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Integrated Soil–Crop System Management with Organic Fertilizer Achieves Sustainable High Maize Yield and Nitrogen Use Efficiency in Northeast China Based on an 11-Year Field Study

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Abstract: To increase crop productivity while reducing environmental costs, an integrated soil–crop system management (ISSM) strategy was developed and successfully adopted in China. However, little information is available on the long-term ISSM effects on maize agronomic and environmental performance. Therefore, we evaluated the effects of ISSM with combining inorganic and organic fertilizers on maize productivity, N use efficiency (NUE) and N balance and losses as compared with farmers’ practice (FP) and high-yielding practice (HY), based on an 11-year field experiment in Northeast China. Maize yield in ISSM (11.7–14.3 Mg ha^{−1}) achieved 97.7% of that in HY and was increased by 27% relative to FP. The excellent yield performance in ISSM was mainly attributed to optimum plant population structure and yield components. Annual N surplus in ISSM was only 7 kg ha^{−1}, which was considerably lower than that in FP (52 kg ha^{−1}) and HY (109 kg ha^{−1}). Consequently, ISSM obtained significantly lower N losses and greenhouse gases emissions and higher NUE. In contrast to FP, crop performance in ISSM showing better sustainability and inter-annual stability. In conclusion, ISSM is an effective strategy to achieve long-term sustainable high crop yields and NUE with less environmental costs in the intensive agricultural system.

Keywords: integrated agronomic management; yield sustainability; crop productivity; nitrogen surplus; environmental cost

1. Introduction

China, as the largest developing country in the world with the largest population, has scored miraculous achievements in agricultural development and food production during the past decades, with less than 9% of the world’s arable land feeding over 22% of the world population [1]. However, enormous agricultural resource inputs in combination with inadequate planting and tillage methods adopted by Chinese smallholder farmers in the current intensive agriculture system, especially in regard to overuse of inorganic fertilizers, are obtaining diminishing returns in crop yield, economic income and resource use efficiency [2–4]. In addition, this resource-dependent intensive agriculture has resulted in a series of negative impacts on the environment and ecosystem, such as widespread soil acidification and imbalance of nutrients [5,6], increased GHG emissions and nitrogen (N) deposition [7,8], eutrophic

surface water and nitrate contamination in groundwater [9,10]. Considering the increasing constraints on the environment and resources, the future food demand in China and other developing countries needs to be achieved by effectively improving resource use efficiency rather than continually increasing agricultural inputs, especially inorganic fertilizers [11]. Therefore, it is essential to develop an agronomic and environmentally acceptable management strategy to achieve the dual goals of improving crop productivity and nutrient use efficiency while reducing fertilizer-derived environmental pollution.

In the last decade, an integrated soil–crop system management (ISSM) strategy has been advocated and developed in China [1,12,13]. The key points of ISSM are to redesign the entire cropping system including crop variety, sowing and harvested dates and planting density to make maximum use of solar radiation and periods with favorable temperatures based on local climatic condition. This strategy also focuses on optimizing soil tillage and nutrient management to improve soil quality and accomplish better synchronization between crop N demand and the N supply from soil, environment and fertilizers. The ISSM approach has been demonstrated to effectively improve grain yield and N use efficiency (NUE) of maize (*Zea mays* L.), rice (*Oryza Sativa* L.) and wheat (*Triticum aestivum* L.), and it also remarkably reduces reactive N losses (RNL) and greenhouse gas (GHG) emissions, based on a total of 153 site-year field experiments across the main agro-ecological regions of China [13]. Moreover, several short-term studies have been conducted to further understand the ISSM effectiveness in terms of yield components, plant dry biomass (DM) accumulation and N uptake dynamics and their pre- or post-silking ratios, root growth and distribution, estimated N balance, measured nitrate leaching and GHG emissions for various cereal crops as well as the double-cropping rotation system [3,14–17]. To date, little information is available for the long-term ISSM effects on crop productivity and environmental impacts. In addition, organic fertilization is widely known to increase soil organic carbon (SOC) content and soil fertility, promote microbial growth and activity, improve soil physical and chemical properties and provide comprehensive nutrients for crops [18–23], and it has received increasing interest for its utility for sustainable intensive agriculture production in China [24–27]. However, organic fertilizer was rarely included in nutrient management practices in the aforementioned ISSM studies. Therefore, the long-term effects of ISSM with combining organic and inorganic fertilizers are still not well understood.

Long-term field experiments provide important opportunities for monitoring changing trends and variations of crop yields, soil properties, nutrient balances and microbial diversity and activity. These experiments play a significant role in identifying and understanding the effects of field management practices, climatic conditions and other factors on sustainable crop production, soil fertility and environmental quality, as well as determining optimal options and guiding agricultural development [19,28,29]. The information from long-term field studies are critical and indispensable to determine whether ISSM is an effective and feasible approach to achieve sustainable high crop yields and NUE with less environmental costs over a long period of time. Therefore, based on an 11-year maize field experiment in Northeast China, the objectives of this study were: (1) to investigate the long-term effects of ISSM on maize yield trends and sustainability and compare yield differences with farmers' practice (FP) and high-yielding practice (HY) from the viewpoints of plant population structure and yield components; and (2) to evaluate NUE, N balance and losses and consequent GHG emissions among the different management practices. The results should provide cogent evidence for the long-term effectiveness and feasibility of ISSM with combining organic and inorganic fertilizers in optimizing intensive agricultural production to meet the ever-growing demands for food and environmental quality in China and other developing countries.

