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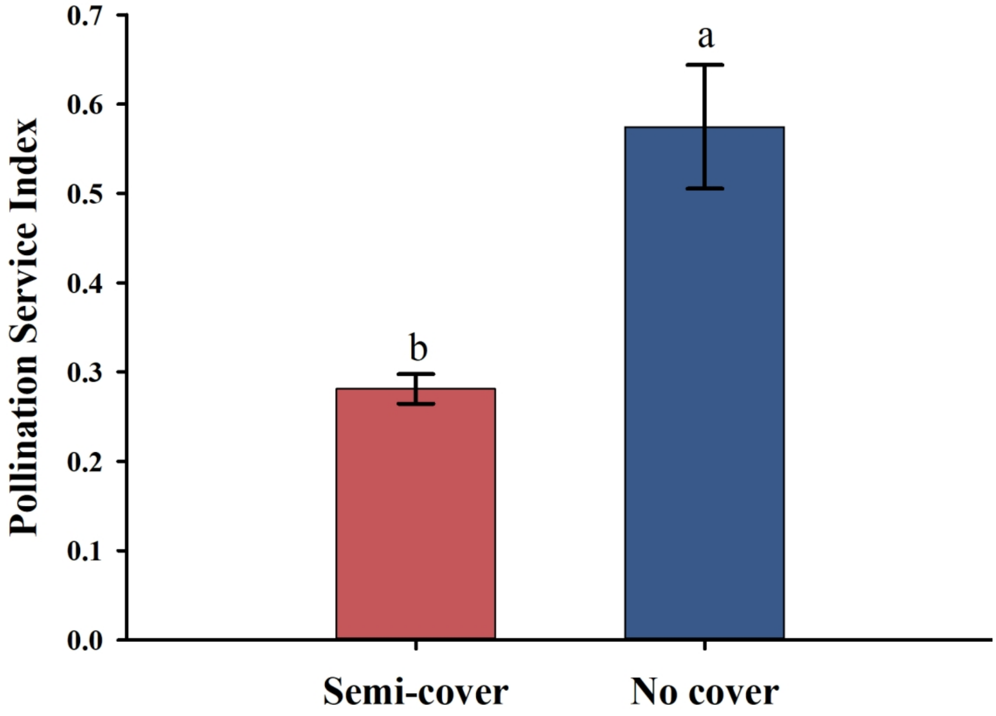

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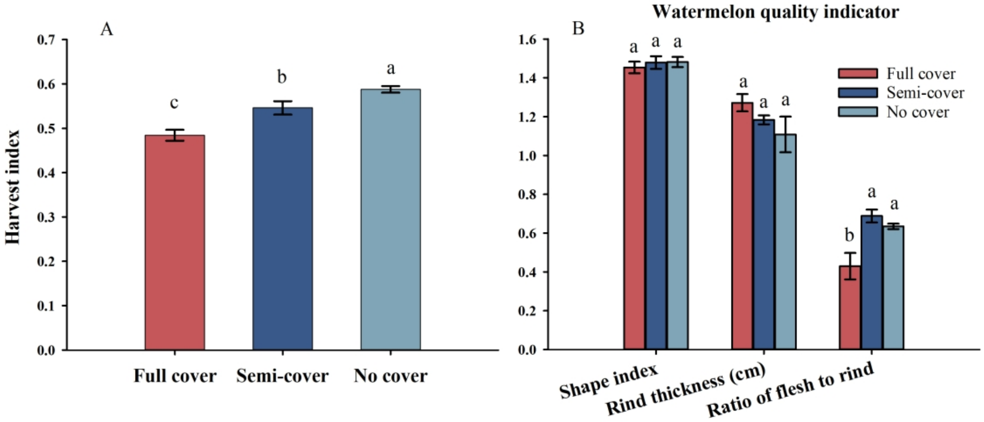

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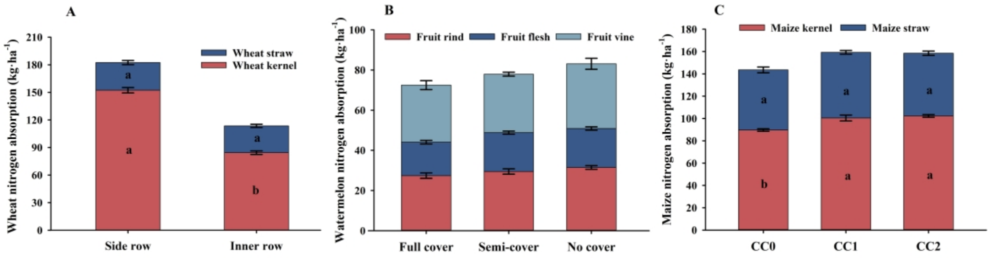

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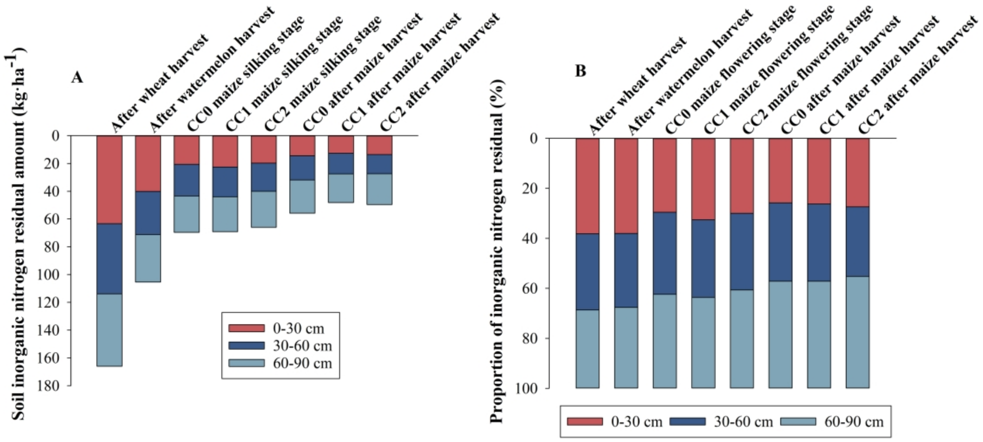

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Ecological intensification measures to improve productivity and decrease nitrogen surplus in wheat-maize/watermelon intercropping system

