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RESEARCH ARTICLE

Spatial-temporal evolution of agricultural ecological risks in China in recent 40 years

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Abstract
Excessive use of agricultural chemicals and unreasonable utilization of agricultural wastes have led to severe agricultural non-point source pollution (ANPSP) problems in China. Based on the agricultural pollution loads and pollution control strength, the ecological risk index (ERI) was constructed and was used to explore the spatial-temporal pattern of agricultural ecological risks in China during 1978–2017. The findings indicated that Chinese agricultural ERI was gradually increased from 0.031 to 0.348 in 1978–2017, which has the same phased change characteristics as the succession of agricultural policies. At present, the ecological risk grade of ANPSP was present in the stair-step distribution characteristics of "high in the east and south and low in the west and north" as a whole. Southern China, as the main producing area of aquatic products, had the higher ecological risks. Northeastern China, the Huang-Huai-Hai Area, and the middle and lower reaches of the Yangtze River, as the grain-producing bases, had moderate ecological risks, but Southwestern China and Northwestern China with the poor agricultural production conditions had the lower ecological risks. It evidently showed that the ecological risk problems faced by the high-quality development of Chinese agricultural industrialization are increasingly severe.

Keywords Agricultural pollution · Agricultural sustainability · Ecological risks · Spatial-temporal pattern · Control strategies

Introduction

Since the reform and opening-up, China's agricultural development has achieved remarkable achievements (Deng and Gibson 2019). The grain yield has increased from 304.8 million tons in 1978 to 661.6 million tons in 2017. The total output of meat and aquatic products has respectively increased to 86.5 million tons and 64.5 million tons from 8.6 million tons and 4.7 million tons. Meanwhile, the consumption of chemical fertilizers has increased from 8.8 million tons in 1978 to 58.6 million tons in 2017. According to the Second National Pollution Source Census Bulletin, the total amount of discharge of chemical oxygen demand (COD), total nitrogen (TN), and total phosphorus (TP) from the planting industry, livestock and poultry industry, and aquaculture industry in 2017 respectively reached 10.7 million tons, 1.4 million tons, and 0.2 million tons. The doubling agricultural output and the massive discharge of pollutants indicated that even if China's agricultural development has achieved remarkable achievements, the issue of agricultural non-point source pollution (ANPSP) is increasingly severe (Bonkosky et al. 2009; Deng and Gibson 2019; Guo et al. 2014). ANPSP even has exceeded industrial pollution to be the main source of water pollution (Li et al. 2011; Liu et al. 2013). For this reason, the central government issued a series of agricultural pollution control policies. However, due to fewer enforcement regulations and technical documents issued by local governments, the government effects of various agricultural pollution control policies were inconspicuous. For example, in 2015, the former Ministry of Agriculture officially issued the Action

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Scheme of Zero Growth for Chemical Fertilizer Usage Amount in 2020. The data showed that since the scheme was implemented, the total usage number of chemical fertilizers had the historical reduction for the fertilizer strength change and plantation structure adjustment, but the surplus of nitrogen-phosphorus nutrients in farmlands still surpassed the environmental safety limit prescribed by FAO (Huang and Jiang 2019; Yang and Lin 2019). Though the Ministry of Agriculture has successively used legislation and formulated discharge standards to control pollution discharge in the livestock and poultry industry since 2001, the proportion of COD, TN, and TP discharged by the livestock and poultry industry in the total amount of agricultural pollutants in 2017 respectively accounted for 94%, 42%, and 56%, resulting in 13% of crop failure (Li et al. 2018). The total output of Chinese aquaculture accounted for 70% of the total output in the world. In 2019, the state issued some opinions of accelerating green development of the aquaculture industry to promote the sustainable development and transformational upgrading of the aquaculture industry. Nevertheless, it is worrying that governments at all levels have not paid enough attention to endogenous pollution problems caused by aquaculture (Meng and Feagin 2019; Zhang et al. 2020b). Even if China is rich in straw resources, their use ratio was lower. Since the state council issued the Comprehensive Utilization Opinions on Accelerating Crop Straws in 2008, the comprehensive use ratio of straws has been 81.68%, but about 150 million tons of straws were incinerated or abandoned in fields every year, resulting in a huge waste of straw resources and huge pollution of the ecological environment (Wang et al. 2018; Zhuang et al. 2020). By aiming at increasingly severe ANPSP problems, the central government definitely claimed to enlarge the pollution control strength, carry out saving mineral fertilizers and pesticides action in agriculture, and facilitate resource utilization of agricultural wastes, such as fecal residue and wastewater, straws, and agricultural films.

Massive discharge of agricultural pollutants inevitably will result in strengthening ecological risks. To control pressure and avoid ecological risks is critical to the long-term development of mankind and the realization of harmonious co-fusion between mankind and nature. First and foremost, it is necessary to do a scientific and reasonable evaluation of ecological risks on the basis of sufficiently harmonious development between humans and nature (Bornhofen et al. 2019). The ecological risk evaluation is an effective tool to evaluate the impacts of chemical pollutants on the ecosystem (Ke et al. 2017). According to the basic connotations of the ecological risk evaluation, the evaluation of agricultural ecological risk is based on the ecological risk evaluation process to quantitatively identify possible adverse consequences caused by the interaction between agricultural production and ecological process under the natural or human factors and supply the probability of occurrence such a consequence. Existing studies mainly evaluate ecological risks caused by different risk sources on the agricultural environment or agricultural development, such as pollution risks of agricultural chemicals on river basin water (Hails 2002; Jiao et al. 2020; Schriever and Liess 2007), potential risks of soil heavy metals on human health in rural areas (Ennaji et al. 2020; Huang et al. 2018; Khan et al. 2013; Liu et al. 2014; Zhang et al. 2020a), sustainable risks of climatic variation on the agricultural development (Dalezios et al. 2014; Qin et al. 2020; Rosenzweig et al. 2014; Zeng et al. 2019), agricultural response risks under the major emergent public affairs (Ker 2020), and agricultural landscape risks incurred by land reclamation projects (Liu et al. 2018b). The assessment methods adopted mainly include the statistical empirical model and mechanistic process model. Lots of empirical studies indicate that both models can gain favorable results (Adu and Kumarasamy 2018; Ongley et al. 2010). The statistical empirical model gains the empirical coefficient between regional natural physical characteristics and pollutant output through the field monitoring, so as to measure the probability and strength of occurring pollution discharge unit risks (Cheng et al. 2018; Ma et al. 2011; Wu et al. 2015; Zhang et al. 2019a). The mechanistic process model constructs a mathematical simulation model and utilizes computers to simulate ANPSP in spatial-temporal sequence via a comprehensive analysis of rainfall runoff, soil erosion, and pollutant migration, so as to quantitatively describe the continuous process of pollution occurrence (Chen et al. 2019; Haregeweyn and Yohannes 2003; Nayeb Yazdi et al. 2019; Ribarova et al. 2008). Since different types of models have all kinds of requirements for estimation parameters, data sensitivity, and locality, their applicability also makes a difference (de Oliveira et al. 2017; Guo et al. 2014).

The key of the ecological risk evaluation of ANPSP lies in reasonably quantifying the background difference of regional agriculture, selecting the reasonable model to measure agricultural pollution loads, and evaluating the probability of potential ecological risks in different pollution sources (Huang et al. 2019; Rosenzweig et al. 2014), so as to provide decision-making reference for formulating differential control measures of ANPSP. Existing studies have identified risks of ANPSP from single input factors (e.g., chemical fertilizers, pesticides, animal manures, and straws) (Alavanja 2003; Gao et al. 2020; Meyer-Aurich and Karatay 2019; Venglovsky et al. 2006). Meanwhile, these studies are lack of comprehensive analysis for multiple risk sources and cannot make horizontal comparisons on differences of different agricultural pollution sources on the same dimension (Ju et al. 2009), so as to weaken the overall cognition on agricultural ecological risks (Sanz-Lazaro and Sanchez-Jerez 2020). Agricultural ecological risks refer to possibilities of threatening the ecosystem when TN, TP, and COD or other pollutants from agricultural production activities are migrated and transformed with the runoff (Bornhofen et al. 2019; Qin et al. 2020). As the sources of triggering agricultural ecological risks, agricultural pollutants are generated from fertilizer application, manure discharge, and straw incineration, and they are featured with latency, endurable harms, and low-efficient treatment, resulting in extremely prominent uncertainty and perniciousness of agricultural ecological risks (Hagenlocher et al. 2019; Wang and Liu 2018). Those are also the main reasons why countries all over the world attach great importance to agricultural ecological risk.

