143	36.86		[0.67, 1.00)	40	10.31
	Senior	35	9.02		[1.00, 1.33)	16	4.12
	Junior college or above	6	1.55		≥ 1.33	63	16.24
Total income / yuan (RMB)	Below 10000	70	18.04	The main source of income for families	Agricultural income	126	48.97
	10000–30000	82	21.13		Independent operation	65	2.04
	30000–70000	112	28.87		Go out for a part-time job	197	50.77
	Over 70000	124	31.96				
Family population number	1	4	1.03	Per capita annual income of households / (yuan (RMB))	< 1000	21	5.41
	2	76	19.59		1000–3000	57	14.69
	3	76	19.59		3000–5000	25	6.44
	4	85	21.91		5000–7000	32	8.25
	≥ 5	147	37.89		> 7000	253	64.21

most interviewees were male, accounting for 65.40% of the total. Interviewees ranging from 50 to 70-year-old accounted for 65.46%, and only 0.77% were less than 30-year-old. Most had earned only a junior high school education or lower, accounting for 89.44%. Most families contained five or more members, accounting for 37.89% of those surveyed. The number of land parcels in the sample farmer households averaged between 3 and 10, accounting for 56.19%. Those with contracted land less than 0.67 ha accounted for 82.48%, and those with a total business area less than 0.67 ha accounted for 69.33%. Among the major sources of household income, 197 households contained migrant workers, accounting for 50.77%. There were 112 households earning a gross household income between 30 000 and 70 000 yuan (RMB), accounting for 28.87% of the total number of households interviewed. Households with an annual average income of more than 7000 yuan (RMB) constituted a relatively high proportion, at 64.21%.

2.3 Research methods

2.3.1 Material flow analysis: research level and scale

Employing the analytical scale and hierarchical framework of SICL (Fig. 2) is a comprehensive approach toward analyzing regional resource allocation, rural development, quality of the ecological environment, and land use patterns. As SICL contains spatial-temporal characteristics, its regional resource allocation and structural optimization have become important aspects of its implementation. In general, with farming households as the subject of cultivated land use, their behaviors and variety of employed methods affect the change and sustainability of land use. The analysis of the SICL mechanism is more effectively performed on a microscopic scale. Different research scales are chosen to depict SICL processes based on the analytical hierarchy of the 'pro-

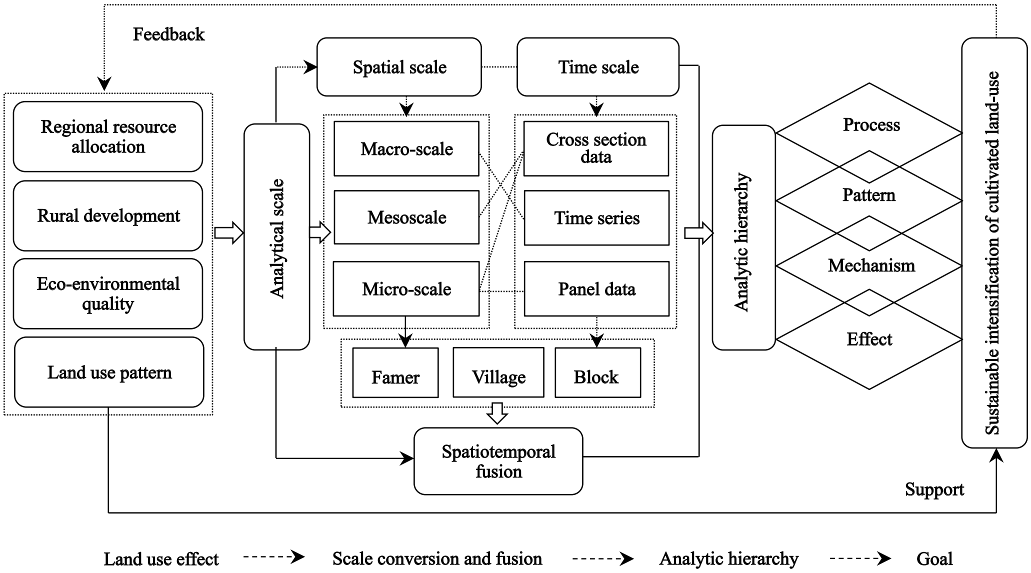

Fig. 2 Analysis of hierarchy and scale framework of sustainable intensification of cultivated land use

cess-pattern-mechanism-effect'. The nature of conversion among the different scales may affect the process of SI over different time periods and spaces, forming a variety of temporal and spatial landscapes and revealing the intrinsic mechanisms of the evolution of intensive utilization of cultivated lands. The characteristics of a time period and evolving laws may be summarized by analyzing the effects of SICL on different scales, rationally allocating regional resources, optimizing land utilization methods, and realizing rural prosperity and ecological civilization. Therefore, farming households were chosen in this study as the basic scale of analysis for research, treating the process of SICL as a subject of analysis and using the behavioral characteristics, differences, and effects of the process as the hierarchy of analysis under a comprehensive analytical framework.