Abstract

Intercropping is a promising ecological intensification practice thanks to its improved crop yield and nutrient use efficiency compared with mono-cropping. However, there are constraints for achieving higher yields and efficiencies, and little is known about how to address such constraints. We conducted two experiments in a wheat-maize/watermelon intercropping study and examined the impacts of pollination services and cover crop addition on productivity and nitrogen (N) surplus, respectively. During the watermelon growing season, we investigated pollination services using three treatments (full cover, semi-cover, no cover) and evaluated fruit set rate, yield and pollination service index. During the maize growing season, we evaluated the impact of cover crop chicory (*Cichorium intybus* L.) on maize growth and soil residual inorganic N using three treatments (no cover crop, one row and two rows cover crop). Compared with the full cover treatment, semi-cover and no cover treatments increased the fruit set rate of watermelon by 42.95% and 73.85%, and fruit yield by 10.84 $Mg\cdot ha^{-1}$ and 11.48 $Mg\cdot ha^{-1}$, respectively. Pollination services accounted for 57.5% of relative watermelon yield. Compared with the control (no cover crops), planting cover crops increased yield and N uptake of the maize while reducing the apparent N surplus by 25.9-26.0 $kg\cdot ha^{-1}$. After the maize was harvested, inorganic N was largely distributed below the 60 cm soil depth. Providing pollination services and planting cover crops can be promising ecological intensification measures that improve productivity and decrease the N surplus of the intercropping system.

Keywords: Crop diversity; Cover crop; Pollination service; Soil inorganic nitrogen; Ecological enhancement

Introduction

Intensive agriculture is characterised by high productivity due to the augmented level of inputs such as fertilizers, pesticides, and irrigation water (Tilman et al. 2002). Highly intensive agriculture will reduce biodiversity that is essential for the resilience and resistance of the agroecosystem, causing ecosystem de-services (Cardinale et al. 2012). Maintaining a reliable food supply while minimizing any adverse impacts of intensive agriculture presents a significant challenge to sectorial sustainable development (Guo et al. 2010; Kopittke et al. 2019). Hence, transformative changes are urgently needed to increase the sustainability of the agri-food system (Wanger et al. 2020). Ecological intensification may provide viable mitigation to the challenge (Bommarco et al. 2013). There are two approaches to attain ecological intensification, ecological replacement and ecological enhancement. Managing biodiversity and integrating related ecosystem services may help to reduce artificial inputs whilst maintaining or increasing productivity (Kleijn et al. 2019).

To pursue high yield, the farmers likely over-apply fertilizers and terrify the sustainability of agricultural development (Blicharska et al. 2019). Although integrating soil-crop system management successfully reduces N fertilizer input (Chen et al. 2011), there is still a large area to apply the ecological principle. Compared with mono-cropping, intercropping is thought to increase biodiversity, improve yields, and improve resource use efficiency whilst reducing disease incidence and artificial inputs-caused environment pollution (Zhang et al. 2019; Xu et al. 2020; Gao et al. 2020; Li et al. 2020; Li et al. 2021b). It is therefore considered as an appropriate and efficient measure of ecological intensification (Brooker et al. 2015).

On the North China Plain, farmers in Quzhou County innovated wheat-maize/watermelon intercropping to meet both the needs for increased food production and income generation (Huang et al. 2015). This cropping system has been optimized across many studies that have identified key criteria such as the suitability of crop varieties, sowing date, or reducing nutrient applications. However, the residual N of this cropping system was still far too high, and the system was not environment-friendly and sustainable (Huang et al. 2018, 2019; Ju et al. 2009). Thus, it is worth exploring ecological intensification measures to further optimize the wheat-maize/watermelon intercropping system in addition to applying the integrated nutrient management.

Watermelon is a highly pollination-dependent crop (Sawe et al. 2020b). However, local farmers frequently ignore the importance of the pollination service due to a lack of knowledge of the pollinator function on yield limitation (Bartomeus et al. 2014). Research in small-scale farms in Africa showed that extra fertilizer and irrigation did not improve the quality and yield of watermelon, while extra pollination significantly increased watermelon yield and sugar content (Sawe et al. 2020a). Therefore, it is reasonable to consider pollination services as an additional agricultural input replacing some fertilizer applications on pollinator-dependent crops, functioning as an ecological replacement. Simplification of cropping systems and overuse of chemicals in intensive agriculture might decrease pollinators' richness and abundance, reducing pollination-dependent crops' yields (Goulson et al. 2015; Pfister et al. 2018). However, the fact about how dependent the fruit yield of watermelon under intensive farming relies on pollination services remains undetermined.

The high profit margins of watermelon encourage farmers to over-apply N fertilizer, consequently reducing N use efficiency and exacerbating N leaching (Huang et al. 2015; Zhang, 2019). In a relay intercropping, the part of the field is bare in a definite period due to the interval period between crops which is the relayed crop is not sown or the early sown crop is harvested. Since no crop is grown, the bare field might increase the risk of nitrate leaching, particularly during rainfall (Wang et al. 2008; Gabriel et al. 2012). Cover crops have been widely used as an effective way to increase biodiversity in farmland and adding cover crops has been regarded as an ecological enhancement measure, as it improves other ecosystem functions, such as weed control and increasing soil organic matter (Bommarco et al. 2013; Shackelford et al, 2019). Studies show that cover crops reduce soil N accumulation and N leaching (Valkama et al, 2015; Abdalla et al, 2019). However, the impact of cover crops on controlling nitrate leaching in relay intercropping is little known.

This study investigated wheat-maize/watermelon relay intercropping to assess the function of applying ecological intensification measures to solve the problem that high fertilizer inputs cause in intensive agriculture. In the watermelon phase, we designed pollination treatments to quantify the contribution of pollination services to the watermelon yield. In the maize growing season, we introduced several cover crop treatments to quantify the impact on reducing nitrate surplus. We hypothesized that ecological intensification measures would increase watermelon and maize yields and decrease the whole system's residual N (Fig. 1).

Material and methods

Experiment site and configuration of wheat-maize/watermelon intercropping

The experiment was conducted from October, 2018 to November, 2019 at Houlaoying village (36°39′N, 114°55′E), Dahedao Township, Quzhou County, Hebei Province, China. The experimental plot was sandy loam with a soil pH of 8.04. The topsoil (0-30 cm) organic matter content was 12.2 $g{\cdot}kg^{-1}$, total N was 1.09 $g{\cdot}kg^{-1}$, and soil available phosphorus and potassium was 34.7 $g{\cdot}kg^{-1}$ and 146 $g{\cdot}kg^{-1}$, respectively. Wheat-watermelon/maize intercropping was composed of wheat (*Triticum aestivum* L. cv. Jimai 22), watermelon (*Citrullus lanatus* cv. Bofeng No. 3) and maize (*Zea mays* L. cv. Denghai 605).