2. Material and Methods

2.1. Experimental Site and Climatic Condition

A field experiment with a monoculture maize cropping system was initiated in 2009 at Lishu County, Northeast China. The experimental site is situated at 43°20'16'' N, 124°03'36'' E, and experiences a temperate semi-humid continental monsoon climate with an average annual air temperature of 5.8 °C

and an average annual precipitation of 570 mm [30]. Monthly air temperature and precipitation during the maize growing season from 2009 to 2019 and for the long-term averages are shown in Figure 1. The soil is classified as an Alluvic Primosol according to Chinese soil taxonomy or an Entisol according to USDA soil taxonomy. Initial soil (0–20 cm) properties were a pH of 5.15, 7.1 g kg⁻¹ organic carbon, 1.0 g kg⁻¹ total N, 29.1 mg kg⁻¹ Olsen-P and 52.0 mg kg⁻¹ exchangeable K, with 47.7% sand, 29.6% silt and 22.7% clay.

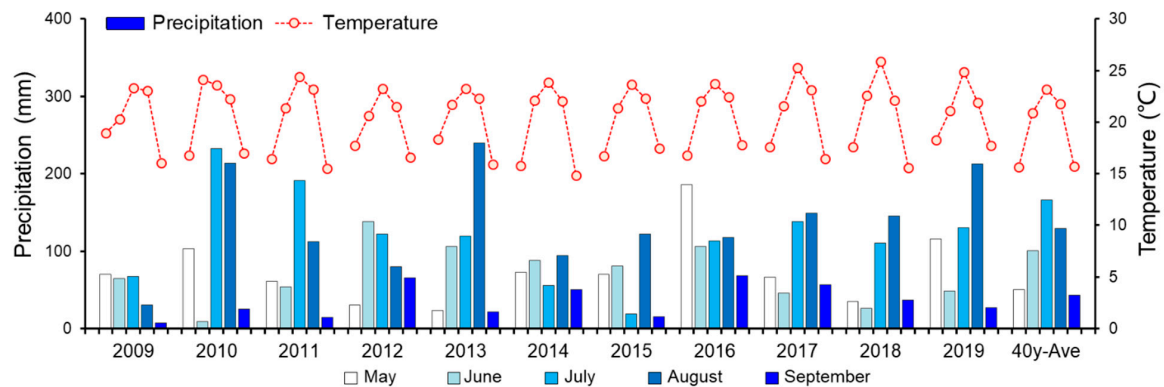


Figure 1. Monthly average air temperature and precipitation during the maize growing season over 11 years from 2009 to 2019 and for the 40-year averages (40y-Ave) at Lishu county, Northeast China.

2.2. Experimental Design and Management

There were four treatments in the field experiment: (1) NF, no fertilization; (2) FP, farmers' practices; (3) HY, high-yielding practices for maximizing maize yield without regard to resource inputs and costs; and (4) ISSM, integrated soil–crop system management for increased maize yield and reduced environmental costs, by redesigning the whole cropping and nutrient management system based on crop varieties, local soil characteristics and environmental conditions. Detailed management information is listed in Table 1. Each treatment had four replicates that were randomly distributed in blocks with a plot size of 120 m². Across all the experimental years, maize was sown from late April to early May, and physiologically mature plants were harvested from late September to early October. Two commercial maize hybrids, Xianyu 335 and Liangyu 99, were sown in this experiment during the periods of 2009–2014 and 2015–2019, respectively. In the NF and FP treatments, the conventional rotary tillage method was performed in the spring before sowing and involved rotary tilling the 0–15 cm topsoil layer. In the HY and ISSM treatments, subsoil tillage was done after harvest in autumn with a subsoiler operated at a depth of 25 cm, followed by rotary tilling the 0–15 cm topsoil layer in the spring before sowing. The inorganic N, phosphorus (P), and potassium (K) fertilizers used in this experiment were urea (46% N), diammonium phosphate (18% N and 46% P₂O₅) and potassium sulfate (50% K₂O), respectively. The organic fertilizer was wet pig manure with about 60–65% water content, that on average contained 5.2 g N kg⁻¹, 4.3 g P₂O₅ kg⁻¹ and 4.7 g K₂O kg⁻¹ on an oven-dry weight basis. The basal fertilizers were evenly broadcasted on the soil surface and incorporated into the soil by rotary tillage. Herbicides and pesticides were applied to control weeds and insects during the growing periods when needed, but no irrigation was applied during this study.

Table 1. Field management in maize production for the no fertilization (NF), farmers' practices (FP), high-yielding practices (HY) and integrated soil–crop system management (ISSM) treatments.