As a traditional great power of agriculture, China is facing severe issues of agricultural ecological risks, arousing the high attention of governments at all levels. However, there is a small sample size of studying Chinese agricultural ecological risks. Moreover, these studies often give priority to the microcosmic regional research or short-term panel data (Huang et al. 2019; Jiao et al. 2020; Liu et al. 2014; Luo et al. 2019), but lack macrovisual studies of the long-term sequence. Also, these studies have not depicted the spatial-temporal pattern of agricultural ecological risks meticulously and sufficiently (Jin et al. 2019; Zou et al. 2020), which may directly affect the environmental policy formulation with the emphasis on preventing agricultural potential risks by the central and local governments. In recent years, scientific research focused on Chinese agricultural ecological risk problems has been gradually recognized by the world. Nevertheless, due to shortage of systematic basic data and extensive field monitoring experiments, weak quantificational research means of ANPSP in the watershed scale, and lagging ANPSP control and management research (Ouyang et al. 2014; Xing et al. 2018), as well as asynchronism of security and measurement, and agricultural planting and breeding structure fluctuating with markets (Liu et al. 2018a; Wang et al. 2017), it is difficult to gain measured data of pollution discharge in different areas or the measured data are severely insufficient. Furthermore, the great difference in pollution prevention strength, agricultural plantation structure, and agricultural plantation conditions in various areas, as well as the spatial-temporal distribution of ANPSP equipped with inhomogeneity (Jin et al. 2019; Zhang et al. 2018a), leads to more difficulties in exploring agricultural pollution status in the national scale. The ecological risk index (ERI) is an important index to inspect the performance of the agricultural sector (Leip et al. 2015). Accurate evaluation of ERI plays a crucial role in figuring out causes for the generation of ANPSP and taking management measures. As a result, the purpose of this paper aimed to delve into the variation and pattern of agricultural ecological risks based on the constructed ERI, discuss the evolution of national agricultural ecological risks, and propose the targeted control strategies for agricultural ecological risks in different regions. The conclusions of this paper could provide the integral cognition for studying Chinese agricultural ecological risks, offer a policy basis to assist the rural revitalization strategy, construct the beautiful ecological and livable countryside and implement high-quality developmental strategies of agricultural industrialization, and show the important significance on sustainable agricultural development of China or even the whole world.

Methods and materials

Research materials

In addition to Hong Kong, Macao, and Taiwan, the provincial administrative regions (including provinces, autonomous regions, and municipalities) of the Chinese mainland were selected as the research units. Data of Chongqing Municipality in 1978–1996 were included in Sichuan Province, and data of Hainan Province in 1978–1987 were contained in Guangdong Province. The ecological risks caused by four kinds of pollution sources between 1978 and 2017 were evaluated, such as mineral fertilizers, livestock and poultry breeding, aquaculture, and farmland straws. The provincial level is currently the best scale for obtaining long-term agricultural observation data in China, and it is also the main institution for local agricultural departments to formulate local policies and regulations. Since there is lack of statistical data of agricultural pollutant loads, pure application of fertilizers, numbers of livestock and poultry, the output of aquatic products, and crop yield were gained from the *China Rural Statistical Yearbook*, *Agricultural Statistical Compilation for 30 years of Reform and Opening-up*, *Agricultural Statistics for 50 years in New China*, *Agricultural Statistics for 60 years in New China*, *China Statistical Yearbook*, *China Fishery Statistical Yearbook*, *China Marine Statistical Yearbook*, *China Agricultural Machinery Industry Yearbook*, and *Chinese Agricultural Statistical Compilation*. Inventory analysis was adopted to estimate the pollutant loads of COD, TN, and TP, which were the main components of agricultural pollutants (Lai 2004). GDP, agricultural economic output, sown area, and arable land area were derived from the *China Rural Statistical Yearbook* (1985–2017) and the provincial *Statistical Yearbook* (1978–1984). The GDP and agricultural economic output regarded the year 1978 as the base period for price deflation. To fully reveal ANPSP problems in different periods and different scales, this paper was based on the Action Scheme of Zero Growth for Chemical Fertilizer Usage Amount in 2020 formulated by the Ministry of Agriculture and referred to the division scheme of modern agricultural regions proposed by Liu et al. (2018b) to divide the whole country into 7 agricultural zones, including Northeastern China, the Huang-Huai-Hai Area, the middle and lower reaches of the Yangtze River, Southern China, Southwestern China, Northwestern China, and the Qinghai-Tibet Region (Fig. 1). Considering that the agricultural

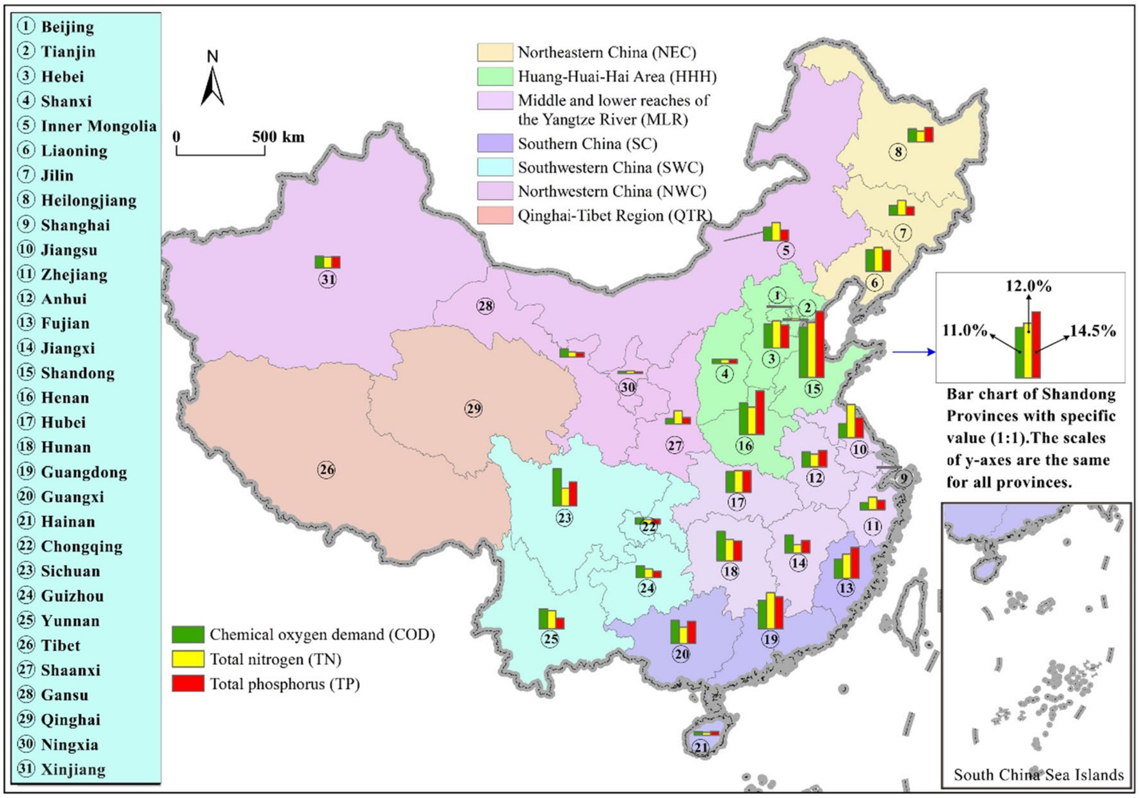

Fig. 1 Spatial pattern of ANPSP loads in 2017 in China. The length of bars in different colors stood for the proportion of COD, TN, and TP in the whole country, respectively

production pattern of Qinghai and Tibet gave priority to animal husbandry. Moreover, the pollution mechanism of livestock and poultry breeding in this region also had an obvious difference from other regions (Yang et al. 2013), so they were not analyzed in this paper.