2.3.2 Material flow analysis

In this study, the material flow method is applied to the SICL evaluation. The framework of this application is shown in Fig. 3. In an SICL dynamic change system based on material flow analysis (MFA), the basic elements include the material productivity (MP) of the material input, hidden flow (HF), and environmental and economic effects (EE) of the material output and stock. Material flow reflects the direction of the flow of both resources and environmental elements, which is known as the cross-feed effect between resource input and pollutant output (Chen et al., 2003; Huang et al., 2007; Zhang et al., 2007). This perspective allows the further analysis of the impact of intensification on ecological environment systems.

Based on the characteristics of input-output production on cultivated land and the characteristics of the site, the input of MFA (Fig. 3) is divided into that of solid, gas and liquid, and the output is divided into that of solid, water and atmospheric emissions. The input and output are classified as M1–M7 and N1–N7 categories, respectively. The stock is an agricultural product (P1), and the HF (O1, O2) is the part not directly entering the system through cultivated land use (Table 2). The M3,

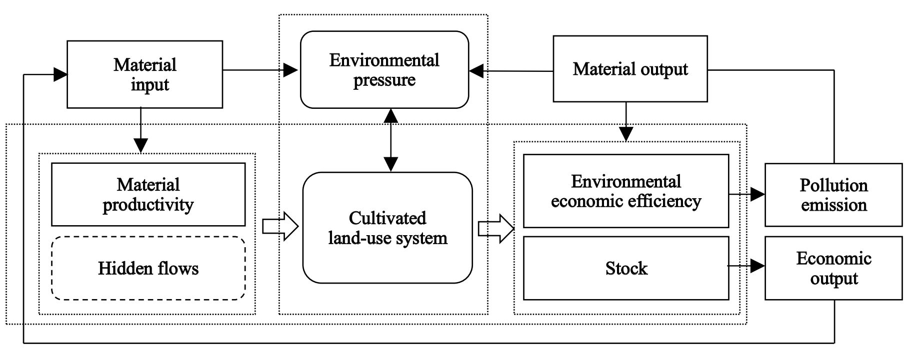

Fig. 3 Dynamic change system of sustainable intensification of cultivated land use based on MFA (Niu et al., 2018)

N2–N7, O1, and O2 indicators were calculated by referring to the relevant literature.

2.3.3 SICL index model

SICL is an interactional function of MP, EE, Stock, and HF, directly proportional to MP and Stock and inversely proportional to EE and HF. The greater the MP and stock are, the higher the degree of SICL is. In contrast, lower EE and HF correspond to a higher degree of SICL. The SICL index I_i was built under the MFA framework.

$$I_i = \frac{MP_i \times STOCK_i}{EE_i \times HF_i} \tag{1}$$

where I_i stands for the SICL index, MP_i is the resource productivity of farmer household i, $STOCK_i$ is the material storage of farmer household i, EE_i is the environmental economic efficiency of farmer household i, and HF_i is the HF of farmer household i (Niu et al., 2018).

Table 2 Variables description of sustainable intensification of cultivated land use

	Index	Class	Subclass	Index connotation
Input	DMI	Solid input	Chemical fertilizer (M1)	Direct material input: input of direct production factors
			Plastic sheeting (M2)	
		Gas input	Soil respiration consumption O_2 (M3) (Zhang, 2009)	
		Liquid input	Pesticides (M4)	
			Herbicides (M5)	
			Irrigation water (M6) (Li, 2005)	
			Agricultural diesel (M7)	
	MP	Material productivity	MP = DMI/G, G is the output value of agricultural economy (yuan (RMB))	The resources consumed by the economic output value of the cultivated land in the unit area (material productivity)
Output	DPO	Solid output	Chemical fertilizer loss (N1)	Domestic processed: direct emissions of pollutants during cropland production
		Liquid output	Plastic film residue (N2) (Zhang et al., 2016)	
			Pesticide loss (N3) (Ministry of Agriculture, 2015)①	
			Herbicide loss (N4) (Ministry of Agriculture, 2015)	
		Gas output	Combustion of agricultural diesel emissions CO_2, SO_2, NO_X and other pollutants (N5) (Huang et al., 2006)	
			Soil respiration emission of CO_2 (N6) (Zhang, 2009)	
			Straw burning pollutants such as CO_2 and SO_2 and NO_X (N7) (Wang and Zhang, 2008)	
	EE	Environmental economic efficiency	EE = DPA/G, G is the output value of agricultural economy (yuan (RMB))	Unit operating area cultivated land economic output value wastegenerated (environmental efficiency)
	Stock		Crops (P1)	Production stock:output of agricultural products
	HF		Hidden flow of agricultural products (O1) (Li, 2008)	Hidden flows: substances that do not enter the material cycle of cultivated land in the production process
			Soil erosion (O2) (Su, 2013)	