Treatment	Tillage Method and Depth	Planting Density (Plants ha ⁻¹)	Fertilizer Rate (kg ha ⁻¹)				Total Nutrient Input (kg ha ⁻¹)			Fertilization Times and Percentages
			N	P ₂ O ₅	K ₂ O	Pig Manure	N	P ₂ O ₅	K ₂ O	
NF	Rotary tillage to 15 cm before sowing in spring	55,000	0	0	0	0	0	0	0	
FP	Rotary tillage to 15 cm before sowing in spring	55,000	225	100	60	0	225	100	60	50% of N, 100% of P ₂ O ₅ and K ₂ O applied as basal fertilizer; and 50% of N applied as topdressing at the jointing stage
HY	Subsoil tillage to 25 cm after harvest in autumn and rotary tillage to 15 cm before sowing in spring	80,000	300	120	150	30,000	355	165	199	35% of N, 65% of P ₂ O ₅ and K ₂ O and 100% of pig manure applied as basal fertilizer; 10% of N and 15% of P ₂ O ₅ and K ₂ O as starter fertilizer applied with the seed at sowing, 35% of N applied as topdressing at the jointing stage; and 20% of N, P ₂ O ₅ and K ₂ O applied as topdressing at the silking stage
ISSM	Subsoil tillage to 25 cm after harvest in autumn and rotary tillage to 15 cm before sowing in spring	70,000	200	67	67	22,500	241	101	104	40% of N, 80% of K ₂ O and 100% of P ₂ O ₅ and pig manure applied as basal fertilizer; 10% of N as starter fertilizer applied with the seed at sowing; and 50% of N and 20% of K ₂ O applied as topdressing at the jointing stage

2.3. Sampling, Measurement and Calculation

At physiological maturity, an area of 65 m² in the center of each plot was hand-harvested for determination of grain yield. The grains were dried at 70 °C to determine moisture content, and grain yield values were adjusted to 140 g kg⁻¹ moisture content. In this study, a sustainable index (SI) was calculated to evaluate the sustainability of grain yield and other measured parameters over the years [31]. In addition, the stability of a parameter was expressed by its variability, represented by the coefficient of variation (CV). In each treatment, the SI and CV of a parameter were calculated as follows:

$$SI = (P_{\text{average}} - SD)/P_{\text{max}} \quad (1)$$

$$CV = SD \times 100/P_{\text{average}} \quad (2)$$

where P_{average} is the average value, SD is the standard deviation and P_{max} is the maximum value of a parameter across the experimental years.

The yield contribution rate (YCR) was calculated to estimate the contributions of fertilizer or soil to maize yields according to the equations described by Han et al. [32] as follows:

$$\begin{aligned} \text{Yield contribution rate from soil (YCR}_S\text{)} &= \text{grain yield in NF} \\ &\times 100/\text{maximum grain yield among three fertilization treatments} \end{aligned} \quad (3)$$

$$\begin{aligned} \text{Yield contribution rate from fertilizer (YCR}_F\text{)} &= (\text{grain yield in fertilization treatment} \\ &- \text{grain yield in NF}) \times 100/\text{grain yield in fertilization treatment} \end{aligned} \quad (4)$$

When determining grain yield, the numbers of harvested plants and ears were measured at the identical harvested area. Moreover, 20 harvested ears in each plot were shelled and kernels were counted to obtain kernel number ear⁻¹, and thousand-kernel weight was determined by using the weight of three random samples of 1000 kernels. To estimate plant total aboveground DM and harvest index (HI), straw from the harvested areas in each plot was cut at ground level, and then subsamples were taken and weighed after drying at 70 °C to constant weight.

Grain and straw samples were analyzed for N concentration using the Kjeldahl method. Plant N uptake was calculated by multiplying N concentration by plant DM. Recovery efficiency (RE_N), agronomic efficiency (AE_N) and partial factor productivity (PFP_N) of N fertilizer were calculated according to the description of Liu et al. [16]. In the HY and ISSM treatments, NUEs were calculated by considering the total N input from both organic and organic fertilizers.

Apparent N surplus was calculated on the basis of added N from inorganic and organic fertilizers minus the amount of total aboveground N uptake by plants at maturity. Furthermore, RNL amount during the maize growing season, including NH₃ volatilization, N leaching and N₂O emission, was estimated by using the empirical models developed by Chen et al. [13] and Cui et al. [2], based on the relationships between RNL (kg N ha⁻¹) from various pathways and N fertilizer rate (kg N ha⁻¹) or N surplus (kg N ha⁻¹). The detailed calculations are as follows:

$$\text{NH}_3 \text{ volatilization} = 0.24 \times \text{N fertilizer rate} + 1.45 \quad (5)$$

$$\text{N}_2\text{O emission} = 1.13 \exp (0.0071 \times \text{N surplus}) \quad (6)$$

$$\text{N leaching} = 25.31 \exp (0.0095 \times \text{N surplus}) \quad (7)$$

The emission factor of NH₃ volatilization from wet pig manure applied as basal fertilizer in maize production is 3.5% according to Zhao et al. [33].

