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RESEARCH ARTICLE

Impacts of the north migration of China's rice production on its ecosystem service value during the last three decades (1980–2014)

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Abstract
The ecosystem services value (ESV) of rice system has received increasing attention in agricultural policy decision. Over the last three decades, China's rice production presented an obviously trend that moving towards north locations. However, the impacts of this migration on the ESV of rice production have not been well documented. In this paper, we analyzed the change of the ESV of rice production in China under "north migration" and "no migration" scenarios during 1980–2014 based on long-term historical data. The results showed that both the positive and negative ESVs of rice production were lower under "north migration" than under "no migration" scenarios. The total ESV during 1980–2014 was reduced by 15.8%. "North migration" significantly reduced the area-scaled ESV since the early 1990s; while its impact on yield-scaled ESV was not significant. The effects of "north migration" on ESV showed great spatial variation. The greatest reduction in total and area-scaled ESV was observed in south locations. While the yield-scaled ESVs of most south locations were enhanced under "north migration" scenario. These results indicated that "north migration" has generated adverse effects on the ESV of rice -

1. Introduction

Rice paddies, providing nearly 26.5% of global cereal grains production, play an important role in world food security especially in Asian countries (FAOSTAT 2015). Besides

gation, summer temperature cooling and chemical pollution (Matsuno *et al*. 2006). Many studies have been conducted to evaluate the integrated ecosystem service value (ESV) of these non-production functions; the results presented that rice paddies provide more positive values in maintaining the sustainability of regional or even global ecosystem (Kim *et al*. 2006; Chiueh and Chen 2008; Yoshikawa *et al*. 2010; Xiao *et al*. 2011; Natuhara 2013). The ESV of rice paddy cultivation has gained increasing recognition and consideration in agriculture policy reform (Zhang *et al*. 2007; Liu *et al*. 2010a).

China ranks the first in annual rice production around the world. During the past decades, rice cultivation in China has migrated northward due to the natural, social and economic

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factors (Anwar *et al*. 2013; Abraham *et al*. 2014). Chen *et al*. (2012) reported that the north boundary of Chinese rice cropping regions was extended northward 80 km in 2006 compared to 1970 with the increased minimum, maximum and mean temperatures during rice growing season. The planted area of single rice in northeast China has increased by 485% from 1980 to 2010 because of the higher profit of rice than that of other crops; and the area of double rice in south China has decreased by 48% due to the shortage of agricultural labor, as most farmers left country for urban jobs with the rapid urbanization (Feng *et al*. 2013). The center of rice production has moved toward northern China (Tong *et al*. 2003). Some studies have reported that north migration of rice cultivation worsen the shortage of agricultural water in northern regions, reduced the yield potential and increased the transport cost of rice grain, which would generate adverse effect on food security (You *et al*. 2011; Xu C *et al*. 2013). However, it is still unclear the impact of this migration on the ESV of rice cultivation.

Rice paddies distributed widely from tropical areas (nearly 18°N) to temperate areas (50°N) in China. Great spatial variation may exist in the ESV of rice production because of the difference in climate, soil and agronomy factors in different regions (Xiao *et al*. 2011; Burkhard *et al*. 2013; van Berkel and Verburg 2014). For example, the results from field experiments showed that the greenhouse gases emitted from paddy field were significantly higher in south double rice cropping areas than in north single rice cropping areas, largely due to the high temperature during rice growing season and double rice planting system in south areas (Yan *et al*. 2003; Saddam *et al*. 2015). Conversely, the flood controlling ability of paddy field should be higher in south areas than north areas because of the higher precipitation in south China during rice growing seasons. Though, some studies have been conducted to evaluate the ESV of rice field in China (Li *et al*. 2006; Qin *et al*. 2010; Xiao *et al*. 2011). Little is focused on the impacts of north migration of rice paddies on its ESV. This limits the overall evaluation of the effect of north migration on the sustainability of rice paddy ecosystem in China and impairs effective decision making.