The field layout, the detailed information of crops sowing or planting and harvesting dates, and the symbiotic period of this intercropping system were shown in Fig. 2-A&B. Each wheat strip was 105 cm wide with seven rows sown at 15 cm intervals. The sowing density of wheat seeds was 225 $kg{\cdot}ha^{-1}$. While wheat was sown, the adjacent strip with 75 cm wide was kept bare until being transplanted watermelon in the following year. The plant spacing and row spacing of the watermelon strips were 5 cm and 180 cm, respectively. The watermelon seedlings grafted with pumpkin rootstock were transplanted to the middle of each strip at a planting density of 10.1×10^3 plants ha^{-1}. Eighteen days after the wheat harvest, two rows of maize were planted at two sides of wheat strips, and the maize strip width was 105 cm, and the plant spacing was 30 cm, with two plants per hill up to the density of 7.4 plants m^{-2}.

Nitrogen application and irrigation were conducted in line with the recommendation by Zhang et al. (2019). The total amounts of N, P_2O_5, and K_2O fertilizers applied to all three crops were 451.25 $kg{\cdot}ha^{-1}$, 175 $kg{\cdot}ha^{-1}$, and 191.25 $kg{\cdot}ha^{-1}$, respectively. Detailed management information for each crop was listed in Table 1.

Pesticides were applied as needed.

Experimental design

The ecological intensification measures included ecological replacement (pollination treatments) and ecological enhancement (cover crop treatments), so this study comprised two experiments conducted separately in two seasons. One experiment investigated the contribution of pollination service to watermelon productivity at the watermelon flowering stage, and another assessed the impact of cover crops on maize yield and N surplus at the maize mature stage. There were 12 plots in total, and each plot was 86.4 m^2 (16 m in length × 5.4 m in width) and applied with the consistent quantities of fertilizers.

Pollination experiment

The pollination treatment was started on 13 June 2018, before the watermelon flowered. We randomly selected 6 plots and split each plot into three subplots, randomly placing three pollination treatments (full cover, semi-cover, and no cover treatment). Each treatment included five adjacent watermelon plants and was repeated six times. Hence, there were 18 subplots in total. The full cover treatment used an iron-framed cage covered with nylon mesh (1 mm × 1 mm). The cage dimension was 300 cm×180 cm×60 cm (length ×width ×height). The fully covered cages prevented access to the watermelon by pollinators. The semi-cover treatment used the same cage type, but it only covered the top of the frame, allowing insects to access the flowers whilst replicating the shading effect of full cover (Fig. 3). No cover treatment involved the plants growing in the open, and pollinators could visit the flowers freely. In July 2018, the watermelon started to develop fruit in the no cover treatment, and all cages were removed from the field.

Cover crop experiment

After the watermelon harvest and at the jointing stage of the maize (when maize stem internode grows rapidly), we commenced the cover crop experiment using chicory (*Cichorium intybus* L.) as a cover crop. This experiment included three treatments, no cover crops (CC0), one row of chicory was sown in the middle of the harvested wheat strips (labelled as CC1), and one row was separately planted in the middle of both harvested wheat and watermelon strips (labelled as CC2). The 12 plots were arranged in random blocks for the three treatments, and each treatment was repeated four times. All cover crops were sown at 3 kg·ha^{-1}, and the plant spacing was 90 cm in early August 2019 (Fig. 2-A). Six rows of chicory were planted in each CC1 treatment plot, and 12 rows of chicory were planted in each CC2 treatment plot.

Evaluation methods

Pollination services index, fruit yield, and quality of watermelon

When the watermelon was mature, the following evaluations were undertaken. The treated watermelon plants were counted as well as the total number of flowers, fruits, and the fruit set rate which was determined as the proportion of fruit to total flower number. The length of the watermelon vine, the fruit setting position, the distance from the vine base to the first fruit, and the blade spacing were measured. The stem thickness was measured using a Vernier calliper.

Fruits and shoots of watermelon were sampled on 29 July, bagged separately, and brought back to the laboratory to measure the fruit yield and quality parameters. The watermelon vines samples were oven-dried at 75 ℃ for 48 hours and then weighed. After weighing fresh weight, the fruit length and diameter were recorded before being cut in half, and the rind thickness was measured with a Vernier calliper. The watermelon length divided by the diameter was used to calculate the fruit shape index. Watermelon flesh was separated from the rind, and the flesh and rind were oven-dried at 75 °C, and the ratio of flesh to rind was calculated.

The pollination service index (PSI) reflected the relative yield contributed by insect pollinators and eliminated the yield affected by climate, soil conditions, and other factors. Since PSI reflected the plant's investment in seed and straw, the index was more robust than direct yield or seed numbers to measure the insect pollination service (Zou et al. 2017a). The calculation of PSI was conducted thus:

$$\mathrm{PSI} = \frac{Yi}{Si} - \frac{Yc}{Sc} \quad (1)$$

where Yi was the watermelon yield at no cover or the semi-cover treatment; Yc was the watermelon yield at full cover treatment. Si was the watermelon straw yield at no cover or semi-cover treatment; Sc was the watermelon straw yield at full cover treatment.

Harvest index and yield of the maize in the cover crop experiment

Once the maize had matured, the shoots of six uniform plants in each block were cut off 2 cm above the soil surface. The ears were firstly taken off from the shoots, and the ears and the stems were stored in mesh bags separately. The shoot samples were oven-dried for 48 hours, and the biomass was weighed and ground. All maize ears were wind-dried for one week, and after being threshed, kernels were weighed. The harvest index was calculated by the dry weight of straw and kernel.

All ears of the maize grown in four rows along five meters were collected. The number of ears was counted, and then ears had been air-dried for one week, then threshed, and the kernels weighed. A subsample of 500 g maize kernels was randomly selected and oven-dried at 75 °C to a constant weight to determine water content and

100-grain weight. The maize yield per unit area was calculated based on the maize density and yield per plant.