The GHG emission amount ($\text{kg CO}_2 \text{ eq ha}^{-1}$) from a maize cropping system during the whole life cycle, mainly including CO_2 and N_2O (CH_4 emission can be ignored in dryland maize agro-ecosystems), was estimated according to Chen et al. [13] and Cui et al. [2] as follows:

$$\text{Total GHG emission} = (\text{GHGp} + \text{GHGt}) \times \text{N fertilizer rate} + \text{GHGothers} + \text{N}_2\text{O} \times 44/28 \times 298 \quad (8)$$

where GHGp is the emission from of N fertilizer production by using mining of fossil fuel as the energy source and GHGt is the emission from N fertilizer transportation. The emission factors of GHGp and GHGt were 8.21 and 0.09 $\text{kg CO}_2 \text{ eq kg}^{-1} \text{ N}$, respectively. GHGothers is the emissions from production and transportation of P and K fertilizers as well as the utilization of diesel fuel, herbicide and pesticide. The GHG emission factors were 0.79 $\text{CO}_2 \text{ eq kg}^{-1} \text{ P}_2\text{O}_5$ for P fertilizer, 0.55 $\text{kg CO}_2 \text{ eq kg}^{-1} \text{ K}_2\text{O}$ for K fertilizer, 3.75 $\text{kg CO}_2 \text{ eq kg}^{-1}$ for diesel fuel and 19.12 $\text{kg CO}_2 \text{ eq kg}^{-1}$ for herbicide and pesticide. Total N_2O emission consists of direct and indirect N_2O emissions. The former was estimated according to the empirical model mentioned above, and the latter was estimated as the ratios of 1% and 0.75% for NH_3 volatilization and N leaching, respectively, according to the IPCC methodology [34].

The RNL intensity and GHG emission intensity (i.e., RNL and GHG emission per unit grain yield, expressed as $\text{kg N t}^{-1} \text{ grain}$ and $\text{kg CO}_2 \text{ eq t}^{-1} \text{ grain}$, respectively) were also calculated to evaluate the environmental costs for producing maize grain.

2.4. Statistical Analyses

The experimental data were analyzed statistically by one-way analysis of variance using SPSS 18.0 software (SPSS, Inc., Chicago, IL, USA). The least significant difference (LSD) test was used to determine the significance of difference among fertilization treatments at the 0.05 probability level. Least-squares linear regression was performed to determine grain yield trends and annual change rates over years for all the treatments.

3. Results

3.1. Maize Yield and Yield Trend

Maize yield showed contrasting changing trends among the various treatments during the experimental periods (Figure 2). Grain yield in the NF treatment was the lowest across all years, and showed a continually decreasing trend from 8.7 to 4.7 Mg ha^{-1} . The total yield reduction during the study period for NF was 45%, with an annual reduction rate of about 0.4 Mg . Correspondingly, the yield contribution rate from soil (YCR_s) decreased continually from 72% in 2009 to 33% in 2019, suggesting considerable soil fertility consumption by maize plants under the unfertilized condition. Across all the years, grain yields in the fertilization treatments were significantly higher than that in NF ($p < 0.01$). The YCR_f in the three fertilization treatments showed continually increasing trends and exceeded the YCR_s after 2014, eventually reaching 56–67% in 2019. The FP maintained grain yield between 8.9 and 11.5 Mg ha^{-1} with an average of 10.4 Mg ha^{-1} , and it showed no significant yield trend over years with a yield change of only 0.03 Mg year^{-1} . The HY and ISSM treatments had no yield differences ($p > 0.05$) in each year; however, both obtained significantly higher grain yields ($p < 0.01$) than the FP treatment across all years. Moreover, both the HY and ISSM treatments showed continually increasing yield trends, also with a similar rate of increase of about 0.2 Mg year^{-1} . On average over the 11-year study period, grain yield in ISSM (13.2 Mg ha^{-1}) achieved 97.7% of that in HY (13.5 Mg ha^{-1}), and it was increased by 27% relative to FP. Moreover, grain yield in ISSM concurrently showed the maximal SI (0.86) and minimal CV (6.6%) over years as compared with HY (0.84 and 7.5%) and FP (0.83 and 7.9%), indicating that the ISSM had better sustainability and stability in producing high maize yield.