Therefore, we conducted this study to investigate the impacts of north migration on the total amount, density and spatial variation of ESV of rice production in China. Our objects are to provide references for the spatial distribution plan and rice production selection for the sustainable development of rice cultivation in China.

2. Materials and methods

2.1. Source of data

Rice is mainly cultivated in four agro-eco zones in China (Fig. 1). Zones I to IV locate in northeast, central east, southwest and south areas of China, respectively provide 15.9, agro-eco zones were kept in a fixed ratio as it was in 1980, representing that no change of spatial distribution was occurred in rice production during 1980–2014. To exclude the impacts of other factors, only the rice planting areas in each province were different between two scenarios; the other data (e.g., rice yield and metrological data) were the same.

In each case, we calculated the ESV of six functions of rice paddies, including four positive and two negative functions, which were respectively used to evaluate the positive and negative effects of rice paddy field on ambient environment. Four positive functions were temperature cooling, O_2 production, CO_2 reduction, and flood mitigation. And two negative functions were chemical pollution and greenhouse gas (GHG) emission. The detailed information of coefficients used in following equations was listed in support information Appendix A.

Temperature cooling Evapotranspiration from rice paddy can take up heat from surrounding air and reduce the air temperature especially in summer. In this study, evapotranspiration from rice paddy was calculated by using Penman-Monteith equation, which is the FAO (Food and Agriculture Organization) proposed methodology for computing crop evapotranspiration. Formulas of Penman-Monteith equation were as follows:

$$ET_0=\frac{0.408\Delta(R_n-G)+\gamma\frac{900}{T+273}u_2(e_s-e_a)}{\Delta+\gamma(1+0.34u_2)} \tag{1}$$

$$V_{TC}=K_c\times ET_0\times P_{TC} \tag{2}$$

In eq. (1), ET_0 is the reference crop evapotranspiration (mm d^{-1}); Δ is the slope of vapor pressure-temperature curve (kPa $°C^{-1}$); R_n is the net radiation (MJ m^2 d^{-1}); G is the soil heat flux (MJ m^2 d^{-1}); γ is the psychometric constant (kPa $°C^{-1}$); T is the mean daily air temperature (°C); u_2 is the mean daily wind speed at 2 m height (m s^{-1}); e_s is saturation vapor pressure (kPa); and e_a is actual vapor pressure (kPa). In eq. (2), V_{TC} is the value of temperature cooling; K_c is crop coefficient for rice; P_{TC} is the cost of water evaporation (USD mm^{-1} ha^{-1}).

O_2 production Rice plants emit O_2 through photosynthesis to refresh the air. The economic value of O_2 production was calculated by follow equation:

$$V_o=1.19\times M_{npp}\times P_o \tag{3}$$

Where, V_o is the economic value of O_2 production of rice plants (USD ha^{-1}); 1.19 is the coefficient of net primary production of rice plants to O_2 production through photosynthesis; M_{npp} is the net primary production of rice plants (kg ha^{-1}); P_o is the cost of O_2 production in the industry (USD kg^{-1}).

CO_2 reduction During rice growing seasons, air is purified by rice plants through photosynthesis as it fixed CO_2. The economic value of CO_2 reduction was calculated by eq. (4):

$$V_c=1.63\times M_{npp}\times P_c \tag{4}$$

Where, V_c is the economic value of CO_2 reduction by rice plants (USD ha^{-1}), 1.63 is the CO_2 absorbing coefficient by rice plants through photosynthesis; M_{npp} is the net primary production of rice plants (kg ha^{-1}); P_c is the international CO_2 trade price (USD kg^{-1}).

Flood mitigation Rice paddy fields can store rain fall by surrounded bunds, and reduce the peak flow to prevent flood. We assumed that the average bund height is 20 cm and the ponding water depth is 5 cm. The remaining 15 cm height of bund can be used for rain fall storage. The value of flood reduction was evaluated by eq. (5):

$$V_f=\sum_{i=1}^{n} r_i\times P_f \tag{5}$$

Where, V_f is the economic value of flood mitigation by paddy field (USD ha^{-1}), r_i is the water retented by paddy field (mm ha^{-1}), P_f is the cost of reservoir construction (USD m^{-3}).