ArcGIS visualization was applied after converting ANPSP loads in proportion established by using the inventory analysis method. According to Fig. 1, the discharges of COD, TN, and TP in the Huang-Huai-Hai Area and the middle and lower reaches of the Yangtze River respectively accounted for 47.9%, 49.9%, and 52.8% of the total release around the country. These two areas had the maximum ANPSP loads, followed by COD, TN, and TP loads in Southern China, respectively reaching 16.3%, 17.5%, and 19.5%. The pollution load proportion of COD, TN, and TP in Southwestern China ranked fourth place, respectively reaching 16.6%, 10.8%, and 10.2%. The load proportion of COD, TN, and TP in Northeastern China and Northwestern China reached the minimum, which was about 10%, respectively. From the provincial perspective, the pollution load proportion in Shandong, Henan, Guangdong, and Sichuan reached the maximum, while the pollution load proportion in Beijing, Tianjin, Shanghai, and Ningxia reached the minimum. The spatial pattern of agricultural pollution loads preliminarily indicated that Chinese agricultural development has had relatively remarkable regional characteristics.

Research methods

To quantify the ecological risk of ANPSP, the concept and calculation model of the agricultural ERI was proposed in this paper, which refers to the risk value size on the ecological environment caused by agricultural pollution, so as to represent the probability of potential ecological risks triggered by ANPSP. The key to evaluate the agricultural ERI is to identify the risk sources. The sources of agricultural ecological risks mainly include natural risk sources and human risk sources (Dalezios et al. 2014; Schriever and Liess 2007). The leading driving force of natural risk sources is the surface runoff and soil leakage caused by rainfall and irrigation. These factors are embodied by different discharge coefficients in the pollution load estimation. The agricultural activity intensity and pollution control strength in human risk sources are dominant factors in determining ecological risks. Between them, the agricultural activity intensity is present in the number of factor units in the pollution load estimation, while the pollution control strength can apply the discharge intensity representation of pollutants. For this reason, the author constructed the agricultural ERI from the aspects of pollution loads and control strength of ANPSP

Step 1: Discharge of agricultural non-point source pollution

Due to a shortage of the runoff coefficient and utilization coefficient around the world, as well as temperature, rainfall, soil, or other monitoring data of long-term sequence, the author applied the inventory analysis method proposed by Lai (2004) to estimate ANPSP loads. The detailed process refers to the research achievements of Zou et al. (2020). It was briefly described in this paper. The inventory analysis method is a cheap and simple operation method, and it is mainly suitable for the ANPSP load estimation of the large-scale areas and long-term sequence. The key lies in recognizing factor units of pollution discharge. It is also the minimum independent unit to be measured, such as nitrogen-phosphorus application rate, the stock number of cows and sheep, output of various aquatic products, and output of various crops (Chen et al. 2006b). According to existing studies, ANPSP mainly contains three categories: the first one is agricultural production, including the application of mineral fertilizers, plastic film and pesticides, straw burning, and stacking. The second one is agricultural cultivation, such as livestock breeding manure discharge and aquaculture manure discharge. The third one is rural life, such as human excreta discharge, domestic sewage discharge, and household waste stacking (Zou et al. 2020). The purpose of this paper aimed to evaluate the ecological risks caused by agricultural production, make comparisons, and accumulate various pollution sources on a uniform scale. Hence, COD, TN, and TP discharge of four pollution sources including mineral fertilizers, livestock and poultry breeding, aquaculture, and farmland straws were estimated with the specific calculation as follows:

$$\begin{aligned} D_{ij} &= \sum_t EU_t \rho_t (1-\eta_t) C_t(EU_t, S) \\ &= \sum_t PE_t \rho_t (1-\eta_t) C_t(EU_t, S) \end{aligned} \tag{1}$$

where D_{ij} was the load of different pollutants generated by different pollution sources (10^4t); EU_t was the index statistics of the unit t and regarded the provincial region as the statistical unit; ρ_t was the pollutant-production coefficient in the unit t; η_t represented the coefficient that characterized the utilization efficiency of the relevant resource; PE_t was the production of agricultural pollutants (10^4t), C_t was the pollutant discharge coefficient, which was determined by the spatial characteristics (S) of the pollution-producing unit and represented the regional soil, rainfall, hydrology, and various management measures to the comprehensive impact of agricultural pollution. This study used the experimental parameters described by Lai (2004) and the correlation coefficients from the First National Pollution Source Census as the pollutant-production and pollutant-discharge coefficients.

Step 2: Discharge intensity of agricultural non-point source pollution

At present, the Chinese agricultural production pattern is featured with “high yield, low efficiency, and high input” (Rao et al. 2012; Zhang et al. 2019b). On the one hand, due to less occupancy volume of cultivated land resources per capita, relatively single rural economic incomes, and pressure from food security, agricultural production shows strong input dependency on mineral fertilizers and other pollution factors, which cause severe environmental pollution problems, even if they enhance agricultural production efficiency, guarantee the effective long-term supply of agricultural products, and bring higher economic incomes to farmers. On the other hand, since economic growth promotes the upgrading of the food consumption structure and rural energy revolution, the breeding scale of meat, poultry, and fish is constantly enlarging, and the utilization mode of regarding straws as the main energy is gradually reducing, so as to directly increase technical handling costs of agricultural wastes, resulting in an intensification of pollution discharge under the circumstance monitoring shortage. In other words, the transformation of the agricultural production mode will discharge lots of pollutants, while increasing agricultural output. ANPSP discharge intensity means the unit discharge during agricultural production and utilization process under the factor input and biological rule, as well as the comprehensive role of different pollution control measure disturbances. This value can intuitively reveal the quantitative relation between the agricultural economic output and pollutant loads. It is an important index to indirectly represent the agricultural pollution control effect (Chen et al. 2013; Halder 2019). The computational formula of the ANPSP discharge intensity was stated as follows:

$$DI_{ij} = \frac{D_{ij}}{OL_i} \times 10000 \tag{2}$$

where DI_{ij} was the discharge intensity of the jth pollutant in the ith pollution source (t/¥10^8yuan); D_{ij} was the pollution load of the jth pollutant in the ith pollution source (10^4t); OL_i was the agricultural economic output, which was respectively represented by planting industry output, animal husbandry output, and fishery industry output (¥10^8yuan). After calculating the discharge intensity of various pollution sources, the intensity control coefficient of pollutants’ ecological risks should be further calculated according to Formula (3).

$$\rho_{ij} = \begin{cases} 1 - \frac{\left(DI_{ij} - \overline{DI}_{ij,1978}\right)}{\left(DI_{max,1978} - \overline{DI}_{min,1978}\right)} & if \quad \frac{\left(DI_{ij} - \overline{DI}_{ij,1978}\right)}{\left(DI_{max,1978} - \overline{DI}_{min,1978}\right)} < 1 \\ 1 + \frac{\left(DI_{ij} - \overline{DI}_{ij,1978}\right)}{\left(DI_{max,1978} - \overline{DI}_{min,1978}\right)} & if \quad \frac{\left(DI_{ij} - \overline{DI}_{ij,1978}\right)}{\left(DI_{max,1978} - \overline{DI}_{min,1978}\right)} \geq 1 \end{cases} \tag{3}$$

where ρ_{ij} was the control coefficient of ecological risk of the jth pollutant in the ith pollution source; $\overline{DI_{ij}}$, DI_{max}, and DI_{min} respectively represented the average discharge intensity, maximum discharge intensity, and minimum discharge intensity of the jth pollutant in the ith pollution source (t/¥10^4yuan). To strengthen the comparability of ecological risks in different periods and areas, the national average discharge intensity, maximum discharge intensity, and minimum discharge intensity in 1978 were respectively chosen as the reference values.