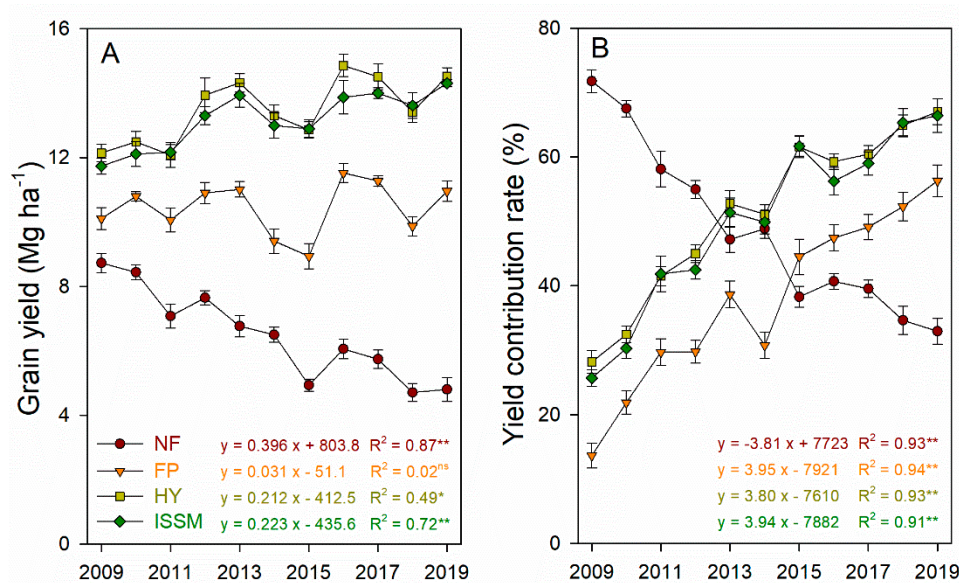


Figure 2. Dynamics of maize yield (A) and yield contribution rate from fertilizer/soil (B) over 11 years from 2009 to 2019 among the different treatments. In the linear equation $y = a x + b$, y is grain yield or yield contribution rate, x is year, a is the slope (i.e., annual yield change rate or annual change of yield contribution rate) and b is the constant. Following the R^2 values, ** and * indicate relationships that are significant at $p < 0.01$ and $p < 0.05$, respectively, while ns indicates that the relationship is not significant.

3.2. Yield Components

All yield component parameters were significantly improved in fertilization treatments as compared with NF, while these parameters showed different trends among three fertilization treatments (Table 2). The ear number was significantly higher in HY than ISSM, while no difference was observed in the ear setting ratio (ratio of ear number to harvested plants density) between these two treatments. Compared with HY and ISSM, FP showed significantly less harvested ear number and lower ear setting ratio. In contrast, kernel number per ear in FP and ISSM was significantly higher than that in HY. With regard to kernel number per unit area, HY and ISSM were significantly increased by 34% and 29% as compared with FP, respectively. The thousand-kernel weight varied from 318 to 329 g, and no significant difference was observed among the three fertilization treatments. Overall, maize plants in the ISSM generated more balanced yield components as compared with either HY or FP.

Table 2. Averages of maize yield components over 11 years among the different treatments.

Treatment	Ear No. (10 ⁴ ears ha ⁻¹)	Ear Setting Ratio (%)	Kernel No. (kernels ear ⁻¹)	Kernel No. (10 ⁴ kernels ha ⁻¹)	Thousand-Kernel Weight (g)
NF	4.96 ± 0.33 d	91.5 ± 5.5 c	378 ± 59 c	1888 ± 382 c	309 ± 7 b
FP	5.19 ± 0.16 c	95.5 ± 3.2 b	550 ± 23 a	2856 ± 193 b	329 ± 8 a
HY	7.74 ± 0.20 a	97.6 ± 2.8 a	494 ± 32 b	3822 ± 280 a	318 ± 9 a
ISSM	6.85 ± 0.12 b	98.4 ± 1.9 a	538 ± 32 a	3686 ± 235 a	322 ± 9 a

Averages followed by different letters in the same column are significantly different among treatments at $p < 0.05$.

3.3. Plant Dry Biomass and N Uptake

Similar with grain yields, both plant DM and NU were significantly increased with fertilizers application over the 11 years (Figure 3). On average, no differences were observed in plant DM and NU between HY (22.9 Mg ha⁻¹ and 246 kg ha⁻¹) and ISSM (22.2 Mg ha⁻¹ and 234 kg ha⁻¹), and the plant DM and NU were significantly higher in HY and ISSM than in FP (18.2 Mg ha⁻¹ and 173 kg ha⁻¹). Compared with FP, ISSM significantly increased DM by 22% and NU by 35%, respectively. In

terms of sustainability and stability, ISSM showed the minimal CVs and maximal SIs for both DM (0.87 and 5.6%) and NU (0.83 and 7.4%), as compared with those in FP (0.83 and 7.1% for DM and 0.78 and 9.8% for NU) and HY (0.86 and 6.4% for DM and 0.82 and 8.4% for NU). In addition to total amounts, fertilization also affected the distribution of DM and NU in grain. The average HIs for DM and NU were equal between HY and ISSM (0.51 and 0.62, respectively), showing significant increases as compared to those in FP (0.49 and 0.60, respectively).

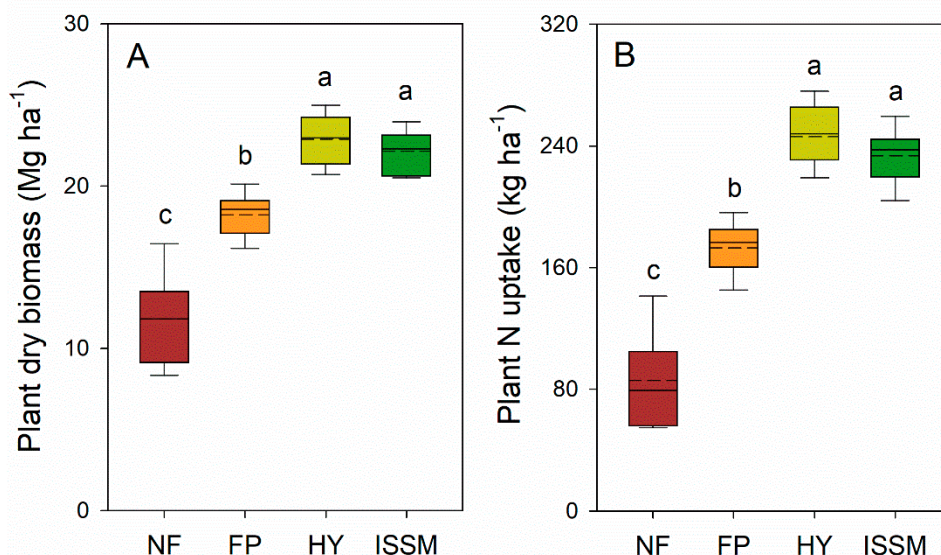


Figure 3. Maize plant dry biomass (A) and nitrogen (N) uptake (B) at maturity over 11 years among the different treatments. Different letters above the boxes indicate significant differences among treatments at $p < 0.05$.