Soil sampling and soil inorganic N determination

Soil cores in all blocks were collected with an auger during the wheat and watermelon harvesting stage, maize flowering and maize harvesting stages. The sampling points in each plot were marked as the black cross symbols in Fig. 2-A. At each sampling point, three soil cores were taken at 0-30 cm, 30-60 cm, and 60-90 cm, respectively. All soil samples were sieved with a 5 mm sieve and then extracted by 0.01 $mol \cdot l^{-1}$ $CaCl_2$. The soil suspensions were filtrated, and the filtrates used a continuous flow analysis (SEAL Auto Analyzer, Germany) to examine the soil NH_4^+-N and NO_3^--N concentrations. After wheat harvesting, the cutting ring method determined the soil bulk density in 0-30 cm, 30-60 cm, and 60-90 cm layers of each plot. Soil inorganic N accumulation content (SIN) was calculated as follows:

$$\mathrm{SIN} = \frac{(a \times 17.25 + b \times 17.25 + c \times (\frac{17.25 + 26.25}{2}) + d \times 26.25 + e \times 26.25) \times \rho b}{90} \quad (2)$$

where a, b, c, d, and e represent the soil Nmin (the sum of NH_4^+-N and NO_3^--N) content at 5 soil sample points (Fig. 2-A), ρb represents the soil bulk density.

Crop N uptake and apparent N balance

After the maize harvest, two rows of chicory plants were harvested at 1 m in length and the aboveground component oven-dried to a constant weight. The samples of the wheat kernel, watermelon straw, flesh and rind, maize straw, and the kernel were ground, and N content was determined. The samples were digested with concentrated H_2SO_4-H_2O_2 and then determined in accordance with the reported method by Thomas et al. (1967). The calculation of crop N uptake and N balance followed the method by Zhang et al. (2018):

$$\text{CNA} = \text{dry weight of plant} \times \text{N content of plant} \quad (3)$$

$$\text{N balance} = (\text{NFI} + \text{NRP}) - (\text{CNA} + \text{NRH}) \quad (4)$$

where NFI represents N fertilizer input and CNA represents the crop N absorption; NRP and NRH represent the residual N amount of soil sampled before planting and after harvesting, respectively.

Data Analysis

All the data were tested for normality of distribution and homogeneity of variance. Data analysis was conducted using One-way ANOVA in SPSS 20.0 computer software package. The least significant difference (LSD) test was conducted to analyse the means of different treatments, and the significant difference of treatments was compared at the probability $P < 0.05$. The plots of results were generated by SigmaPlot 14.0 (Systat Software Inc., Chicago, IL, USA) software package.

Results

Effects of ecological intensification measures on crop yield and quality

Pollination treatments significantly affected vine length (p=0.004), fruit setting position, and stem thickness (Table 2). The watermelon fruit setting position in the semi-cover and no-cover treatment decreased by 11.06% and 34.07%, respectively, compared to the full cover treatment (p<0.001). This indicated that if pollination was insufficient (full cover treatment), the fruit set was positioned away from the main stem of the watermelon with a longer watermelon vine length between fruits. Cover treatments reduced vine length and stem thickness compared with no cover treatment (p<0.001). The number of male flowers at full cover treatment was higher than that at no cover and semi-cover treatment (p=0.563).

The pollination treatments had a significant effect on the fruit set rate, and yield of watermelon (Fig. 4). Watermelon fruit set rate and yield in the full cover treatment were significantly lower than in the semi-cover and no cover treatment (p<0.001, Fig. 4-A). Semi-cover and no cover treatments improved fruit set rate by 42.95% and 73.85% and increased yield by 27.59% and 29.21%, respectively (Fig. 4-A and B, p=0.008). However, the dry matter weight of the watermelon vine at full cover treatment was significantly higher than that at semi-cover or no cover treatments (p<0.001, Fig. 4-C).

Pollination treatment also had a significant effect on the harvest index of watermelon (p<0.001). The harvest index of watermelon at full cover treatment was lower than that of semi-cover treatment and no cover treatment (Fig. 5-A). The fruit shape index and the ratio of flesh to rind were highest at no cover treatment, while the rind thickness of watermelon was highest at full cover treatment (Fig. 5-B). The fruit shape index and the ratio of flesh to rind are useful indicators to reflect the quality of watermelon. The watermelon with a higher fruit shape index and the ratio of flesh to rind looks well-proportioned and has more watermelon flesh. Pollination exclusion decreased the quality of watermelon and changed the dry matter distribution of watermelon flesh and rind.

The pollination service index (PSI) reflected the relative contribution of insect pollinators to the watermelon yield. Pollination treatment had a significant effect on PSI (p=0.002). The relative yield contribution by pollinators was 28.1% for semi-cover and 57.5% for no cover treatment (Fig. 6). The difference in relative yield contribution between semi-cover and no cover demonstrated that although the insect pollinators had a chance to visit flowers in the semi-cover treatment, the contribution of pollinators to watermelon yield was limited by the cage. The yield limitation of watermelon caused by shading was lower than that caused by the full cover, which means insufficient pollination was also an important limit factor for watermelon yield.

Compared to the CC0 treatment, the yields of the maize at CC1 and CC2 treatments increased by 8.86% and 9.32%, respectively (*p*=0.094, Table 3). The harvest density, kernel per spike, hundred-grain weight, and harvest index of CC0 treatment were lower than those of CC1 and CC2 treatments. Planting cover crops in spare strips increased maize yield.

The apparent N balance and soil inorganic N concentration under ecological intensification measures

For wheat, kernel N content in the side rows was significantly higher than for inner rows ($p<0.001$, Fig. 7-A), and the N content of the kernel was higher than that of the straw. The N content of watermelon flesh and rind for full cover treatment was lower than that of no cover treatment, and the N content of watermelon vine was greatest for the no cover treatment. The N content of watermelon flesh decreased by 15.89% and 16.49% at semi-cover and no cover treatments (Fig. 7-B). The N content of maize kernels in the no cover treatment (CC0) was significantly lower than cover crop treatments (CC1 and CC2) (p=0.001). The total N content of maize for the CC0 treatment was 14.89-15.73 $kg{\cdot}ha^{-1}$ lower than CC1 and CC2 treatments (Fig. 7-C).

Planting cover crops significantly decreased the apparent N balance of the intercropping system ($p<0.001$). Compared to the CC0 treatment, the crop total N uptake at CC1 and CC2 treatments increased by 25.89 $kg{\cdot}ha^{-1}$ and 25.96 $kg{\cdot}ha^{-1}$, respectively (Table 4). Adding cover crops reduced the risk of nitrogen leaching.