Chemical pollution Excessive application of chemical fertilizer and pesticide in rice cultivation has been complained as a main non-point pollution source, which has adverse effect on famer health, water quality and biodiversity. The value of chemical pollution was assessed by the method reported by Li *et al*. (2001):

$$V_{cp}=V_{pr}+V_{eu}+V_{ni}+V_{fa}+V_{bi} \tag{6}$$

Where, V_{cp} is the value of total chemical pollution (USD kg^{-1}); V_{pr} is the value of pollution in agrochemicals production (USD kg^{-1}); V_{eu} is the value of eutrophication and fishery loss (USD kg^{-1}); V_{ni} is the value of nitrate pollution in drinking water (USD kg^{-1}); V_{fa} is the farmers health loss (USD kg^{-1}); V_{bi} is the biodiversity loss by using pesticide (USD kg^{-1}).

GHG emission Rice paddy field is also a primary anthropogenic source of greenhouse gas emission. The greenhouse gases emitted from paddy field include the direct emission of CH_4 and N_2O and the indirect CO_2 emission in the production of agrochemicals, e.g., inorganic fertilizer and agricultural film. The greenhouse gas emission from paddy field was calculated using the methods proposed by IPCC (2006):

$$T_{GHG}=25\times E_{CH_4}+298\times N/E_{N_2O}+N\times E_N+P\times E_P+K\times E_K+AF\times E_{AF} \tag{7}$$

$$V_{GHG}=T_{GHG}\times P_c \tag{8}$$

In eq. (7), T_{GHG} is the total amount of GHG emission; E_{CH_4} is the coefficient of CH_4 emission from paddy field during rice growing season (kg ha^{-1}); N, P, K, and AF are the nitrogen, phosphorus, potassium, and agricultural film used in paddy field during rice growing season; E_{N_2O} is the coefficient of N_2O emission per unit nitrogen (kg kg^{-1}); E_N, E_P, E_K, and E_{AF} are the coefficients of indirect CO_2 emission in the production process of these agrochemicals. The economic value of greenhouse gas emission was evaluated by eq. (8). In which, V_{GHG} is the ESV of greenhouse gas emission, P_c is the international CO_2 trade price (USD kg^{-1}).

Total ESV, area- and yield-scaled ESV The total ESV of above six functions was calculated by eq. (9):

$$T_{ESV}=V_{TC}+V_{o}+V_{c}+V_{F}-V_{cp}-V_{GHG} \quad (9)$$

In which, T_{ESV} is the total amount of ESV; V_{TC}, V_o, V_c, V_F, and V_{cp} are the ESVs of temperature cooling, O_2 production, CO_2 reduction, flood mitigation, and chemical pollution, respectively.

Area- and yield-scaled ESV were used to analysis the density of ESV of paddy field. Area- and yield-scaled ESV respectively represented the total ESV per unit paddy field (m^2) and unit rice yield (kg).

3. Results

3.1. Difference in area- and yield-scaled ESV

The primary characteristic of north migration of rice production was the change of rice planting area and rice types among four zones (Appendix B). So, we firstly compared the density of ESV among different zones and rice types. The results showed that there was significant difference in area- and yield-scaled ESV among four zones (Fig. 2). Zone IV showed the highest area-scaled ESV during 1980–2014, followed by zone III (Fig. 2-A). Zones I and II were the lowest. As for yield-scaled ESV, zones III and IV were similar and significant higher than zones I and II (Fig. 2-C). Among three rice types, early and middle rice showed similar area-scaled ESV (Fig. 2-B). The area-scaled ESV of late rice was significant lower than that of early and middle rice. Regard to yield-scaled ESV, early rice was significantly higher than middle and late rice. These results further indicated that "north migration" of rice cultivation would have a considerable impact on ESV of rice production in China.