Step 3: Ecological risk index of agricultural non-point source pollution

The evaluation model of agricultural ERI was designed and optimized by referring to the heavy metal pollution environment risk evaluation method proposed by Hakanson (1980). The advantage of this computational formula is to introduce the coefficient of toxicity. The control coefficient was introduced during the agricultural ERI evaluation process in this paper, concluding that the higher the ERI, the higher degree of risks. The specific computational formula was described as follows:

$$ERI_i = \sum_{j=1}^{m} \frac{D_{ij} \cdot \theta_{ij}}{D_j} \times \rho_{ij} \tag{4}$$

where ERI_i was the agricultural ecological risk index of the ith pollution source; D_{ij} was the discharge of the jth pollutant in the ith pollution source (10^4t); D_j was the national total discharge of the jth pollutant. With the purpose of strengthening the comparability of the ERI, the national average discharge in 1978 was selected as the reference value (10^4t); θ_{ij} was the ecological risk weight of the jth pollutant of the ith pollution source. This paper was based on the research achievement of Dalezios et al. (2014) to respectively set up the ecological risk weight of TN and TP of mineral fertilizers as 0.5. The ecological risk weights of COD, TN, and TP of livestock and poultry breeding, aquaculture, and farmland straws were respectively set up as 0.30, 0.35, and 0.35; m represented the agricultural pollutant type. After gaining the ERI of various pollution sources, the weighted sum should be further utilized to calculate the comprehensive ERI with the specific computational formula as follows:

$$ERI = \sum_{i=1}^{n} ERI_i \times \omega_i \tag{5}$$

where the ERI was the total agricultural ecological risk index; w_i was the ecological risk weight of the ith pollution source. Based on the expert experience to comprehensively judge factors of the agricultural environment, agricultural pattern, and agricultural structure in different areas, the analytical hierarchy process (AHP) was respectively used to identify the weight of 4 kinds of pollution sources in different areas (Table 1); n was the type of agricultural pollution sources.

Results

National agricultural ecological risks

In 1978–2017, the agricultural ERI in China maintained an upward trend as a whole. Moreover, the pollution loads and discharge intensity had the same staged change characteristics. According to Fig. 2, the ERI was gradually increased to 0.348 from 0.031, which was amplified by 10.4 times. The ERI in 2014 reached a peak (0.352), indicating that the ecological risk problems faced by the agricultural development were increasingly severe. From the perspective of the changing trend, the agricultural development in 1978–1985 remained the free development stage, and the range of the ERI was 0.031–0.044. By then, though the agricultural economy developed a leading role in the national economy, the agricultural foundation was extremely weak. Moreover, the rising amplitude of ecological risks was small and had a low level as a whole. In 1986–1996, the agricultural development remained the promotion stage of reform and the ERI ranged from 0.051 to 0.192. The agricultural production became energetic under the incentive of the land contracting system and the market mechanism reform. The agricultural factor input and agricultural scale enlargement generated lots of pollutants while increasing the output. Also, ecological risks were rapidly rising. In 1997–2006, the agricultural development remained the market regulation stage, and the scope of the ERI was 0.190–0.250. Affected by the financial risk in Asia, China's entry into WTO, and the removal of agricultural tax, the agricultural industrial structure was constantly adjusting. The rising amplitude of ecological risks was small, but the overall level was higher. The agricultural development in 2007–2017 remained the policy incentive stage, and the scope of the ERI was 0.246–0.348. The Central No. 1 Document continuously focused on the issue of "agriculture, rural areas, and rural residents". Moreover, after the policy dividend of removing the agricultural tax started appearing, the agricultural industrial structure was also constantly adjusting driven by the food consumption structure and rural energy revolution.

Table 1 Ecological risk weight based on expert experience

Pollutant sources	Northeastern China	Huang-Huai-Hai Area	Middle and lower reaches of the Yangtze River	Southern China	Southwestern China	Northwestern China
Mineral fertilizers	0.285	0.285	0.262	0.241	0.293	0.312
Livestock and poultry breeding	0.264	0.276	0.284	0.285	0.308	0.348
Aquaculture	0.195	0.174	0.236	0.320	0.216	0.167
Farmland straw	0.256	0.265	0.218	0.154	0.183	0.173

The internal vitality of agricultural development was aroused again. The ERI continued rising and maintained a slight reduction trend in the terminal stage.

According to the change features of different pollution sources, the ERI of all pollution sources was on the rise. Moreover, the change amplitude had an obvious difference. Figure 2 showed that the increasing amplitude of the agricultural ERI of mineral fertilizers, livestock and poultry breeding, and farmland straws was relatively small, which was respectively increased to 0.172, 0.133, and 0.169 from 0.030, 0.033, and 0.036. The ERI was respectively enlarged by 4.7 times, 3.0 times, and 3.7 times. The direct reason was attributed to the improper fertilization technology and management of the planting industry, as well as the livestock and poultry industry. However, the primary cause should be in-depth problems, such as the agricultural policy and the operation system (Deng and Gibson 2019; Hu and McAleer 2005). In 1978–2017, the ERI of aquaculture was dramatically increased to 0.888 from 0.036, showing that it was amplified by 45.6 times. The reason was that the consumption demand for aquatic products was dramatically increasing, resulting in a constant increase in the aquaculture output and scale (Chang et al. 2020; Wang et al. 2020). In light of the preliminary estimation, the annual average growth rate of China's aquaculture output and area in 1978–2017 respectively reached 7.0% and 2.5%. Particularly, the annual average growth rate of the mariculture output and area respectively reached 10.2% and 8.1%, indicating that the mariculture products would take a crucial position in China's aquatic products. The change features of agricultural ERI indicated that the current Chinese agricultural modernization development not only should prevent ecological risks generated by the traditional agricultural production mode but also should notice the new ecological risks that might be triggered by the transformation of the agricultural structure.

Regional agricultural ecological risks

Furthermore, the regional differences of agricultural ecological risks were explored in accordance with the stage characteristics. As a whole, the regional differences in the ERI from different pollution sources were obvious. Moreover, such differences had a distinct spatial variation as time goes by. In light of the total agricultural ERI, the average ERI in four stages reached 0.037, 0.100, 0.214, and 0.314 in succession. In 1978–1985, only Northwestern China was lower than the national average level, while other areas were slightly higher than the national average level (Fig. 3a). The comprehensive ERI in 1986–1996 showed a distinct polarization. The maximum occurred in Southern China (0.190), while the minimum showed in Northwestern China (0.028) (Fig. 3b). The spatial pattern of polarization in 1997–2017 was further strengthened. Particularly, the comprehensive ERI in Southern China in 2007–2017 was up to 0.806, while that of Northwestern China only reached 0.073 (Fig. 3c–d).