In the wheat-maize/watermelon intercropping system, the soil inorganic N concentration and distribution at various soil layers differed between treatments. Across three sampling periods, soil inorganic N concentration was highest at the wheat harvest stage, 63.36 kg·ha^{-1}, 50.55 kg·ha^{-1}, and 52.11 kg·ha^{-1} at the soil layer of 0-30cm, 30-60cm, and 60-90cm, respectively (Fig. 8-A). Soil inorganic N decreased over time, but inorganic N concentrations at different treatments were insignificant. After the maize was harvested, the inorganic N concentrations at CC1 and CC2 treatments decreased by 7.67 kg·ha^{-1} and 6.28 kg·ha^{-1} (Fig. 8-A). The soil inorganic N was primarily distributed in the 0-30 cm layer at wheat harvest and gradually leached downward across the soil layers of 30-60 cm and 60-90 cm over time (Fig. 8-B).

Discussion

Our results suggest that ecological intensification measures increased the productivity of wheat-maize/watermelon intercropping and decreased soil N surplus. This emphasizes the importance of pollination services for pollinator-dependent crop productivity and indicates the feasibility of applying ecological inputs to replace artificial inputs, such as fertilizer (Hudewenz et al. 2014; Sawe et al. 2020a). Cover crops increased maize yield and decreased soil N surplus, indicating crop diversification practices could be a measure of ecological enhancement without yield reduction (Duru et al. 2015; Tamburini et al. 2020).

The function of pollination service on the productivity of watermelon

Pollinators are essential to producing most fruit, vegetables, and oil seed crops (Klein et al. 2007). One estimate found that insect pollination services provide 180 million tons to 22 main crops in China (Ouyang et al. 2019). Our research proved that pollination services increased the watermelon fruit set rate, yield and quality. The PSI at semi-covered pollination treatment was 0.28, indicating that insect pollinators could contribute 28% of watermelon yields under shading conditions. The PSI for no cover treatment was higher than semi-covered, indicating the yield at semi-covered was limited by the pollination service and shading. If there is no shading effect, the insect pollinators could contribute 57.4% of watermelon yields. Pollination limitation has often been assessed by comparing yield differences between open and hand pollination (Holland et al. 2020; Wu et al. 2021). In our experiment, we quantified the contribution of pollination services, irrespective of any potential yield or seed set gap between open pollination and hand pollination. Determining any possible impact of such a gap requires further research.

The number of male watermelon flowers in the full cover treatment was higher than in semi and no cover treatments, which concurs with a recently reported study by Zou et al. (2017b), who found pollination deficits led to increased flower production. Planting flower strips and hedges have proven to increase pollination services (Haaland et al. 2011; Albrecht et al. 2020). The next step to optimize the wheat-maize/watermelon intercropping is to integrate ecological intensification measures, such as planting flower strips at field edges or planting nectar-producing plants in the field to enhance pollination services and increase watermelon productivity. Moreover, appropriate management of non-crop areas is also required so that the pollinator community can obtain food resources to overwinter successfully (Nicholls and Altieri 2013).

Intensive mono-cropping systems rely heavily on chemicals, such as pesticides and fertilizers, negatively impacting biodiversity. Homogenous landscapes reduce semi-natural habitat, which is important for pollination services as it provides season refuge for pollinator communities (Bartual et al. 2019). Management practices such as insecticide use influence pollinator visits to crops (Holzschuh et al. 2016; Pfister et al. 2018). Thus, pollination services are understood through single factors, but the effect of combined drivers on pollination services remains unresolved. There is a need to investigate multi-factor drivers and productivity of pollination services in intensive agricultural systems.

Effects of ecological enhancement measure on maize yield and soil residual N

In the wheat-maize/watermelon intercropping system, fertilizer use of watermelon strips was higher, and the transplanting days after the wheat harvest was shorter, resulting in higher soil residual inorganic N. Although the apparent N surplus was reduced by optimizing the fertilizer inputs and maize sowing date, the apparent N surplus was still more than 100 kg·ha^{-1} (Huang 2015), which caused serious N losses. We tackled this problem in two ways. One was to increase crop yields, and another was to plant cover crops effectively to reduce N leaching (Constantin et al. 2010; Zhang et al. 2019). For watermelon, a pollinator-dependent crop, it is useful to improve yield through pollination services. However, maize is self-pollination and does not rely on insect pollinators, but wind pollination can have a contribution to maize yield (Richards 2001). Thus, we can employ ecological intensification measures to improve the yield and sustainability of intensive agriculture through integrating pollination services into the watermelon period and/or adapting cover crops into the maize period.

Adding one crop might cause the yield reduction of others due to competition for resources, but the presence of chicory in this study increased maize yields. The reason might be that chicory has different root characteristics from maize, resulting in complementary effects and increasing nutrient availability (Zhang et al. 2014; Li et al. 2014; Li et al. 2021a). In the wheat-maize/watermelon intercropping system, the root depth of wheat and maize was greater than watermelon and chicory, and the competition for nutrients was partially mitigated. Another reason might be that cover crops improved the soil structure and fertility, increasing N mineralization and benefiting crop growth (Lynch et al. 2016). The different placement of cover crops at

CC1 and CC2 treatments did not affect maize yield and N content. This was mainly because the growth of cover crops planted in watermelon strips was poor, owing to the shade effect of maize. The function of cover crops did not fully develop in watermelon strips. Hence, it is the need to adjust the sowing dates of maize and/or cover crops to make both grow better, as what we did in the wheat-maize/watermelon intercropping system (Huang et al., 2018), resulting in the impact of cover crops being enhanced.

After the maize harvest, the soil inorganic N was mainly located below the soil 60 cm due to leaching through irrigation or rainfall. In the North China Plain, there was substantial rainfall during the summer, and soil nitrate is likely to be leached down to the deep soil layer (Wang et al. 2016). The root distribution of chicory was relatively shallow. To better absorb and utilize the deep soil N, we should consider other cover crops, such as cereal rye, whose roots reach the 50 cm soil horizon and more effectively reduce soil residual N (Sainju et al. 1998).