3.2. Impacts of north migration on the total amount of ESV

As compared with "no migration", "north migration" reduced the total ESV of rice production in China (Fig. 3). The mean ESV was 339.2 and 371.9 billion USD for "north migration" and "no migration", respectively. And the reduction is increasing from 1980 to 2014. The total ESV was reduced by 15.8% by "north migration" as compared with "no migration".

"North migration" reduced both the positive and negative ecosystem service functions of rice paddies (Fig. 4). The ESV of positive functions was reduced by 13.4, 14.4, 13.4, and 27.7% for CO_2 reduction, flood mitigation, O_2 production, and temperature cooling in 2014, respectively. The ESV of negative functions was mitigated by 22.7 and 13.1% for GHG emission and chemical pollution in 2014, respectively.

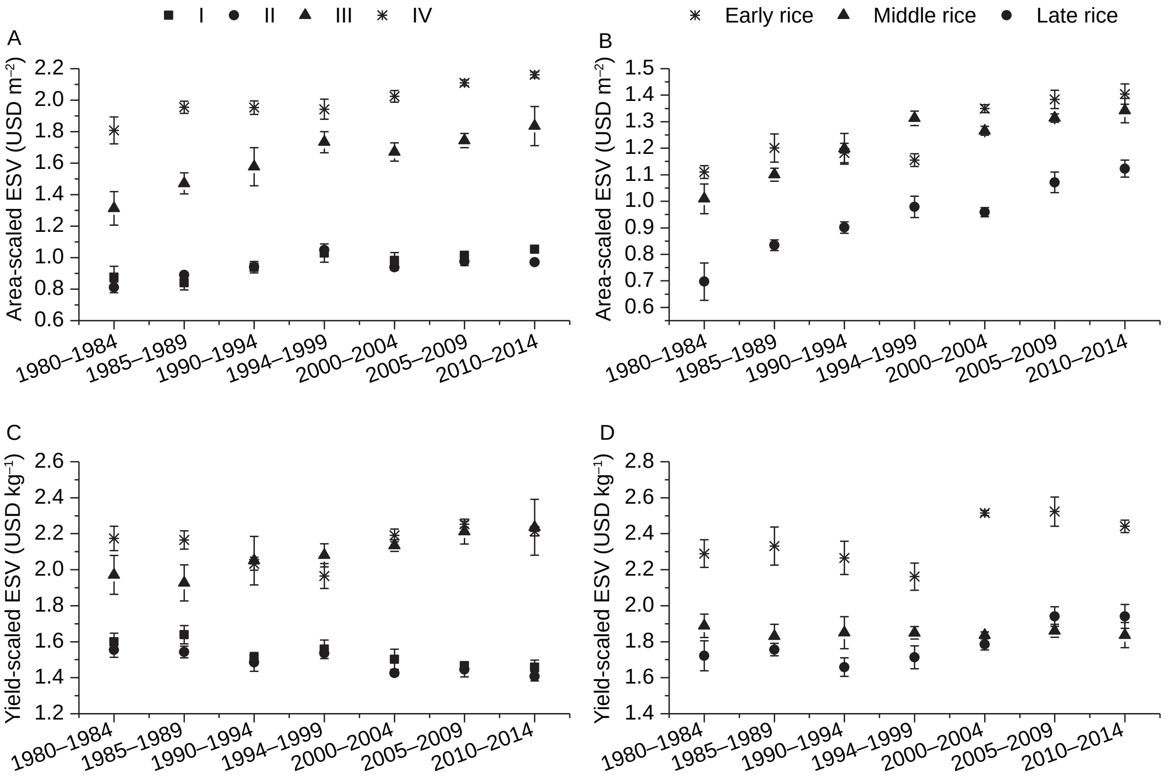
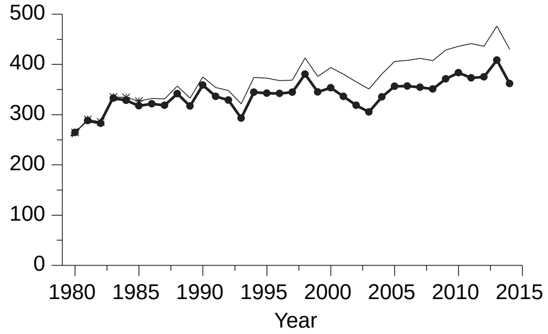


