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RESEARCH ARTICLE

Winter hairy vetch-spring maize rotation can improve nitrogen-utilization efficiency on the North China Plain

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Abstract
Background and aims Understanding the contributions of winter cover crops (CCs) to nitrogen (N) uptake of succeeding spring maize will help achieve more efficient soil N use.
Methods A single-factor field experiment was conducted to quantify residual N effects of contrasting cover crop tops on spring maize N utilization and environmental benefits. ^{15}N-labeled fertilizers were applied at the time of CC establishment in a microplot experiment to determine the contribution of aboveground residue N of winter cover crops (hairy vetch (HV), February orchid (OV), hairy vetch/ February orchid mixture (HO)) to the following spring maize.
Results Compared with the winter fallow, HV, OV and HO treatments decreased N fertilizer input by 30%, 9%, and 28%, respectively. The spring maize N derived from the residues was 27 (HV), 6 (OV) and 22 (HO) kg ha^{-1} and the total contribution to the N uptake of spring maize from the aboveground residues was 2.2 ~ 10.3%. The fallow treatment had the highest N surplus (167 kg N ha^{-1}), and HV, OV and HO treatments significantly reduced them to 78, 127 and 102 kg N ha^{-1}, respectively.
Conclusions Introducing hairy vetch or hairy vetch/ February orchid mixture in the sole spring maize cropping system will deliver significant improvements in nitrogen use efficiency on the North China Plain.

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Abbreviations

CC	Cover crop
N	Nitrogen
HV	Hairy vetch
OV	February orchid
HO	Hairy vetch/ February orchid mixture
Fal.	Fallow
W-M	Winter wheat–summer maize
BNF	Biological N fixation
^{15}N	Nitrogen-15
V6	6-leaf stage
R1	Silking stage
R6	Physiological maturity
EA	Excess atom fraction ^{15}N
RF	Recovery rate of the applied ^{15}N enriched fertilizer
Ndfa	Percentage of CC-N derived from atmosphere
Nds	Amount of CC-N derived from soil plus applied ^{15}N-labelled fertilizer

Introduction

Sustainable intensification of cropping systems is essential to achieve global food security and environmental security (Cui et al. 2018). Based on local natural resource, developing new cropping systems with matching agronomic management (irrigation, fertilizer input and tillage etc.) can maintain high yields while reducing environmental costs (Chen et al. 2011). The North China Plain is one of the main grain-producing areas in China, and the dominant winter wheat–summer maize (W-M) double-cropping system provides 59% and 26% of the national wheat and maize production, respectively (National Bureau of Statistics of China (NBSC) 2020). Currently, the grain yields of the region have increased significantly during the last six decades. However, development of intensive agricultural systems has been associated with overuse of chemical nitrogen (N) fertilizer, low fertilizer N use efficiency (NUE) and high reactive N losses (Ju et al. 2009; Zhang et al. 2016). We urgently need to explore sustainable cropping systems with N-management practices to ensure food security and environmental sustainability (Chen et al. 2014; Liang et al. 2022). Based on the in-season root-zone N management in the W-M double-cropping system, the amount of annual N fertilizer has been reduced to 379 kg N ha^{-1}, and nitrate leaching to 51 kg N ha^{-1}, but this still does not meet the requirements of agriculture green development (N fertilizer input and nitrate leaching should be less than 300 kg N ha^{-1}and 35 kg N ha^{-1}, respectively) (Cui et al. 2018). Developing alternative cropping systems with optimized agronomic management will provide new solutions for improving resource use efficiency and crop yields in the NCP (Meng et al. 2012).

Many studies have examined the N use efficiency and the environmental impacts of alternative cropping systems, including a single spring maize per year and three crops harvested in two years (e.g., Liu et al. 2008a; Meng et al. 2012). Compared with the traditional W-M cropping system, the W-M–spring maize rotation with three crops in two years under optimized management (in-season root-zone N management with deep placement of urea, water saving irrigation and maize stalk returning) can reduce N-fertilizer input by 52% and reducing fertilizer N losses while maintaining food security, and the planting pattern has potential to achieve sustainable agricultural development on the North China Plain (Meng et al. 2012). However, fallows during the period (October to May) after summer maize is harvested and before spring maize is planted may lower land-use efficiency due to lower use of light and heat resources (Tonitto et al. 2006), and increasing the amount of nitrate leaching (Couëdel et al. 2018).