3.4. Nitrogen Use Efficiency

The ISSM treatment showed significantly higher RE_N , AE_N and PFP_N as compared with both FP and HY over 11 years (Table 3). The RE_N and AE_N had no difference between FP and HY treatments, while PFP_N was significantly higher in FP than HY. The N surplus was estimated based on the N balance between total N inputs from inorganic and organic fertilizers and N removal by plant uptake, which was the lowest in ISSM and the highest in HY. Compared with FP, the average N surplus doubled in HY, but was reduced by 86% in ISSM.

Table 3. N recovery efficiency (RE_N), agronomic efficiency (AE_N), partial factor productivity (PFP_N) and nitrogen (N) surplus in maize production over 11 years among the different treatments.

Treatment	RE_N (%)	AE_N (kg kg ⁻¹)	PFP_N (kg kg ⁻¹)	N Surplus (kg ha ⁻¹)
FP	38.8 ± 16.0 b	17.6 ± 6.7 b	46.4 ± 3.7 b	52 ± 17 b
HY	45.2 ± 13.2 b	19.7 ± 5.9 b	38.0 ± 2.8 c	109 ± 21 a
ISSM	61.4 ± 19.0 a	27.8 ± 8.8 a	54.7 ± 3.6 a	7 ± 17 c

Averages followed by different letters in the same column are significantly different among treatments at $p < 0.05$.

3.5. Environmental Costs

The environmental costs were estimated by calculating reactive N losses (RNL) and greenhouse gas (GHG) emission per unit area and the intensity per unit grain yield (Figure 4). Both the highest RNL and GHG emission were observed in HY, and followed by FP, while the lowest values were obtained in ISSM. On average, annual total RNL and GHG emission in ISSM were 79.6 kg N ha⁻¹ and 3475 kg CO₂ eq ha⁻¹, respectively, which were reduced by 47% and 34% as compared with HY, respectively, and reduced by 20% and 13% as compared with FP, respectively. The RNL intensity

showed a similar trend as total RNL amount among the different treatments, as the lowest value of 6.1 kg N Mg^{-1} grain was obtained in ISSM, which was reduced by 46% and 37% as compared with HY and FP, respectively. The lowest GHG emission intensity of $265 \text{ kg CO}_2 \text{ eq Mg}^{-1}$ grain was observed in ISSM, which was reduced by 30% as compared with both HY and FP.