Fig. 2 Differences in the area- and yield-scaled ecosystem services value (ESV) among four rice planting zones and three rice types.

3.3. Impacts of north migration on the density of ESV

As shown in Fig. 5-A, “north migration” reduced the area-scaled ESV compared with “no migration”. The mean area-scaled ESV of five years was significantly lower under “north migration” scenario than “no migration” scenario since 1990–1994. In recent five years (2010–2014), the mean area-scaled ESV of “north migration” (1.62 USD m^{-2}) was 14.2% lower than that of “no migration” (1.89 USD m^{-2}). However, “north migration” didn’t present significant impact on yield-scaled ESV (Fig. 5-B). No significantly difference in yield-scaled ESV was observed between “north migration” and “no migration” scenarios.

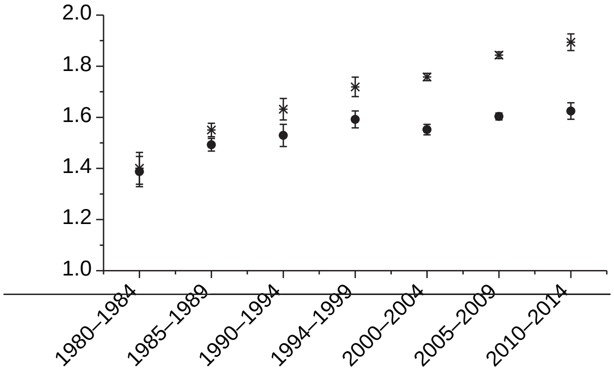


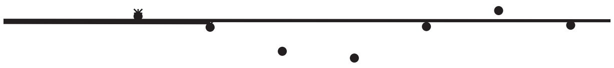
3.4. Impacts of north migration on the spatial distribution of ESV

In order to evaluate the impacts of “north migration” on the spatial distribution of ESV, we compared the difference of mean ESV of 18 locations in four zones in 2010s (2010–2014) between two scenarios. The results showed that “north migration” greatly changed the spatial distribution of total ESV in 18 primary rice cultivation locations in China (Fig. 6). As compared with “no migration”, the ESV of three provinces in zone I was increased by 28.52 billion USD (1 225.1%) for Heilongjiang, 5.16 billion USD (157.4%) for Jilin, and 2.36 billion USD (52.8%) for Liaoning, respectively, in the 2010s. As in zone II, the ESV of Henan and Anhui provinces was respectively enhanced by 3.34 billion USD (41.5%) and 2.95 billion USD (10.1%). However, the ESV of other two provinces in zone II was respectively reduced by 8.99 billion USD (19.1%) for Hubei and 5.98 billion USD (13.3%) for Jiangsu, respectively. As in zones III and IV, the ESVs of all locations were reduced. The total ESV of zones III and IV were mitigated to 7.79 (15.5%) and 83.46 billion USD (32.2%), respectively. The greatest reduction was observed in Zhejiang and Guangdong provinces. The ESV of these two provinces was reduced by 17.26 billion USD (55.4%) and 27.88 billion USD (53.3%), respectively.