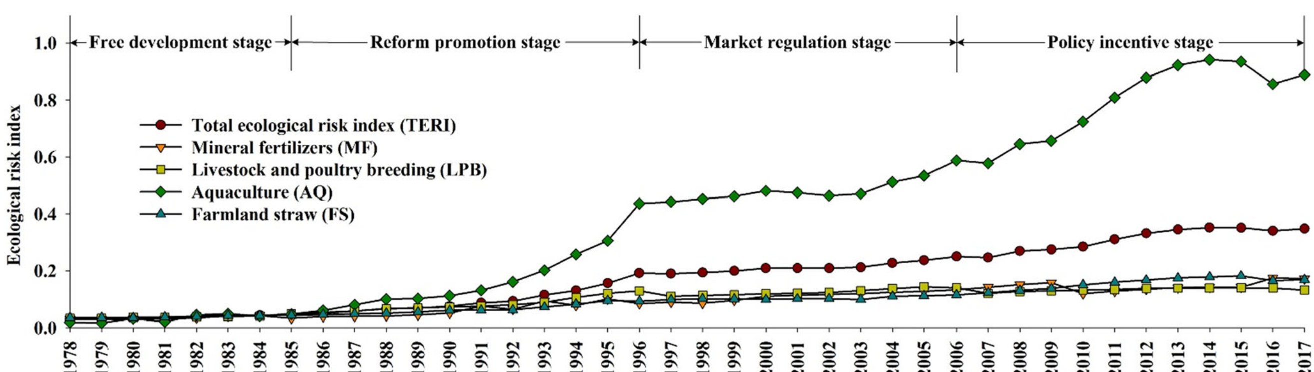

Fig. 2 Variation trend of agricultural ecological risk indexes between 1978 and 2017 in China

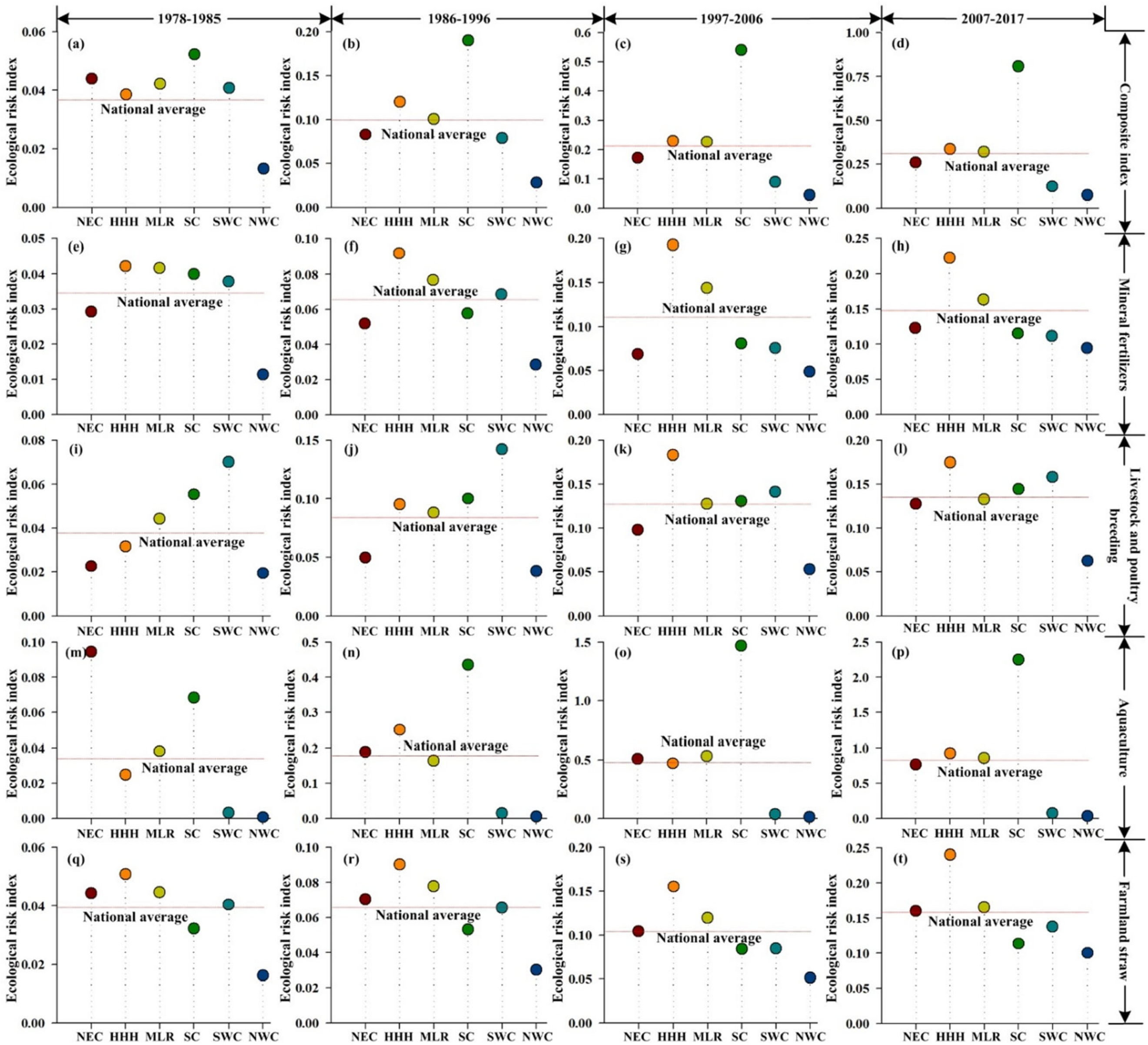

Fig. 3 Agricultural ERI in different areas and stages of China. **a**–**d** The total ecological risk index (ERI); **e**–**h** the ERI of mineral fertilizers; **i**–**l** the ERI of livestock and poultry breeding; **m**–**p** the ERI of aquaculture; **q**–**t** the ERI of farmland straws. NEC, HHH, MLR, SC, SWC, and NWC are the abbreviations of Northeastern China, the Huang-Huai-Hai Area, the middle and lower reaches of the Yangtze River, Southern China, Southwestern China, and Northwestern China, respectively

According to mineral fertilizers, the ERI in Northwestern China with the poor agricultural natural conditions was remarkably lower than the national average level (Fig. 3e–f), while the ERI of the Huang-Huai-Hai Area with favorable agricultural natural conditions in 1997–2017 was remarkably higher than the national average level (Fig. 3g–h). From the perspective of livestock and poultry breeding, the spatial grade features of the ERI in 1978–1985 were relatively obvious. The maximum and minimum respectively occurred in Southwestern China and Northwestern China (Fig. 3i). Such a feature in 1986–1996 was slightly reduced, but the feature that Southwestern China and Northwestern China were deemed as the high–low poles was never changed (Fig. 3j). The grade features of the ERI in 1997–2007 were further weakened. Moreover, the ERI in the Huang-Huai-Hai Area reached the maximum in the country (Fig. 3k–l). Considering the aquaculture, different regions in 1978–2017 had a great gap in the ERI, but except that, the relative level in Northwestern China was slightly reduced, the relative level in other areas had a small variation. As the national leading supply market of aquatic products, Southern China had the maximum ERI, while Southwestern China and Northwestern China with the poor aquaculture conditions had the minimum ERI (Fig. 3m–p). Based on farmland straws, the spatial pattern of the ERI in 1978–2017 was relatively stable. The ERI of Northwestern China, the Huang-Huai-Hai Area, and the middle and lower reaches of the Yangtze River, as the major grain-producing bases, was higher than the national average level, but Northwestern China reached the minimum (Fig. 3q–t).

Due to great differences in the agricultural resource endowment, the economic industrial structure, and the agricultural planting and breeding scale, China's agricultural ecological risks had a relatively obvious regional difference. As the important grain-producing bases, Northeastern China, the Huang-Huai-Hai Area, and the middle and lower reaches of the Yangtze River have flat farming terrain, excellent water, fertile soil, sufficient labor force, and a high agricultural modernization level (Bu et al. 2011; Zhang et al. 2018b). Predominant agricultural resource conditions enabled the agricultural ecological risks in these areas to remain the same as the national average level. Southern China had a poor agricultural planting environment but showed high consumption demands for meat, poultry, and fish. Particularly, with the rapid enlargement of the mariculture scale in recent years (Wang et al. 2020), agricultural ecological risks in this area were obviously higher than the national average level. Southwestern China had a less per capita cultivated land scale, a higher land fragmentation degree, and relatively low agricultural production efficiency (Zeng et al. 2019). The planting industry and aquaculture industry had relatively low ecological risks, but there were high ecological risks caused by the large-scale livestock and poultry breeding in this area. Northwestern China had poor natural conditions of agricultural production and factor input level, showing the extensive agricultural production mode (Li et al. 2015; Liu et al. 2018b). Agricultural ecological risks from different types of pollution sources always remained at the minimum level around the country. The regional differences of agricultural ecological risks indicated that under the comprehensive effect of the agricultural natural environment and social-economic environment, the regional pattern of Chinese agricultural production has been preliminarily formed.