Note: This table has been compiled based on Yin (2016)

① Ministry of Agriculture of the People's Republic of China, 2015. http://www.moa.gov.cn/govpublic/ZZYGLS/201505/t20150525_4614695.htm

2.3.4 Tobit model

The Tobit model, also known as the sample selection model or the limited dependent variable model, is used as a model to limit the dependent variables. It was created by James Tobin, an American economist, and is applicable to situations in which a dependent variable is of a cut or segment value. As the average SICL under the MFA model is greater than 0, when the dependent variable is truncated or censored, a limited dependent variable may be adopted. The use of traditional ordinary least squares may cause errors, and the limited Tobit model is used to quantitatively reveal the influential factors of SICL at the household scale. The Tobit model can also be used to estimate partial data among samples (Lu et al., 2018) to meet the demand of regional regression analysis. The basic structure of the model is as follows:

$$y_i = \begin{cases} \beta' x_i + \varepsilon_i \beta' x_i > 0 \\ 0, \quad \text{otherwise} \end{cases} \tag{2}$$

where y_i is the observed dependent variable; x_i is the independent variable; and β' is the parameter vector to be estimated, $\varepsilon_i \sim N(0, \sigma^2)$.

3 Results and Analysis

3.1 Types of SICL

According to variables description of sustainable intensification of cultivated land use (Table 2) and the analysis of the sample farming households, SICL index (I_i) (Table 3) was calculated based on the index measurement method (Niu et al., 2018). And on this basis the classification of SICL levels at the household scale is summarized in Table 3. These are mathematical foundations for the comprehensive analysis of various influencing factors of the SICL.

3.2 Factor analysis of farming households with different utilization types

Eviews 9.0 was adopted to perform a Tobit analysis on the influencing factors of the SICL, with the result shown in Table 4. The characteristics of individuals and

Table 3 Classification of sustainable intensification of cultivated land use levels at the farming household scale

Degree division	High-level	Medium level	Low-level	Unsustainable
SICL index	> 100	(10, 100]	[1, 10]	(0, 1)
Classification	Category 4	Category 3	Category 2	Category 1

Table 4 Tobit model results

Variable name	Influence factors	Code	Coefficient	Standard error	*P*-values
Individual characteristics	Gender of respondents	A	–0.012*	0.007	0.062
	Respondents' age	B	–0.041**	0.016	0.012
	Respondents' education level	C	–0.011	0.019	0.559
Family characteristics	Family size	D	0.004	0.025	0.886
	Agricultural labor population	E	0.004	0.033	0.895
	Annual household income	F	0.079	0.064	0.217
	Proportion of non-agricultural income	G	–0.015	0.014	0.293
Characteristics of land management	Cultivated land area	H	0.823***	0.212	0.0001
	Degree of land fragmentation	I	–0.863***	0.236	0.0003
Farmers' cognition	Cognition of environmental effects	J	0.012	0.016	0.429
Location factors	Location dummy variable	K	0.005	2.000	0.570
	The distance to the nearest town	L	0.072***	0.020	0.0002
Constant			0.066	0.002	0
Log likelihood			451.440		
Prob > chi2			0		

Notes: ***, **, * represent 1%, 5%, 10% significant level, respectively land management are vital factors for the SICL. Among the individual characteristics, the *P* of the regression coefficient between the gender (A) and ages (B) of respondents is showing a significance level under 10%, 5%. Among the characteristics of land management, the *P* of the regression coefficient of cultivated land area (H), degree of land fragmentation (I), the distance to the nearest town (L) showing a significance level below 1%. Among the location factors, the *P*-value of the regression coefficient of the distance to the nearest town (L) is 0.0002 < 0.01, displaying a significance level below 1%. In summary, the respondents' gender (A), respondents' age (B), cultivated land area (H), degree of land fragmentation (I), and distance to the nearest town (L) have a clear impact on the SICL level. The impact of cultivated land area (H), degree of land fragmentation (I), and distance to the nearest town (L) was slightly higher than that of the respondents' gender (A) and age (B).