“North migration” only changed the area-scaled ESV of 14 locations in zones II, III and IV (Fig. 7). The area-scaled ESV of three provinces in zone II was decreased by 0.03, 0.10 and 0.22 USD m^{-2} for Hubei, Jiangsu and Anhui provinces, respectively. Only Yunnan Province in zone III showed increased area-scaled ESV; while the other two provinces

(Guizhou and Sichuan) presented reduced area-scaled ESV. Most of the locations in zone IV (except Guangxi) showed reduced area-scaled ESV caused by “north migration”. The reduction in area-scaled ESV was in the order: Hunan (0.46 USD m^{-2})>Zhejiang (0.27 USD m^{-2})>Jiangxi (0.27 USD m^{-2})>Fujian (0.25 USD m^{-2})>Anhui (0.22 USD m^{-2})>Hainan (0.14 USD m^{-2})>Guangdong (0.02 USD m^{-2}). The mean reduction in area-scaled ESV was more in zone IV than in zones II and III.





Though “north migration” didn’t affect the yield-scaled ESV of total rice production in China (Fig. 5), it greatly influenced the yield-scaled ESV of most locations (Fig. 8). Three provinces in zone II presented increased yield-scaled ESV under “north migration” in comparison with “no migration” scenario. The changes of yield-scaled ESV for Yunnan, Guizhou and Sichuan provinces in zone III were less than 0.01, indicating that the impacts of “north migration” on these three provinces were negligible. As in zone IV, five provinces (Zhejiang, Anhui, Fujian, Hainan, Jiangxi) presented increased yield-scaled ESV caused by “north migration”; while the other two provinces (Guangdong and Hunan) were observed reduced yield-scaled ESV. The greatest enhancement and reduction in yield-scaled ESV were respectively observed in Zhejiang (0.42 USD kg^{-1}) and

Hunan (0.19 USD kg^{-1}) provinces.

4. Discussion

The non-production functions of rice paddy have gained widely consideration in the regional land use plan (Kim *et al*. 2006; zhang *et al*. 2007). In the last decade, increasing studies have been conducted to quantitatively evaluate the regional or national ESV of rice ecosystem in China (Li *et al*. 2006; Sheng *et al*. 2008; Wang *et al*. 2011; Xiao *et al*. 2011; Liu *et al*. 2015). Though more than 10 positive and negative benefits of rice paddy have been identified in previous studies (Natuhara 2013), the methodologies to quantitatively estimate these benefits have not been well established. Most previous studies evaluated the ESV of rice paddy by empirical formula based on annual statistic data (Li *et al*. 2006; Sheng *et al*. 2008; Wang *et al*. 2011; Liu *et al*. 2015); only a little used field measured data (Xiao *et al*. 2005; Qin *et al*. 2010). However, great spatial temporal variation existed in the non-production benefits during rice growing season due to the difference in climate, soil and agronomy factors (Verburg and Van der Gon 2001; Xiao *et al*. 2005; Liu *et al*. 2010a). The methodologies based on field monitoring data could provide more reliable results. In this study, the value of GHG emission was calculated by using the integrated results of field measured CH_4 and N_2O emission during the last three decades in China. And the value of temperature cooling and flood mitigation was estimated by using the daily meteorological data during rice growing season. However, the value of CO_2 production, O_2 production and chemical pollution was only calculated by using annual statistic data. The field experiment conducted to measure these benefits was still limited. More work is needed to investigate the methodologies to precisely estimate the non-production benefits of rice ecosystem in future studies.

The results of this study showed that "north migration" reduced the total ESV of rice paddy in comparison with "no migration" (Fig. 3). This was primarily because that "north migration" greatly increased the planting area of middle rice in northeast and central east regions (zones I and II), and reduced the planting area of double rice in south regions (zone IV) (Tong *et al*. 2003). The area-scaled ESV of rice cultivation was significantly higher in zone IV than in zones I and II (Fig. 2). "North migration" reduced not only the value of positive functions but also the negative functions (Fig. 4). The value of CO_2 reduction and O_2 production was mainly determined by rice production. The yield of middle rice was higher in south regions than in north regions. And double rice cropping system in southern China gains more harvest index and higher yield than single middle rice cropping system in northern China. Therefore, "north migration" reduced the total rice production and then the value of CO_2 reduction and O_2 production. The reduction in the value of flood mitigation and temperature cooling was mainly because that the precipitation and temperature were higher in south regions than north regions during rice growing season. Previous studies have reported that the emission coefficient of GHG (CH_4 and N_2O) was in the order: zone I<zone II<zone III<zone IV (Yan *et al*. 2003; Feng *et al*. 2013). Thus, "north migration" mitigated the negative value of GHG emission. However, the reduction in the ESV of positive functions was more than that of negative functions.