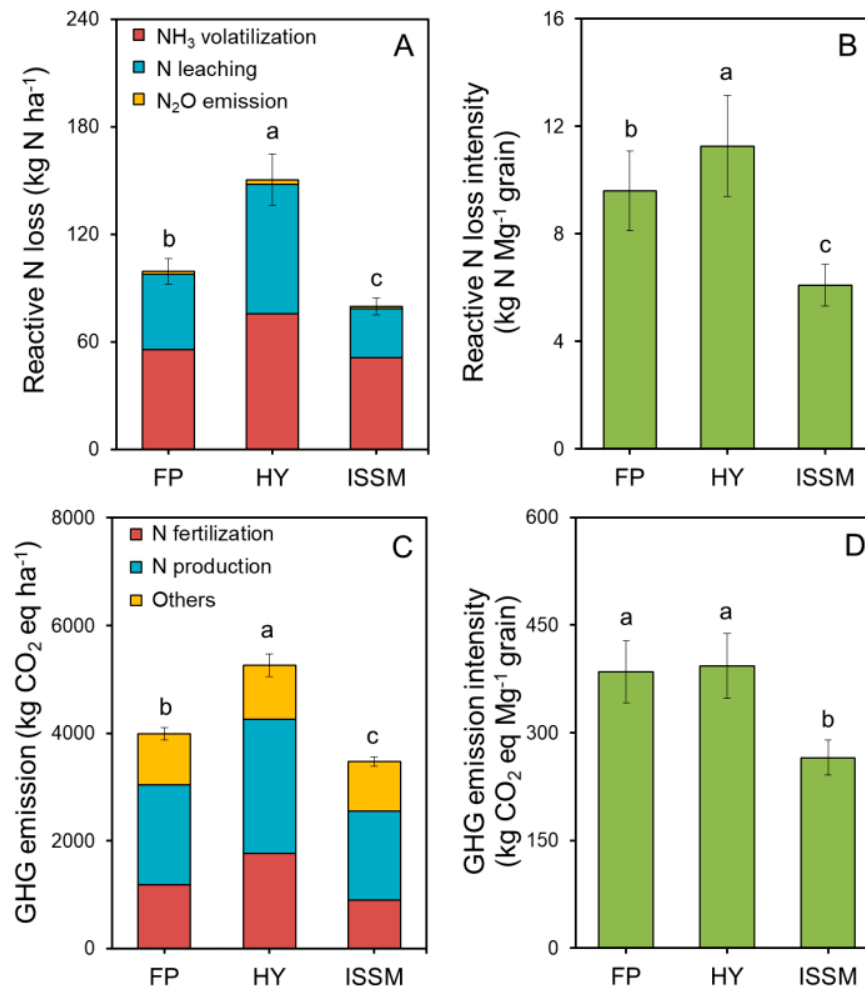


Figure 4. Annual averages of reactive nitrogen (N) losses (A) and greenhouse gas (GHG) emissions (C) and the intensity per unit grain yield (B,D) over 11 years among the different treatments. Different letters above the bars indicate significant differences among treatments at $p < 0.05$.

4. Discussion

Consistent with previous studies [6,29], in this study, maize yield in the NF treatment declined continually over years due to nutrient uptake and removal by crops and lack of nutrient supplement from fertilizers. Correspondingly, the yield contribution rate from soil (YCR_S) decreased dramatically from 72% to 33% over 11 years. A similar result was reported for wheat in a 32-year field experiment, in which the YCR_S decreased sharply from 90% to less than 20% during the initial five years and recovered to about 30% after a 10-year period [29]. This indicates that high crop productivity in an intensive mono-cropping system cannot be sustained totally by the nutrient supply from soil and instead largely relies on exogenous fertilizers. However, improper fertilization practices make it difficult to sustain high crop yields. Numerous studies have demonstrated that long-term sole inorganic fertilization decreased crop yields and sustainability due to soil acidity and degraded soil quality associated with lower soil organic carbon (SOC) [21–23]. Continual imbalanced inorganic fertilization based on high rates of N or N plus P can alter soil nutrient stocks and directly affect crop nutrient uptake and grain yield, because of lacked essential nutrients including K and micronutrients that might be available in

organic fertilizer [21]. In this study, the FP treatment might lead to degraded SOC and imbalanced soil nutrients by solely applying inorganic fertilizers with more N and P but less K. In addition, continuous shallow rotary tillage in the FP treatment could generate a hard plow pan at a soil depth of 15–20 cm, easily causing increased bulk density and decreased hydraulic conductivity and infiltration rate. These changes in soil physical properties limited root growth and extension and further reduced the capture of water and nutrient from deeper soil layers [17,35]. Under such circumstances, soil physic-chemical properties and nutrient supply in the FP treatment are insufficient to sustain high crop yields and nutrient uptake, and thus showed little yield improvement over years and larger variation during the experimental period. Despite using appropriate maize varieties and sowing dates, lower plant density might have been another factor limiting crop yields in the FP treatment. In Northeast China, current maize density is usually less than 60,000 plants ha⁻¹ in farmers' fields [36]. In this study, the lower plants density (55,000 plants ha⁻¹) in the FP treatment promoted individual plant growth with a larger ear with more kernels (mean = 550 kernels ear⁻¹), but kernel number per unit area was still significantly lower than those in ISSM and HY. On the other hand, lower planting density can decrease leaf area index and light interception rate of plant population, thereby reduced photosynthetic capacity and plant DM accumulation [17,37]. Therefore, the lower source strength and smaller sink size (lower kernel number per unit area) concurrently limited biomass distribution towards grain (lower HI) and resulted in lower grain yield in the FP treatment.

For ISSM in this study, the entire management strategy and involved practices were redesigned, mainly via optimizing nutrients supply with combining organic and inorganic fertilizers, altering fertilization times and ratios, adopting subsoil tillage and increasing plant density, aiming to improve soil properties, nutrient supply and the plant internal source–sink relationship for sustainable high grain yield. The sufficient and balanced nutrient supply based on a combined application of organic and inorganic fertilizers is the most important foundation for yield improvements in ISSM, and the benefits could be explained by several reasons. First, it can be assumed that continuous organic fertilizer addition effectively increased SOC content and soil fertility, having direct and indirect effects on soil processes and crop productivity [28,38]. Increased SOC storage has positive effects in improving grain yield while reducing inter-annual yield variation. It has been estimated that cereal yield was increased by 430 kg ha⁻¹ and yield variability was reduced by 3.5% with a 1% increase for SOC in topsoil [24,25]. Second, besides macronutrients supplied by inorganic fertilizer, organic fertilizer provides comprehensive macro- and micro-nutrients to meet crop demand, as well as improves synchronization between crop absorption and nutrient supply with slow decomposition and continuous nutrient release from organic matter [18,19]. Meanwhile, organic acids produced during organic matter decomposition might reduce P fixation in soil while increasing solubilization and availability of several cations such as calcium, zinc and iron due to chelation [22,23]. Third, long-term organic fertilization effectively increases soil microbial biomass, diversity and activity, and it has been found useful for improving soil bio-chemical properties and promoting mineralization of soil nutrients and crop uptake [20,21]. Moreover, long-term organic material addition has positive influences on soil structure and physical properties, such as decreased bulk density; increased aggregate stability, soil aeration and porosity; and improved holding capacity for water and nutrients [27,28,39]. Overall, the combined application of organic and inorganic fertilizers is superior to sole inorganic fertilization to achieve sustainable high crop yield and efficient nutrient uptake, and it has been highly recommended for intensive cropping systems in Northeast China [40]. In addition to optimizing nutrient management, ISSM implemented subsoil tillage at a depth of 25 cm to break the hard plow pan and probably improved soil physical properties and water storage, consequently promoting root growth and nutrient uptake [17,41]. On the basis of improved soil properties and optimal nutrient supply, maize density in ISSM was increased to 70,000 plants ha⁻¹, which is within the appropriate density range of 67,000–75,000 plants ha⁻¹ for maize in Northeast China [36,42]. The balanced population structure and individual plant growth in ISSM treatment produced significantly more kernels per unit area without reducing kernels number per ear