Provincial agricultural ecological risks

For the ERI from different agricultural pollution sources, the natural breaking point was applied for a hierarchical display. The findings indicated that the agricultural ecological risk grade (ERG) had remarkable spatial-temporal evolution features. The agricultural development vitality in 1978–1985 was insufficient and the social-economic difference was small. The ERGs of various pollution sources generally could be divided into grade 1 or grade 2. Meanwhile, the spatial agglomeration features of agricultural ecological risks' comprehensive grades were unapparent (Fig. 4a, e, i, m, and q). The agricultural production structure and the agricultural economic structure in 1986–1996 tended to be diversified. The ERGs in most provinces have been enhanced, except for livestock and poultry breeding. Nearly two-thirds of provinces' ERGs from other various pollution sources ranked grade 1 or grade 2. The spatial agglomeration features of agricultural ecological risks' comprehensive grades started showing up (Fig. 4b, f, j, n, and r). The agricultural policies in 1997–2006 were featured with protecting agricultural production, supporting the increase of farmers' incomes, and promoting rural development. Though nearly two-thirds of provinces' ecological risks ranked grade 1 or grade 2, the number of ecological risks with grade 4 or grade 5 from various pollution sources was obviously increased. Spatial agglomeration features of agricultural ecological risks' comprehensive grades were further strengthened (Fig. 4c, g, k, o, and s). In 2007–2017, the agricultural industrial structure upgrading was completed, and the agricultural modernization construction began to take shape. About half of the provinces still ranked grade 1 or grade 2 in the ERGs. The ERGs of some provinces were upgraded to grade 5, such as risks caused by mineral fertilizers in Henan (Fig. 4d), risks caused by livestock and poultry breeding in Shandong, Henan, and Sichuan (Fig. 4h), risks from aquaculture in Shandong, Guangdong, and Fujian (Fig. 4l), and risks from farmland straws in Shandong, Henan, and Hebei (Fig. 4p). The comprehensive grades of agricultural ecological risks were present in the feature of "high in the east and south and low in the west and north" in space, especially for the maximum risk grade in Shandong, Guangdong, and Fujian, reaching grade 5 (Fig. 4t).

Based on the comprehensive ERGs (Fig. 4q–t), 9 provinces remained changeable for three reasons as follows: Beijing, Tianjin, and Shanghai generally maintained grade 1. As the administrative-economic centers in China, these areas had a small agricultural scale and an active non-agricultural economy. Most of the administrative areas in Shanxi, Shaanxi, Gansu, and Ningxia are situated in the Loess Plateau of the Northwest with the climatic environment of arid and semiarid, less than 400mm of the annual average rainfall, and the poor agricultural resource endowment. Moreover, abundant petrifaction resources would reduce the positivity of developing agriculture to some extent (Li et al. 2018; Liu et al. 2018b). Guizhou and Chongqing are located in the Karst Region of Southwestern China. This region has adequate rainwater, but the cultivated land has a large slope, small plot, thin soil layer, poor moisture and fertility conservation capacity, and low agricultural mechanization level. The ERGs in 7 provinces including Guangdong, Henan, Sichuan, and Shandong had large rising amplitude. These provinces had an adequate agricultural labor force, favorable agricultural basic conditions, a high scale operation degree (Chen et al. 2006a; Hu and McAleer 2005), and a large livestock breeding scale, resulting in the fast rise of the regional ecological risks. It is worth noting that Shandong, Guangdong, and Fujian had the

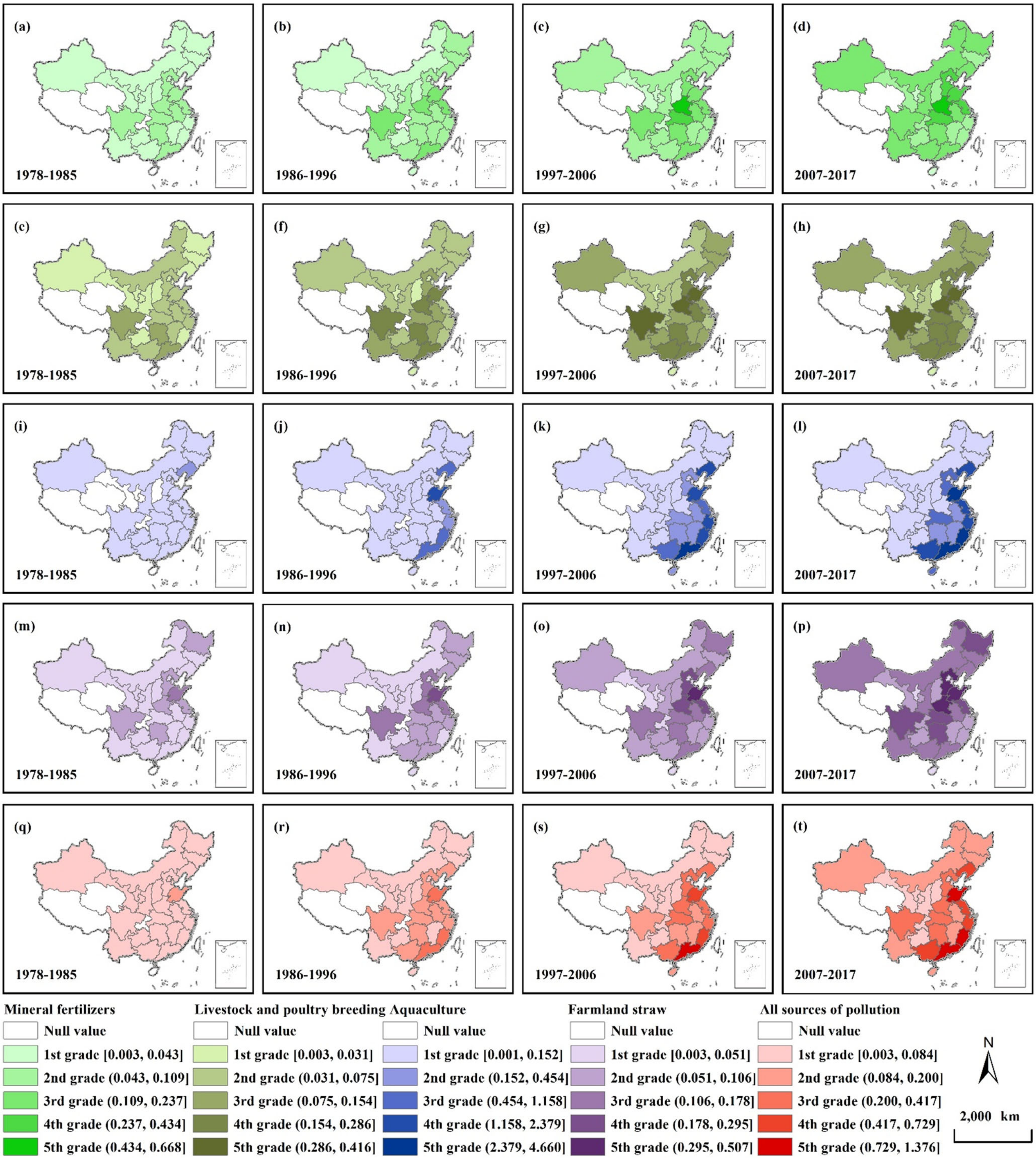

Fig. 4 Spatial-temporal pattern of China's provincial agricultural ecological risk grades (ERGs) in 1978–2017. **a**–**d** The ERGs of mineral fertilizers; **e**–**h** the ERGs of livestock and poultry breeding; **i**–**l** the ERGs of aquaculture; **m**–**p** the ERGs of farmland straws; **q**–**t** the comprehensive ERGs of all the pollution sources

maximum comprehensive grades of ecological risks. Particularly, the ERI of aquaculture in 2017 respectively reached 5.103, 4.538, and 3.704. Apparently, aquaculture has already become the primary agricultural ecological risk source. The change features of the agricultural ERGs in different provinces indicated that traditional agricultural factors including the agricultural population scale, agricultural resource abundance, and the agricultural planting and breeding scale still should be important factors of determining the spatial-temporal pattern of ecological risks, but the agricultural structure transformation has already become the dominant factor of driving pattern evolution.