(1) Impact of gender of respondents on SICL types in farming households

The impact of respondent gender on the SICL behavior of farming households is significant at 10%. As seen in Fig. 4a, the proportion of males to females in Category 1 (unsustainable), Category 2 (low level), Category 3 (medium level), and Category 4 (high level) are 55.5% and 45.5%, 59.7% and 40.3%, 16.3% and 83.7%, and 39.3% and 60.7%, respectively. From the perspective of the same gender, the number of males in each quadrant gradually decreased with the increase in the level of SICL, whereas the number of females showed a decreasing trend, followed by an increase in the improvement process of SICL. From the sustainable state of cultivated land use, more males are present at low levels of SICL than females, whereas, females are more common at high levels of SICL than males. The main reason for this phenomenon is that females engaged in agricultural activities tend to be younger than males in the survey area, demonstrating the significance of the age factor of farmers. Gender differences mainly affect farmer perceptions of cultivated land use in terms of economy, environment, society, cost input, and technical training. The specific impact mechanism needs to be obtained based on the relevant research of multidimensional perceived value and cultivated land use behavior. Compared with older males, young females have comparative advantages in agricultural machinery and agronomy and accept new agricultural concepts more easily. In particular, younger females tend to recognize the practical advantages of mechanized technology in improving production efficiency, whereas older males give greater attention to the comprehensive value of mechanization technology in terms of economic, environmental, and societal considerations. In summary, the proportion of males declines and that of females gradually rises with an increasingly higher level of SI. The regional differentiation of SICL with gender characteristics is not caused by gender differences, but rather by the structure of the rural labor force and multidimensional perceptions.

(2) Impact of respondent age on types of SICL in farming households

The impact of respondent age on the SICL behavior of farming households is significant at 5% (Fig. 4b). In Category 1, the proportions of those under 40, 40–50, 50–70, and over 70-year-old are 5.2%, 6.8%, 29.3%, and 58.6%, respectively. Therefore, the main age distribution in Category 1 is those over 70-year-old, as it is in Category 2, in which it accounts for 80.5% of the total. The proportion of households of those aged 50–70 in Category 3 is high, at 63.0%. The main age distribution in Category 4 is 50–70 years old, followed by ages between 40 and 50 years old at a proportion of 35.7%. According to the age distribution in each quadrant, the older the farmers, the lower the SICL level, whereas higher levels of SICL farmers correspond to younger farmers. Thus, age is evidently the key factor affecting the SICL. The results also show that the age of farmers engaged in agricultural activities is relatively old and worthy of attention with regard to the intergenerational inheritance of the agricultural modernization development process. With different generations of farmers in different stages of the life cycle, great differences are demonstrated in growth experience, personal demands, value evaluation, and behavior logic, which result in differences in SICL behavior. As the main body of agricultural production, farmers are the key decision-makers and final implementers of agricultural technology. Whether the development concept, cultivation mode, and agronomic skills under the background of SICL can be effectively applied depends on the success of farmer adoption. Meanwhile, it is of little significance to adopt the concept of SICL in stages or in the short term. Only if farmers adopt SICL persistently can the comprehensive efficiency of SICL be brought into full play, and input costs such as the excessive application of pesticide fertilizer can be reduced, with the realization of long-term protection of the ecological environment and cultivated land quality. In general, the lower the age distribution the higher the SICL level among farming households.