Regarding the intercropping system, the nutrient balance was commonly calculated based upon the entire cropping system. In this study, the N balance calculated based upon the wheat-maize/watermelon intercropping system was the difference between the total N input and output of the whole system. The total N input included the total amount of N fertilizer applied to three crops and the nitrate content of 0-90 cm soil measured before wheat sowing. The total N output included the total N uptake of three crop cover crops and the nitrate content of 0-90 cm soil measured after maize harvesting. We only sampled watermelon at no cover treatment, which is fully open to pollinators, so the impact of pollination on watermelon growth was at the same level across all treatments of cover crops. Hence, the difference in N balance between the treatments without and with cover crops indicated the impact of cover crops on N balance. Our results prove that integrating two ecological intensification measures into farms can reduce the N residual of the wheat-maize/intercropping system. Adopting multiple ecological intensification measures, for instance, pollination service and cover crops in this case, and fundamentally redesigning the cropping system and agricultural landscape may achieve greater agricultural regeneration and sustainability (Landis 2017; Kremen 2020). More experiments applying the principle of ecological intensification are urgently needed to explore the potential application of these measures.

Conclusions

In the wheat-maize/watermelon intercropping system, no cover treatment significantly increased the fruit set rate and watermelon yield compared to full cover. The N content of watermelon at the no cover treatment was higher than for full cover. Planting cover crops increased maize yield by 0.78-0.82 Mg·ha^{-1} compared to no cover crops and reduced the apparent N balance of the intercropping system by 25.89-25.96 kg·ha^{-1}. Through ecological intensification measures, the productivity of wheat-maize/watermelon intercropping increased, and the apparent N surplus decreased. The effect of applying the ecological intensification concept to intensive agriculture needs more exploration.

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Disclosure statement

The authors report there are no competing interests to declare.

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Table 1 The information on fertilizer and irrigation in wheat--maize/watermelon intercropping system

Crop	Period	Fertilizer inputs ($kg \cdot ha^{-1}$)			Irrigation
		N	P_2O_5	K_2O	(mm)
Wheat	Before wintering	100	100	60	115
	Wheat jointing	60	0	0	115
	Wheat flowering	-	-	-	115
Watermelon	Watermelon transplant	56.25	56.25	56.25	115
	1st topdressing for watermelon (vine extension stage)	60	0	0	115
	2nd topdressing for watermelon (fruit production stage)	75	18.75	75	115
Maize	Maize jointing	100	0	0	115

Table 2 The growth indicators of watermelon under different pollination treatments

Treatment	Vine length (m)	Fruit setting position (m)	Stem thickness (mm)	Blade spacing (cm)	Number of male flowers in 5 plants
No cover	3.83±0.06a	1.49±0.05c	8.15±0.20a	10.61±0.36a	14.58±1.98a
Semi-cover	3.51±0.04b	2.01±0.07b	7.50±0.18b	9.88±0.22a	10.83±2.09a
Full cover	3.47±0.10b	2.26±0.08a	7.04±0.14b	10.22±0.34a	15.17±4.41a

Note: The letters in the same columns indicate a significant difference between treatments at level $P<0.05$; the values are presented as means ± standard error (n=6).

Table 3 Yield composition and harvest index of maize under different cover crops treatments

Treatment	Yield ($t\cdot ha^{-1}$)	Harvest density ($plant\cdot m^{-2}$)	Kernel per spike	Hundred Grain weight (g)	Harvest Index
CC0	8.80±0.13a	6.33±0.22a	563.87±14.80a	27.76±0.72a	0.49±0.01a
CC1	9.58±0.26a	6.58±0.22a	572.83±14.40a	27.92±0.47a	0.50±0.03a
CC2	9.62±0.23a	6.65±0.15a	563.87±11.20a	29.88±0.84a	0.53±0.01a

Note: The different letters in the same columns indicate a significant difference between treatments at level $P<0.05$, the values are presented as means ± standard error (n=4). CC0 indicated no cover crops, CC1 indicated that chicory was planted in the harvested wheat strip, and CC2 indicated that chicory was planted in harvested wheat and watermelon strips.

Table 4 Apparent N surplus of wheat-maize/watermelon intercropping system under ecological intensification measures

Treatment	Fertilization input ($kg\cdot ha^{-1}$)	Crop nitrogen uptake ($kg\cdot ha^{-1}$)				Apparent N balance ($kg\cdot ha^{-1}$)
		Wheat	Watermelon	Maize	Chicory	
CC0	451.25	104.25	78.74	143.58	0	124.67±0.77a
CC1	451.25	103.48	82.55	159.31	7.11	98.78±5.66b
CC2	451.25	-	-	158.47	8.03	98.71±2.65b *

Note: The different letters in the same columns indicate a significant difference between treatments at level $P<0.05$, the values were presented as means ± standard error (n=4). * denotes the calculation of apparent nitrogen balance in CC2 treatment. Before planting cover crops, the wheat and watermelon samples in the CC2 treatment were not sampled, so the N uptake of wheat and watermelon in the CC2 treatment refers to the CC1 treatment.

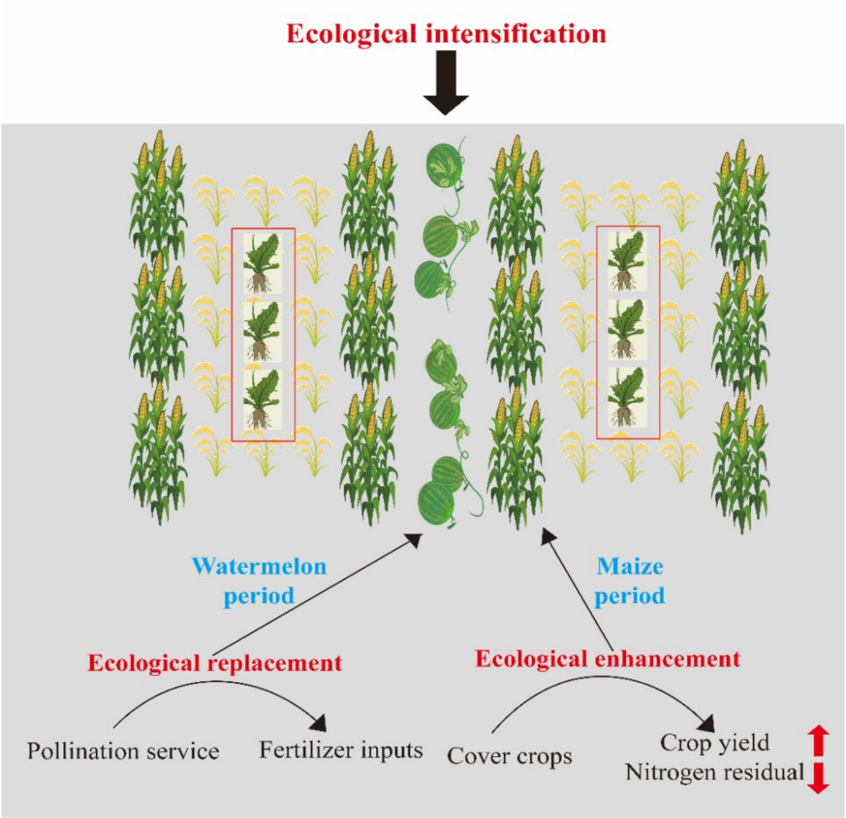

Fig. 1 The schematic diagram of ecological intensification measures in the wheat-watermelon/maize intercropping. Enhancing pollination services can act as an ecological replacement measure in that pollination services act as an agricultural input to replace part of the fertilizer leading to increased watermelon yield. Planting cover crops can be an ecological enhancement measure that increases the maize yield and reduces the N residual.