Discussions

Reasons for increasing agricultural ecological risks

For a long time, agricultural production activities cause a strong pressure and risk on the self-regulation and recovery capacity of the natural ecosystem. Agricultural ERI represents the potential probability of occurrence for ecological risks. It is also an important index to evaluate the high-quality development of agricultural industrialization. In view of the acquisitiveness of research data and limitation of research contents, this paper constructed the ERI from two aspects, including the agricultural pollution loads and pollution control strength, and also analyzed the spatial-temporal pattern of China's agricultural ecological risks in recent 40 years. China's agricultural ERI in 1978–2017 was gradually increased to 0.348 from 0.031, showing remarkable stage characteristics. Under the circumstance of an insufficient agricultural pollution control system, the national system reform and agricultural policy orientation are indicators to guide the agricultural ERI variation (Liu et al. 2020; Wu and Ge 2019). For example, on the one hand, agricultural product marketization, implementation of agricultural product price subsidy, and implementation of land reclamation can motivate farmers to amplify the sowing area and increase input, resulting in enhancing agricultural ecological risks. On the other hand, limitation on the land scale operation and reduction of agricultural technical input will restrain the positivity of agricultural operation, so as to relieve the rise of agricultural ecological risks. Furthermore, since the reform and opening-up, the Chinese agricultural production organizations have focused on farming small families and breeding retail investors. The improper conduct of farmers in agricultural production is the direct cause of increasing agricultural ecological risks (Ma and Feng 2013). Due to a lack of systematic technical training and guidance, farmers increase mineral fertilizer input to gain high agricultural output, so that our mineral fertilizer consumption is higher than the global average level (Huang and Jiang 2019; Yang and Lin 2019). At the same time, because of limited time, insufficient labor force, and fuel structure adjustment, lots of crop straws burn in fields or stack in the open air to destroy the soil structure and water pollution (He et al. 2020; Zhang et al. 2019c). With the upgrading of the food consumption structure, the agricultural planting structure realizes the transformation from food crops to meat, poultry, fish, eggs, milk, (high-end) vegetables, and fruits. In the recent 40 years, the stock of pigs and poultry has been respectively increased by 336% and 2532%. The stock of cows and sheep has been respectively increased by 28% and 78%. During the process, the state positively promoted the transformation of the livestock and poultry industry from the traditional extensiveness to scale, intensification, and industrialization and successively issued relevant policies to standardize the discharge of animal manures. However, livestock breeding pollutants still should be the leading source of water pollution (Ouyang et al. 2016). Only some nutrients in baits of aquaculture can be ingested by creatures, but most of them can be released to the aquaculture water areas, resulting in an increasingly prominent eutrophication problem (Meng and Feagin 2019). The increase of the non-staple crop areas will increase agricultural chemical input, such as mineral fertilizers, pesticides, and mulching films (Huang et al. 2014). Hence, the adjustment of the national system and agricultural policies, farmers' empirical production conduct features, and causing transformation of the agricultural production structure are primary causes for the constant increase of agricultural ecological risks.

Regarding to the regional scale, the great differences in the ecological industrial structure, agricultural planting intensity, and pollution regulation strength had led to the obvious regional differences in agricultural ecological risks. Figure 5 indicated that the agricultural output value of Northeastern China accounted for 27.3% of the regional GDP, but due to the high degree of large-scale operation and low planting intensity, especially for the active adoption of key technologies such as the poisonous and harmful chemical pollution prevention control technology, farmland drainage emission reduction and recycling technology, and high-efficient utilization technology of straws and excrements of livestock (He et al. 2020; Li et al. 2018), agricultural ecological risks could be effectively controlled. The farming system in the Huang-Huai-Hai Area, the middle and lower reaches of the Yangtze River, and Southern China is double-cropping a year and triple-cropping a year (Yang et al. 2020; Yang et al. 2021). High-strength agricultural planting mainly depends on high-density production factor input, leading to the higher regional agricultural ecological risk level as a whole. In addition to the poor water and fertilizer retention ability in farming soil, agricultural ecological risks in Southwestern China were obviously affected by the agricultural planting intensity and ecological industrial structure (Zeng et al. 2019). For instance, the ratio of Guizhou's agricultural output in regional GDP was 25.1%, and the planting intensity coefficient was 1.25. The dependency of Northwestern China on the agricultural economy was still stronger. For example, the ratio of Xinjiang's agricultural output in regional GDP was 29.8%. And this was the important cause for higher agricultural ecological risks. To sum up, national agricultural developmental policies have decided the overall level and prevention strength of agricultural ecological risks from the macro level. Hydrothermal status, social conditions, and policy environment of agricultural development in each region have shaped the regional pattern of agricultural ecological risks from the micro level.

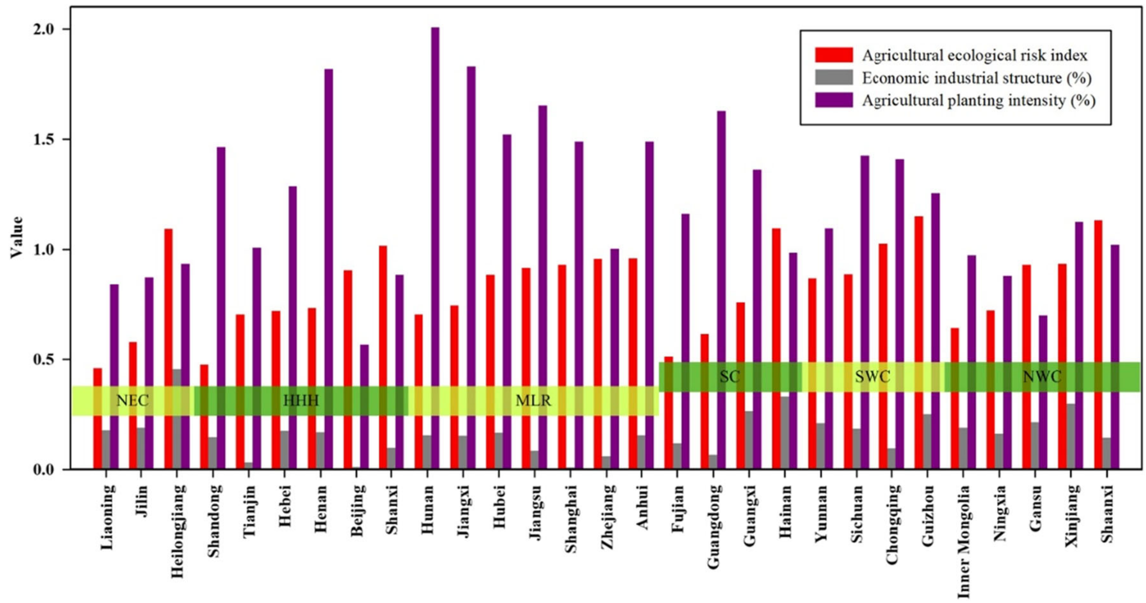

Fig. 5 China's agricultural ecological risk index (ERI), agricultural planting intensity, and economic industrial structure in 2017. Agricultural ERI was calculated based on Formula 5. The economic industrial structure was represented by the output of agriculture, forestry, animal husbandry, and fishery/ GDP, and the agricultural planting intensity was denoted by the sown area/arable land area. NEC, HHH, MLR, SC, SWC, and NWC are the abbreviations of Northeastern China, the Huang-Huai-Hai Area, the middle and lower reaches of the Yangtze River, Southern China, Southwestern China, and Northwestern China, respectively