(3) Impact of cultivated land area on types of SICL in farming households

The impact of cultivated land area on household

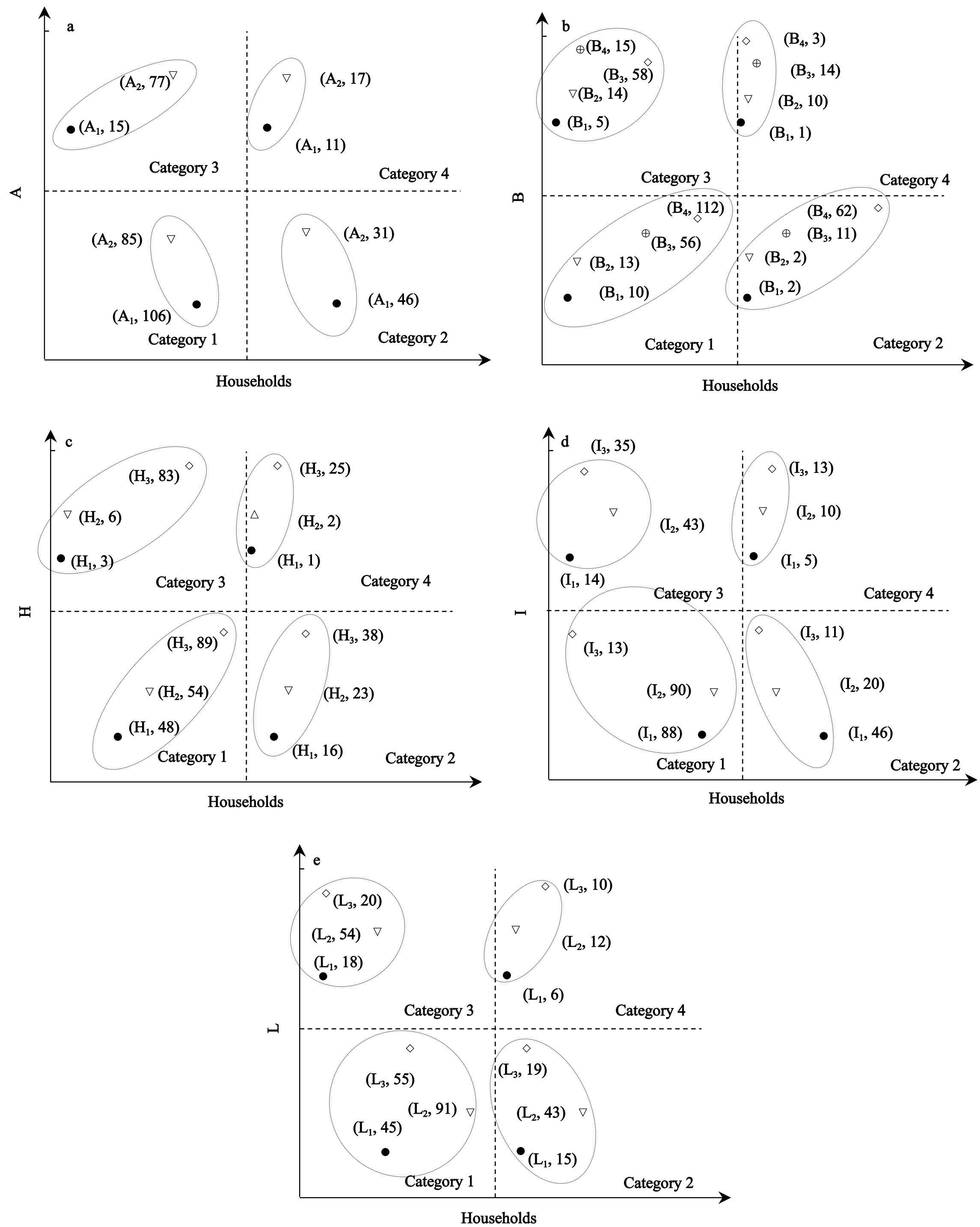

Fig. 4 Factor distribution of farmers with different types. A, gender (A_1 = male, A_2 = female), B, age (years old) ($B_1 < 40$, B_2 = [40, 50), B_3 = [50, 70), $B_4 \geq 70$), H, cultivated land area (ha) ($H_1 < 0.33$, H_2 = 0.33–1.33, $H_3 \geq 1.33$), I, land fragmentation degree (ha) ($I_1 < 0.1$, I_2 = 0.1–0.3, $I_3 \geq 0.3$), L, distance to the nearest town (km) ($L_1 < 1$, L_2 = 1–5, $L_3 \geq 5$). Meanings of Category 1–4 see Table 3

SICL behavior is significant at 1%. As seen in Fig. 4c, households with an area of cultivated land less than 0.33 ha account for 48% of Category 1, with households of areas between 0.33 and 1.33 ha accounting for 54%, and those with an area of more than 1.33 ha accounting for 89%. In summary, most households in Category 1 have cultivated land areas greater than 1.33 ha. In Category 2, 38 households have an area of cultivated land of more than 1.33 ha, at a proportion area in Category 2 of 49.4%. The households with higher proportions in both Category 3 and Category 4 are those with areas larger than 1.33 ha, at 90.2% and 89.3%, respectively. From the distribution of cultivated land area in each quadrant, the SICL level increases with an increase in the farmer land management area. In particular, high-level SICL is basically supported by the larger area of cultivated land. Therefore, the large-scale management of cultivated land area is the basis for promoting the sustainable use of cultivated land; however, the coupling and coordination of cultivated land area and the SICL index needs to be further explored at a more detailed level with the consideration of the spatiotemporal changes of soil elements. Generally, the larger the scale of cultivated land use, the greater the comprehensive benefits for cultivated land use. Large-scale and intensification are interrelated and restricted to each other. The degree of coordination of large-scale cultivation and intensification determines the development of agricultural modernization. Thus, depicting the spatial pattern of regional cultivated land scale management and exploring the coupling and degree of coordinated development of large-scale cultivation and intensification in typical regions is of great practical significance. This is also very important for enhancing the level of SI. However, the large-scale operation of cultivated land is affected by multiple factors, such as the degree of concurrent operation of farmers, average social income, and income of grain production, which may be in a dynamic and reasonable range. Exploring the standard range of appropriate cultivated land management scales in different regions is also a key factor in achieving the goals of SICL. In general, the larger the cultivated land area, the higher the household level of SICL.

(4) Impact of land fragmentation degree on the SICL type.