Area- and yield-scaled ESV are two important references for the ecological compensation of rice ecosystem (Liu *et al*. 2012). The results of this study showed that "north migration" reduced the nationally area-scaled ESV by 0.9–14.2% compared with "no migration" scenario (Fig. 5). However, its effect on nationally yield-scaled ESV was not significant. This was mainly because that the reduction caused by "north migration" in total ESV (2.8% per year) was similar as that in rice production (1.9% per year). However, the impacts of "north migration" on regional yield-scaled ESV showed great spatial variation (Fig. 8). The yield-scaled ESV of nine locations in zones II and IV was enhanced under "north migration" scenarios; while that of the other two locations was reduced. The change of yield-scaled ESV was determined by the alteration of rice cropping system under "north migration" scenario. For example, as in Hunan Province, the area-scaled ESV was higher for early and late rice than for middle rice. Thus, the reduced ratio of double rice under "north migration" scenario mitigated the yield-scaled ESV.

"North migration" is one of the key characteristics in the spatial change of rice cropping system in China. Most of previous studies focused on analyzing the driving factors contributing to the migration of rice cultivation (Tong *et al*. 2003; Yang and Chen 2011; Xu Z *et al*. 2013). However, a detailed knowledge is still lacked for the impact of this spatial change on the non-production functions of rice production. This study firstly evaluated the influence of "north migration" on the total amount and density of the ESV of rice system. The results of this analysis showed "north migration" reduced the total amount and area-scaled ESV of rice system. While its impacts showed great spatial variation. The greatest reduction was presented in south provinces in zone IV, most of which are the economically developed areas. With the rapidly urbanization in these provinces the area of arable land declined sharply (Liu *et al*. 2003; Liu *et al*. 2010b). Rice paddy plays more important role in maintaining regional environmental health (Zhang *et al*. 2007). "North migration" was not beneficial to the ecosystem service of rice cultivation in south regions. It is essential to enhance the ESV of rice paddy field in southern China by optimizing rice cropping system and improving rice planting area. Furthermore, You *et al*. (2011) has reported that "north migration" of rice production worsen the soil degradation and water shortage. Therefore, more attention is needed to be paid to the influence of "north migration" on the sustainability of regional rice production and environment stress.

5. Conclusion

By analyzing the change of ESV of China's rice production during 1980–2014 under "north migration" and "no migration" scenarios, we finally came to the conclusions as follows: (1) As compared with "no migration" scenario, "north migration" reduced both the positive and negative ESVs of rice paddies. The ESV was reduced by 13.4–27.7% for four positive functions and by 13.1–22.7% for two negative functions, respectively. The mean total ESV during 1980–2014 was reduced by 15.8%. (2) "North migration" significantly reduced the area-scaled ESV. The mean area-scaled ESV of five years was significantly lower for "north migration" than for "no migration" since 1990–1994. However, "north migration" didn't present significantly impact on yield-scaled ESV. (3) The effects of "north migration" showed great spatial variation. It enhanced the total ESV of all three locations in zone I and half locations in zone II; while reduced the total ESV of other locations. "North migration" also influenced the density of ESV in each location. Most locations in zones II, III and IV presented decreased area-scaled ESV under "north migration" scenario. Nearly half of the locations showed enhanced yield-scaled ESV under this scenario. These results increased our knowledge on the effects of spatial change of rice cultivation on its non-production benefits, and provided good references for rice production plan in future.

Acknowledgements

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Appendix associated with this paper can be available on http://www.ChinaAgriSci.com/V2/En/appendix.htm

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