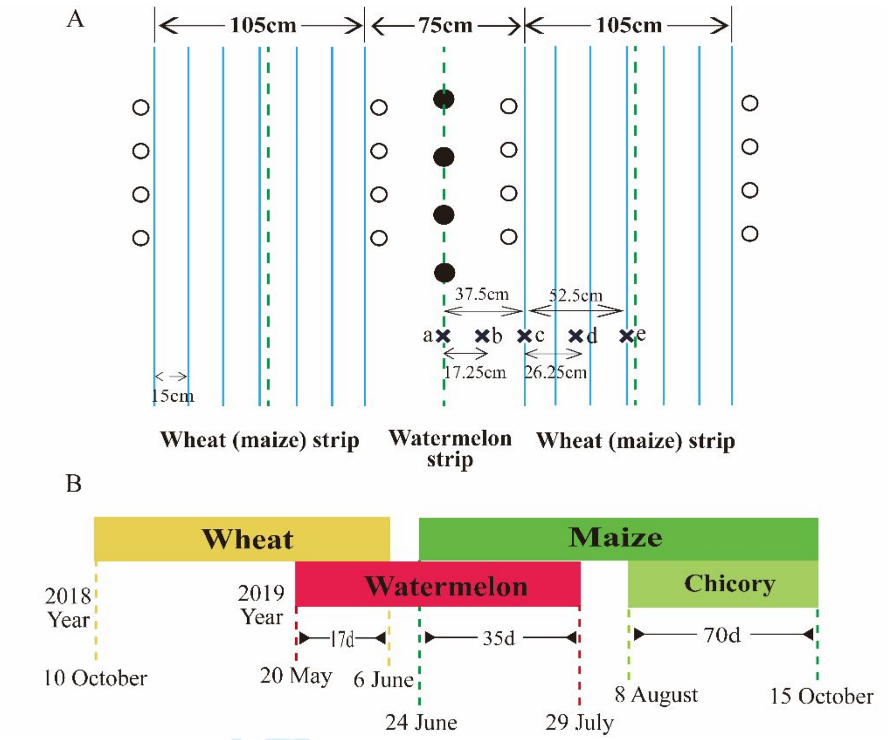

Fig. 2 Schematic representation of wheat--maize/watermelon intercropping system. Panel A showed the layout and soil sample sampling points of the system. The solid blue lines indicated wheat rows, the solid black circles indicated watermelon plants, and the hollow black circles indicated maize plants. Green dashed lines indicated cover crop chicory plants. Points a-d denoted the sites of soil sampling. Panel B showed each crop's sowing and harvesting dates in the wheat--maize/watermelon intercropping system. The symbiotic period of wheat and watermelon was 17 days, and the symbiotic period of watermelon and maize was 35 days. The symbiotic period of maize and chicory was 70 days.

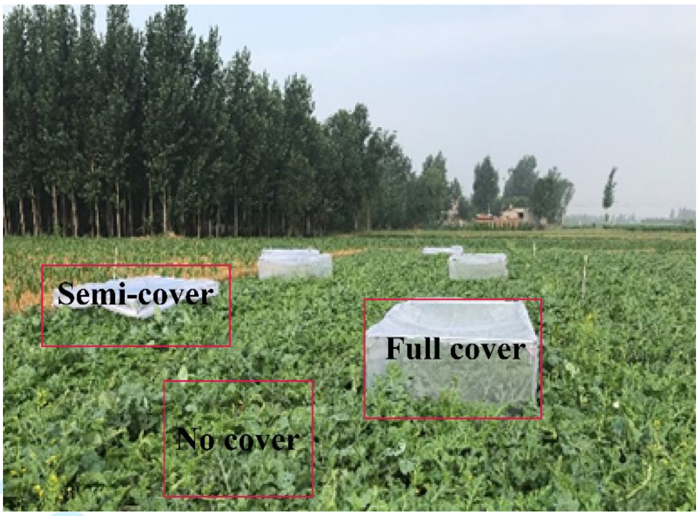

Fig. 3 Watermelon pollination treatments in the field. The pollination experiment was started on 13 June and ended by 10 July.

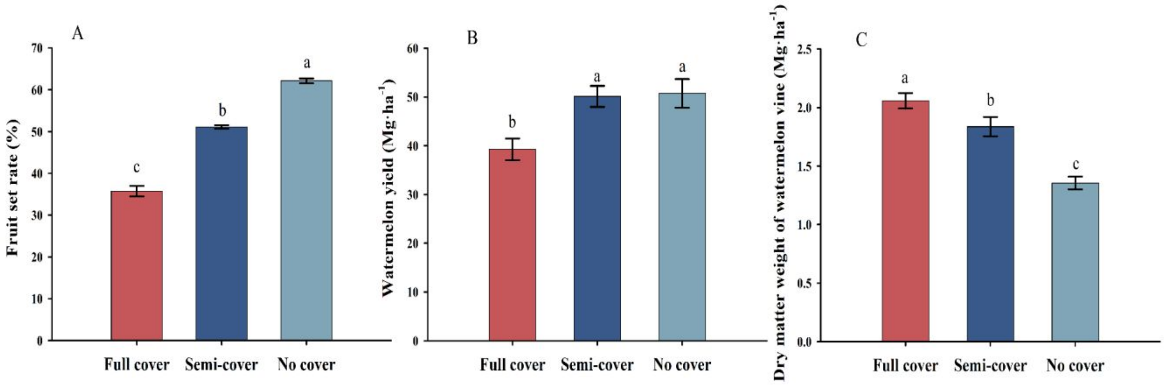

Fig. 4 Effects of different pollination treatments on watermelon yield indicators. The letters indicate a significant difference between treatments at level $P<0.05$. The bar presents the means ± standard error (n=6).