and thousand-kernel weight, and thus resulted in 27% higher grain yield and better sustainability over years as compared to the FP treatment.

Increasing planting density is considered as an effective approach to increase maize yield and NUE, by improving total resources capture based on greater population [12]. In Northeast China, yield potential for rainfed maize was estimated as 15.4 Mg ha⁻¹ [43]. Previous studies reported that grain yield over 15 Mg ha⁻¹ could be obtained when planting density exceed 80,000 plants ha⁻¹ in North China [17]. To maximize grain yields, plants density in HY treatment was designed as 80,000 plants ha⁻¹, on the basis of substantial nutrient inputs and higher fertilization frequency during the growing season. The average grain yield obtained in HY was 13.5 Mg ha⁻¹, achieving 87% of the yield potential in this region. Despite higher nutrient inputs and plants density, HY did not show significant increases in grain yield and plant N uptake as compared with ISSM. The extremely high density of 80,000 plants ha⁻¹ in HY may have exceeded appropriate density for maize in this region, intensifying the intraspecific competition for light and water [17,37]. This severely limited individual growth and yield in HY, reflected by significantly fewer kernels per ear, which in turn restricted total yield from reaching the preconceived higher level. Moreover, high planting density and high N input tend to increase the risk of plant lodging and can induce yield reduction [37].

The increasing environmental problems are seriously threatening human survival worldwide; however, the environmental costs in intensive agricultural system are barely in the focus of a farmer. In general, substantial reactive N losses occur with increasing N surplus in the soil–plant system, due to overuse of N fertilizer and inappropriate fertilization practices [13]. In this study, N input in HY far exceeded maize demand during the entire growing season and caused substantial N surplus, resulting in lower NUE and most probably will cause serious pollution of atmosphere and likely waterbodies as well. Although FP had lower N input relative to HY and even to ISSM, its limited plant DM production lead to less plant N uptake, and it also showed lower NUE and higher N surplus. Therefore, both HY and FP were not sustainable for the current intensive agriculture from the views of NUE and N losses. In contrast, the optimal N supply and higher plant N uptake in ISSM effectively reduced N surplus to only 7 kg ha⁻¹, resulting in higher NUE. Furthermore, our calculations also showed significantly less GHG emissions in ISSM as compared with the FP and HY treatments, considering the production, transportation and application of fertilizers. In addition to fertilizer effects, it can be assumed that tillage practices also affected GHG emissions by altering soil physical and biochemical properties [44]. However, the effect of tillage on cycles and releases of carbon and N in soil are extremely complicated, showing contradictory results for GHG emissions due to various soil environments and management operations [4]. In the FP treatments, shallow rotary tillage greatly disturbed topsoil structure and most likely accelerated SOC decomposition and subsequent CO₂ emission [44]. Moreover, long-term shallow rotary tillage tends to promote subsoil compaction and further form a hard plow pan, causing increased bulk density and decreased gas diffusivity and water infiltration [17]. These physical changes can result in an anaerobic soil environment, which might favor denitrification and methanogen activity, thus increasing the potential for N₂O and CH₄ production [45]. Compared to the FP treatment, both the HY and ISSM treatments broke the hard plow pan by implementing subsoil tillage, improving gas diffusivity and water infiltration in the soil profile and thereby eliminating the anaerobic environment and reducing N₂O and CH₄ emissions. However, in the subsoil tillage treatments, CO₂ emission might be increased with enhanced microbial activity in subsoil due to improved soil moisture availability and organic fertilizer addition [4]. From a long-term perspective, tillage improvement in combination with organic amendment could improve soil aggregates and promote SOC sequestration, and consequently reduce total carbon losses. Compared with the HY treatment, ISSM might have environmental benefits with lower CO₂ and N₂O production potentials due to appropriately reducing N and organic fertilizer rates. Actual determination of the environmental costs of ISSM requires further research.

5. Conclusions

The 11-year field experiment in Northeast China showed that maize yield in integrated soil–crop system management achieved 97.7% of that in high-yielding practice and was increased by 27% relative to farmers' practice. The ISSM also significantly increased NUE as compared with both HY and FP, while substantially reduced N surplus. The results demonstrate that ISSM practice, through appropriately combining organic and inorganic fertilizers with optimal tillage practices and planting density, indeed has excellent long-term effects for sustaining high crop productivity and NUE while reducing environmental costs. Therefore, ISSM has great potential as a promising and feasible approach for wide extension and adoption in intensive agricultural systems around the world.

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