The impact of fragmentation on household SICL behavior is significant at 1% (Fig. 4d). In Category 1, 178 farming households exhibit an average parcel area of less than 0.3 ha, accounting for 93.2%. In Category 2, the proportion of households with an average area of parcels smaller than 0.1 ha is 59.7%, whereas the proportion for those with areas smaller than 0.3 ha is 26.0%. In Category 3, the proportion of households with an average parcel area greater than 0.3 ha is 38.0%. In Category 4, the parcels with an average area greater than 0.3 ha constitute the highest proportion. According to the distribution of the degree of land fragmentation in each quadrant, the degree of land fragmentation is higher at low SICL levels, whereas that at high SICL levels is primarily low. The main reason is that the degree of land fragmentation is related to the integrity of land property rights, which is also a practical obstacle to the large-scale operation of cultivated land and mechanization of agricultural production. The degree of land fragmentation directly limits the mode of agricultural production. Super-small-scale agricultural production is in contrast to the advantages of large-scale cultivated land management, as it seriously hinders the sustainable development of agriculture. Moreover, land fragmentation under different terrains and locations lead to differences in cultivated land quantity, spatial layout, and landscape pattern index. It also causes the interaction of different landscapes and changes in structure or function. The construction of a farmland landscape ecological security pattern guarantee system is the key factor in achieving SICL, especially the coordination degree between cultivated land spatial form and natural habitat. However, land fragmentation also provides us with unique research perspectives, that is, to study regional cultivated land use and quality change from site conditions and geochemical characteristics, which is also an area of scientific research related to SICL. Therefore, the lower the degree of land fragmentation, the higher the level of SICL.

(5) Impact of the distance to the nearest town on types of SICL.

The distance to the nearest town has a significant effect on SICL, at the level of 1%. As can be seen in Fig. 4e, in Category 1, the households located at 1–5 km to the nearest town accounted for the highest proportion, at 47.6%, with those in Category 2 accounting for 55.8%. In Category 3 and Category 4, the proportions of households that were 1–5 km from the nearest town were high, at 58.7% and 42.9%, with 50 and 12 households. From the distribution of the distance to the nearest town in each quadrant, L_2 always appears the most frequently in each quadrant. Obviously, it is not that the closer to the town, the more level of SICL can be promoted. Meanwhile, a meaningful conclusion is obtained that the urban-rural integration circle with a radius of 1–5 km may be the best functional space for SICL at farming households scale. This mainly reflects the differences in the spatial form of different villages, such as banded, clumped, clustered or scattered. The diversity in the nature of villages under different spatial patterns will lead to differences in the development and evolution of agricultural materials, agricultural economy and social space in suburban villages, new resettlement villages, suburban agricultural villages and traditional agricultural and forestry villages. It is particularly obvious that the rural areas far away from the towns tend to have single spatial functions, while those close to the towns have diversified spatial functions. When the location conditions affect the comprehensive benefits of cultivated land use, it is shown that the central town is the center of the circle, which extends outward to form a concentric circle. In summary, the closer the distance to the nearest town (1–5 km), the higher the level of SICL will be.

3.3 Effect of farmer behavior on SICL

Based on research, the analysis framework for the influencing mechanisms of SICL on the farmer scale is generated to further describe discrepancies in response to behaviors among the different types of SICL. Respondent gender and age, cultivated land area, degree of land fragmentation, and distance from the nearest town all affect SICL at the farming household scale. With a higher level of SICL, the proportion of males declines, and that of females gradually increases. Meanwhile, the younger the age distribution, the higher the area of cultivated land, and the lower the degree of land fragmentation will be. A higher level of SICL among farming households is realized with reduced distance to the nearest town (1–5 km).

As the SICL characteristics and their changing processes are closely related to temporal and spatial scales, there are a variety of intensive drive mechanisms on different scales. As shown in Fig. 5, on the microscopic scale of farming households, farmer personal characteristics, characteristics of farmer families, management of land characteristics, farmer acumen, and location factors all play different roles in SICL. They promote the transformation of SI levels from unsustainable to sustainable and drive the conversion of SI levels from high to low. Meanwhile, crop yields, crop diversity, ecological system services, and the coordination of the man-land relationship, to a certain extent, produce a feedback effect that restrains SICL. Under certain areas of cultivated land, crop yields may be reduced, crop diversity may be lowered, ecological system service may decline, and a striking contradiction between people and land may be