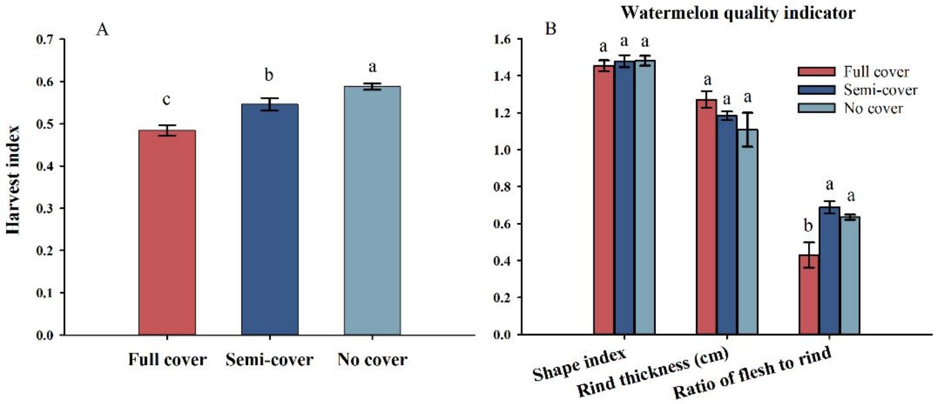

Fig. 5 Effects of different pollination treatments on watermelon quality indicators. The letters indicate a significant difference between treatments at level *P*<0.05. The bar represents the means ± standard error (n=6).

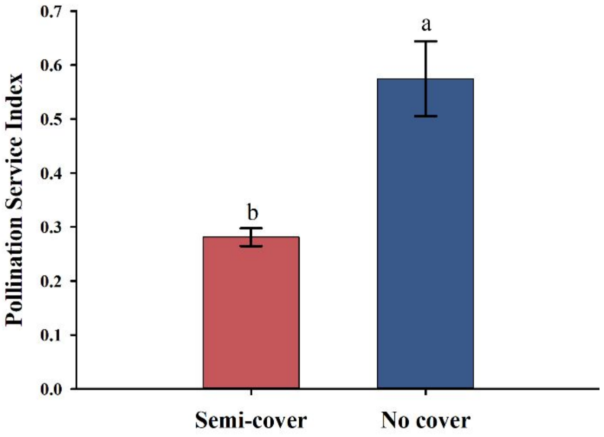

Fig. 6 The pollination service index of different pollination treatments. The letters indicated a significant difference between treatments at level *P*<0.05. The bar indicated the means ± standard error (n=6).

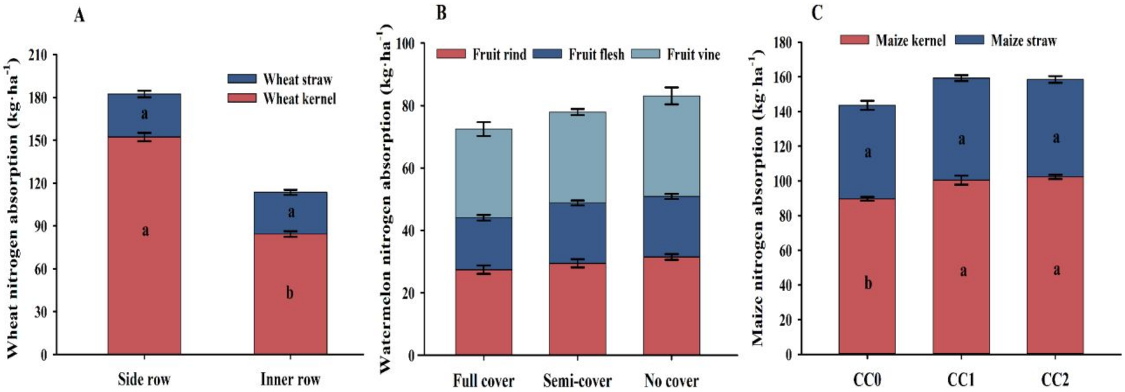

Fig. 7 The N content of wheat/maize/watermelon under different ecological intensification measures. The letters indicate a significant difference between treatments at level $P<0.05$. The bar indicated the means ± standard error (for wheat and watermelon n=6, for maize n=4).

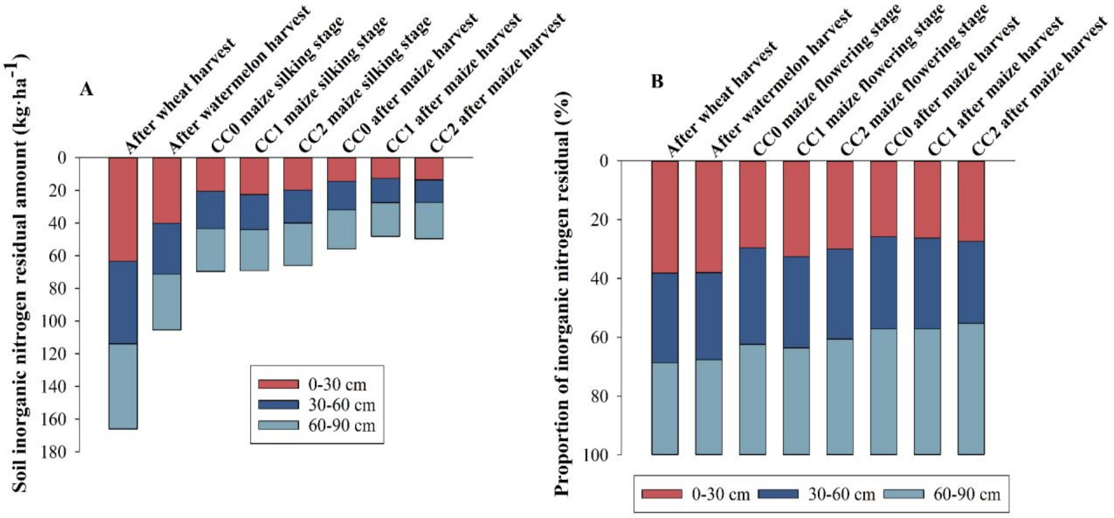

Fig. 8 The residual amount and distribution of soil inorganic N under ecological intensification measures during different periods.