Control strategies of agricultural ecological risks

China's agricultural ERI in 1978–2017 had obvious regional differences. The regional pattern of agricultural production has taken shape. Southern China, as the main producing area of aquatic products, had high ecological risks. Northeastern China, the Huang-Huai-Hai Area, and the middle and lower reaches of the Yangtze River, as grain-producing areas, had moderate risks. Southwestern China and Northwestern China with poor agricultural production conditions had low risks. Considering that the geographic spatial pattern, the agricultural resource endowment, the agricultural industrial structure, and the agricultural management measures have important impacts on agricultural ecological risks (Liu et al. 2020), the state and regions can formulate some specific control strategies to balance their regional differences. At the national level, it is necessary to establish a uniform agricultural pollutant discharge permit trading platform, realize market regulation of agricultural pollution discharge amount through the combination of national "quota" and "claim" of local governments (Zhang et al. 2021). On the one hand, based on the developmental status of local agricultural departments, the state allocates agricultural pollutant discharge amount with a certain quota. On the other hand, local governments apply for the agricultural pollutant discharge amount in accordance with self-developmental status. If the quota "allocated" by the state exceeds the quota "claimed" by the local governments, the state will subsidy the exceeded amount. On the contrary, if the quota "claimed" by the local governments exceeds the quota "allocated" by the state, local governments should purchase the exceeded discharge permit in the form of market bidding.

At the regional level, as the crucial grain-producing bases, Northeastern China, the Huang-Huai-Hai Area, and the middle and lower reaches of the Yangtze River have the high consumption of mineral fertilizers and abundant crop straw resources, so it is necessary to design and formulate a set of fertilization technology indexes and regulations of partition, classification, and quantification for promotion and popularization (Zhang et al. 2020c), positively promote accurate fertilization, adjust the mineral fertilizer use structure, promote testing soil for formulated fertilization, apply organic fertilizers to replace mineral fertilizers, and strengthen the technical promotion of straws into soils (e.g., fast corruption into soils, deep scarification into soils, and rotary tillage into soils) and off-field utilization (e.g., foddering, fueling and raw materials) (Cong et al. 2019), so as to reduce the environmental pollution caused by field incineration. As the leading aquatic product supply market, Southeastern China had the maximum ERI. During the process of facilitating green development of the aquaculture industry, this area should select the reasonable breeding type, enhance the bait use ratio, and explore and promote the comprehensive multi-nutrient breeding mode (Chopin et al. 2012; Sanz-Lazaro and Sanchez-Jerez 2020). Livestock breeding and farm straws in Southwestern China had a relatively high ERI. Hence, this area should generalize the technology of straws into soils; speed up the livestock breeding waste treatment and resource utilization through the agricultural subsidy policy; positively carry out the ratio research of using animal manures to replace chemical fertilizers; formulate technical specifications of safe use for different soils and crops (Luo et al. 2019); utilize calcium magnesium phosphate, lime, and calcium silicon to improve acid soils; and explore the water-fertilizer integration technology for high-efficient economic crops and horticultural plants (Zeng et al. 2019; Zhuang et al. 2020). Agricultural ecological risks in Northwestern China remained at the national minimum level. However, this area had poor soil fertility and scarce water resources. The ANPSP control should gather water-fertilizer resources, coordinate with laminating plantation to generalize the high-efficient controlled release fertilizers, combine with engineering measures to use gypsum to improve saline-alkali soils, implement the scientific land regulating engineering in water and soil loss areas, combine agricultural pollution control and water-soil loss control, and realize the collaborative governance of the slope and groove, as well as the harmonious development of ecological development and agricultural production (Liu and Li 2017). Through the differential governance of ANPSP in different areas, it is essential to safeguard the national grain safety and effective supply of important agricultural products and promote grain output increase, increase of farmers' incomes, and ecological environment safety.

Limitations

In this paper, the agricultural ERI estimation model was established from the perfectives of agricultural pollution loads and pollution control strength. However, it had some limitations. First of all, it did not fully consider the impact of soil and water resources on agricultural ecological risks, especially the resource environment carrying capacity of risk receptors. The resource environment carrying capacity refers to the maximum support capacity or highest safeguard degree of the natural environment for human production and life activities. The stronger the carrying capacity of risk receptors is, the lower probability of triggering ecological risks will be (Fan et al. 2017). Secondly, it did not "directly" evaluate the effect of various pollution control measures, but adopted the pollution discharge intensity to "indirectly" represent the pollution control strength. This may ignore the regional differences in the pollution control effect (Liu et al. 2013; Ouyang et al. 2016; Yu et al. 2019). Moreover, it just evaluated the potential ecological risks of the COD, TN, and TP in four kinds of pollution sources, but did not evaluate agricultural ecological risks triggered by pesticides, heavy metals, and ammonia nitrogen (Jiao et al. 2020; Liu et al. 2014). Besides, with the frequent occurrence of global warming and extreme weather (Meza et al. 2020; Rosenzweig et al. 2014), the changes in the internal and external environment including the international grain trade, residents' consumption structure, and agricultural breeding structure (Aznar-Sánchez et al. 2019; Bornhofen et al. 2019; Hails 2002) inevitably will cause the input changes of production factors, such as the land, labor force, capital, and technology. How to impact the spatial-temporal pattern of agricultural ecological risks by these changes should be a scientific problem to be continuously concerned in the subsequent research.

Conclusions

Based on the early-stage research, we analyzed the spatial-temporal characteristics of China's agricultural ecological risks in 1978–2017 from the national, regional, and provincial scales. The findings indicated that the ERI of the Chinese agricultural pollution in 1978–2017 was gradually increased to 0.348 from 0.031, which had similar characteristics of phased change to the succession of agricultural policies that was, it has experienced four stages of free development, reform promotion, market regulation, and policy incentive. The adjustment of the national system and agricultural policies, farmers' empirical production conduct features, and causing transformation of the agricultural production structure should be primary causes for the constant increase of agricultural ecological risks. The current ERG was present in the stair-step distribution feature of "the high in the east and south, and low in the west and north". Specifically, Southern China, as the main producing area of aquatic products, had high ecological risks. Northeastern China, the Huang-Huai-Hai Area, and the middle and lower reaches of the Yangtze River, as the grain-producing bases, had moderate ecological risks. Southwestern China and Northwestern China with poor agricultural production conditions had lower ecological risks. The research conclusions indicated that the ecological risk issue faced by Chinese agricultural development was increasingly severe. Though the agricultural pollution scale, agricultural resource abundance, and the agricultural planting and breeding scale still should be the important factors of determining the spatial-temporal pattern of ecological risks, the agricultural structure transformation has already become the dominant factor of driving pattern evolution. In the future, the Ministry of Agriculture not only should implement the "Zero Growth" plan of mineral fertilizer consumption, animal manure resource utilization, and comprehensive straw utilization, but also should pay more attention to the ecological risks that may be triggered by the aquaculture, enhance the agricultural ecological environmental quality, and safeguard rural revitalization with both lucid water and lush mountains.

Availability of data and materials All data and materials are available if the paper is published.

Author contribution Lilin Zou: conceptualization, methodology, and writing–original draft. Yongsheng Wang: formal analysis, data curation, and editing. Yansui Liu: supervision and funding acquisition.

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Declarations

Ethics approval This study will not cause any mental or physical harm to anyone and will not bring harm to their safety and rights.

Consent to participate Not applicable.

Consent for publication After the paper has been seriously revised, we agree to publish it.

Competing interests The authors declare no competing interests.

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