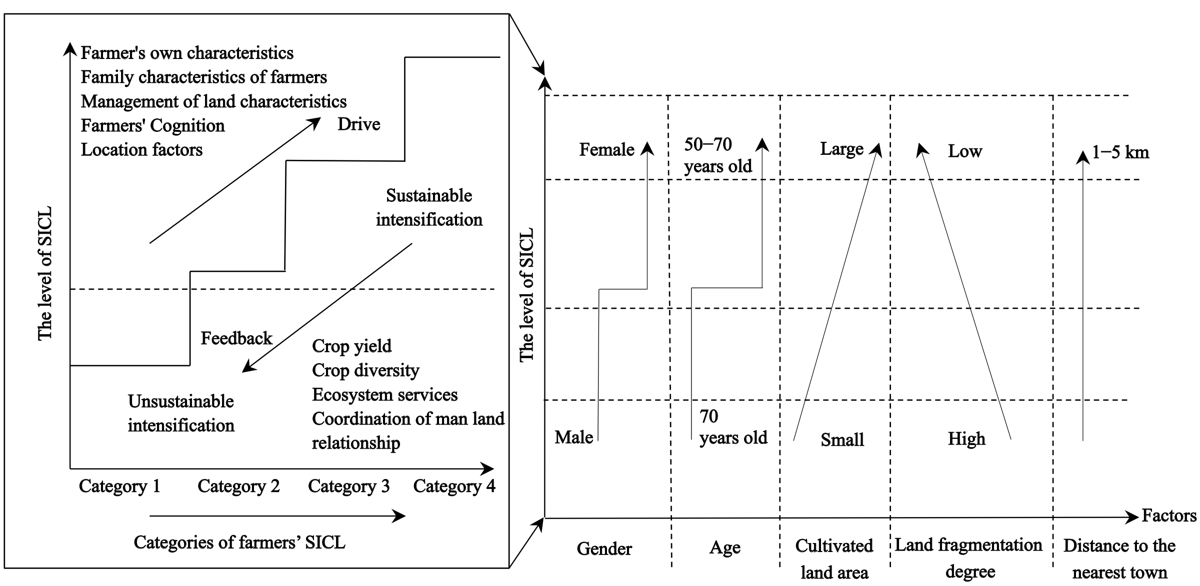

Fig. 5 Response analysis of sustainable intensification of cultivated land use (SICL) at the farming household scale

exposed. That is to say, cultivated land cannot be sustainably intensified. SICL may reach a dynamic equilibrium of sustainability by promoting drive mechanisms and the feedback effect in stages, ultimately realizing the adaptive control path of SICL with Chinese characteristics.

With the further development of new urbanization, rural revitalization, and urban-rural integration, the gender structure of agricultural production in China has changed. The number of males assisting females in farming has increased on the basis of nonagricultural work. However, older farmers (over 70-year-old) tend to use traditional farming methods that give less attention to the relevant policies of conventional breeding, planting structure, biotechnology, and green development of agriculture. These aspects of contemporary farming damage the balance between the physical and chemical structure of the soil, reducing the productive capacity of cultivated land. This phenomenon will be improved as the average age of the farmer decreases, which will become more significant depending on the SICL level. As is well known, larger cultivated land areas are more conducive to the formation of scale agglomeration effects. Not only can the input cost and management cost per unit of cultivated land area be effectively reduced in larger cultivated areas, but also agricultural production technology can be obtained and modern agricultural technology can be adopted at a lower cost, which is conducive to the promotion of environmentally friendly production technology. Land fragmentation has a significant impact on agricultural scale production and agricultural mechanization services, and fragmented cut plots are generally not easy to adjust. Therefore, the level of sophisticated management of agricultural production and planting would be limited, and the efficiency of agricultural machinery services would be low, which would have a negative impact on SICL. Meanwhile, agricultural production mode has its own spatial allocation principle. According to the theory of agricultural location, the sustainable intensive level of cultivated land utilization also follows a gradation law at the spatial level, in which the highest level of SICL is at the level of 1–5 km from the nearest town. This is closely related to agricultural production objectives, agricultural product market transactions, and regional spatial allocation. In regions with different levels of economic development or cities with different natural resource endowments, there are clear regional differences in the SICL level at the farming household scale.

4 Discussion

4.1 Basic concept of sustainable intensification of cultivated land use

As our research shows, SICL is the core objective in the transition of cultivated land use. Some studies have argued that land use transition is the transformation from one form of utilization (including dominant and recessive forms) in a certain region and certain time period to another (Long et al., 2009; Long, 2012). The recessive form refers to land use that is difficult to perceive and attainable only through inspection, analysis, testing, and investigation. Land use transition focuses on changes in land use trends (Song et al., 2014). To conclude, SICL is the realization of the conversion of the recessive form, which is in the research area of land use transition. The concepts of sustainable intensification should be integrated to enable the selection of a suitable scale and find typical regions to further explore the processes, landscapes, effects, and trends of SICL. This will also require the identification of the optimal adaptive mode by adjusting measures to local conditions and exploring a variety of combined differentiated implementation strategies and control paths with Chinese characteristics.

4.2 Practical change for cultivated land use under the multiple influencing factors of SICL

According to the level of SICL, the farming households in our sample are SICL-inefficient. This means that there is a potential for farming households. And once the cultivation methods are optimized, the SICL level will also be improved. In view of the impact of gender of respondents on SICL types in farming households (Figs. 4a, 4b), we should establish new regional service centers for professional farmers and train a group of local experts, agricultural professional managers who are rooted in the countryside. Furthermore, all types of managers should be encouraged to change the way of resource utilization from the aspects of scientific technology and production ideas. In this way, the ability of sustainable agricultural development can be improved, and the endogenous problems caused by gender structure and differences in age can be eliminated. In addition, the aims of sloving the long-standing agricultural non-point source pollution problem, farmer awareness of the ecological protection of cultivated land, the rational application of pesticides and fertilizers, and the scientific use of irrigation technology should be promoted. However, on account of multiple types of villages have different spatial functions (Fig. 4e), new strategies and technologies suiting for distance to the nearest town could be introduced by farmers to reduce wastage in energy, machinery fuels, and crop protection to improve environmental impacts.

In light of the impact of the degree of land fragmentation on the SICL type (Fig. 4d), we can intensify the work of comprehensive land consolidation in rural areas, take land consolidation and property rights trading as platforms to promote the centralization of farming plots, and fundamentally solve the problem of land fragmentation. Relying on the third national land resource investigation, the awareness of rural land property rights and the certification of agricultural land rights should be strengthened. We should take multiple measures to reasonably guide the transfer of farmland. This is not only convenient for agricultural mechanization services, but also convenient for gradient promotion of farmers' agricultural production scale. As mentioned above (Fig. 4e), we should also scientifically and systematically analyze the regional spatial allocation structure of agricultural production, clarify the links between agricultural production areas and adjacent towns, and optimize the planting structure of agricultural management.

4.3 Comprehensive policy recommendations for strengthening SICL

Combined with discussions of the concept and influencing factors of SICL, efforts should be made to form a multidimensional policy system of SICL, which is based on household contracts as a foundation, intensive management as a method, and sustainable development as a goal. According to the regional resource endowment, a planning for agricultural development was formulated based on economic development level, soil physical and chemical structure, land use patterns (Mao et al., 2019), topography, landform, pollution degree, and centralized connectivity. Concurrently the policy agendas should seek to internalize the costs and benefits in the prices of production inputs and improve price mechanisms, aiming to reduce soil erosion and land degradation and provide regulatory systems and incentives to minimize negative externalities originating from agricultural production and processing.

4.4 Limitation and prospect

This study introduces the MFA method and independently builds a model of the SICL index at the household scale, conducting an exploratory investigation into the level of sustainable intensification of farming households. However, the specificity and adaptability of the index must be further demonstrated. Specifically, the development of new scientific research methods, integrating an understanding of SICL theory, has become an ongoing challenge.

It may be necessary to address the following key scientific topics in the future: 1) The driving mechanisms of SICL in the context of urbanization and agricultural modernization should be interpreted and analyzed. There may be a complicated link between SICL and urbanization and between urban-rural integration and ecological environment. It is a focus of future research to systematically analyze the multiple systems that affect sustainable intensification, conduct further study into the coupled response to the ecological environment and SICL, and avoid the negative environmental impact of intensified land use. 2) Reveal the feedback mechanisms of the SICL processes in the human-land relationship. Based on in-depth research on the coupling response between ecological environments and SICL, extra attention must be paid as to how the impact of sustainable intensification on systems involving the human-land relationship can be evaluated and how SICL and its effects under different environmental conditions and different temporal and spatial scales can be quantitatively assessed to achieve SICL and green urbanization.

5 Conclusions

In this study, characteristic regions in Shandong Province are used as examples, depending on questionnaires from 388 farming households, and the material flow analytical method is used to measure the SICL level, analyzing the influential factors and action mechanisms through a Tobit model. The following conclusion is drawn through research:

(1) The overall SICL level in Shandong is relatively low, and the spatial distribution is imbalanced. There are many farming households incapable of sustainable

intensification while less households of medium and low levels of sustainable intensification. And yet, households of high SICL are even more less. Of the four types of utilization, households incapable of sustainable intensification are mainly located in Dongping County, with those of medium and low levels of SICL residing mainly in Wulian County and those of high-level SICL residing mainly in Kenli District. Therefore, the SICL in different areas is distinctively spatiotemporal heterogeneity and regional adaptability. Moreover, according to the combination models of natural and human conditions of cultivated land in different regions, it is more beneficial for exploration of the SICL mechanism under the multiple regional interaction.

(2) There are clear factors that influence the various types of SICL among farming households. The population of females is higher than that of males in farming households with a high SICL level, and they are relatively younger. Meanwhile, with larger cultivated land areas, there is a lower degree of land fragmentation, with a higher level of SICL corresponding to a smaller distance to the nearest town closer within 1–5 km from the town center. It can be concluded that there is a high relevance between the characteristics of land management and the level of SICL. In corresponding with the comprehensive impact of multiple influencing factors of SICL, the profound theoretical analysis and systematically empirical researches of SICL should systematically analyze the coordination model among livelihood type, policy coordination and resource effect.

(3) The characteristics of SICL and the changing processes are closely related to temporal and spatial scales. On the microscopic scale, the characteristics of individual farmers, characteristics of farmer families, management of land characteristics, cognition of farmers, and location factors can each play a role in the transition from unsustainable to sustainable intensification and drive the conversion of SICL levels from low to high. The core tasks of the application of SICL is to deepen the comprehensive research, reveal the micro-coupling mechanism and establish the regional application path, and its theoretical connotation is mainly reflected in three dimensions of time, space, and management. Crop yields, crop diversity, ecological system services, and the coordination of the man-land relationship are promoted by staged driving mechanisms and the feedback effect, further making the SICL dynamically sustainable and balanced.

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