Cover crops (CCs) grown in annual rotations between two cash crops offer an effective solution for reducing nitrate leaching and providing a green manure service due to their ability to capture soil mineral nitrogen (Blanco-Canqui et al. 2015; Drinkwater and Snapp 2007). For instance, cruciferous species grown as CCs strongly decrease nitrate leaching because of their deep root distribution, and leguminous species can efficiently provide N to the following main crops via biological N fixation (BNF) (Thorup-Kristensen et al. 2003). CC mixtures composed of legume and non-legume species could decrease nitrate leaching and provide a green manure service simultaneously by combining advantages of both sole crop species. In China, several studies have confirmed that CC mixtures composed of legumes and non-legumes can increase the grain yield of spring maize in winter

CCs-spring maize rotation, limit nitrate leaching and improve soil fertility (Bai et al. 2013; Zhang et al. 2010). However, their experimental design followed the same N fertilizer input and ignored the green manure service by releasing acquired N to the subsequent cash crops after incorporation into the soil. Quantifying the contribution of CCs to the N uptake of subsequent cash crops helps to evaluate N use efficiency and the environmental impacts of given cropping systems, especially when considering alternative cropping system designs (Zhang et al. 2021a, b).

The fate of N from fertilizers applied to a CC to the subsequent crop are variable and affected by species, soil type, local climate and management (Doltra and Olesen 2013). Nitrogen-15 (^{15}N) isotope labeling and tracing techniques are suitable approaches to quantitatively study BNF in legumes, to estimate the belowground N, to determine the fate of fertilizer N in rotation, and to distinguish the relative contribution of fertilizer and soil N to subsequent crop uptake (Fillery and Recous 2001). This method showed that less than 25% of fertilizer N can be recovered by the following crops when N is applied to a CC (Maltais-Landry and Crews 2020; Langelier et al. 2021). Previous studies have shown that the optimization of conventional N fertilization and irrigation practices can significantly increase NUE (Ju et al. 2009). Compared with broadcast N and flooding, in-season root-zone N management with deep placement of urea and sprinkler irrigation can significantly lower N losses (Wu et al. 2017). Thus, considering the effects of CC type and these management practices on NUE, the fate of fertilizer N and N surplus require further study for design of new winter CCs-spring maize rotation.

The objectives of this study were: (1) to determine the influence of CC type on grain yield and total N uptake of spring maize; (2) to use ^{15}N-isotope labeling and tracing techniques to establish the ability of each CC (i) to capture N applied and (ii) to transfer this N to spring maize; (3) to evaluate the influence of CC type on the N surplus of the cropping systems. Two hypotheses were tested:

(1) Compared with the fallow treatment, sole leguminous CC and CC mixtures have lower N fertilizer inputs and can slightly improve grain yield of spring maize.
(2) Spring maize with sole leguminous CC and CC mixtures derive more nitrogen from CC than non-leguminous CC and have a higher NUE than the fallow treatment.

Materials and methods

Experimental design and cover-crop management

The field experiment was set up at Quzhou experimental station (36.87°N, 115.02°E) in Hebei province in November 2019. The site is at an altitude of 40 m above sea level and has a temperate monsoon climate. The annual mean temperature is 13.2 °C and the annual mean precipitation was 494 mm (1980 to 2010; range 213–840 mm), with 68% of the annual precipitation falling between June and September (Meng et al. 2012). Precipitation and daily average temperature during the field experiment are shown in Fig. S1 and Fig. S2, respectively. The soil was sandy loam. The soil at 0–20 cm had a bulk density of 1.36 g cm^{-3}, a pH of 7.95, an organic matter content of 6.37 g kg^{-1}, total N concentration of 0.75 g kg^{-1}, Olsen-P of 3.02 mg kg^{-1}and plant-available K (Mc Lean and Watson 1985) of 173 mg kg^{-1}. These values were determined on one composite soil sample across the whole experimental field before the start of the field experiment.

A single-factor experiment was established to determine the effects of CC types. Four types of CCs were tested: (i) a control with no CC (Fal.); (ii) hairy vetch (*Vicia villosa Roth.*) (HV); (iii) February orchid (*Orychophragmus violaceus.*) (OV); (iv) a mixture of hairy vetch (*Vicia villosa Roth.*) and February orchid (*Orychophragmus violaceus.*) (HO). The experiment was a completely randomized design with four replicates in blocks. The surface area of the elementary plot, containing 20 rows for each treatment, was 24 m^2 (6 m×4 m). To avoid plant–plant competition effects between adjacent treatments, only the twelve rows in the middle of the plot were harvested and used for soil measurements.

Species grown as sole crops were sown at densities recommended by cover crop seed companies, breeders, and agricultural advisors. The seeding rate of hairy vetch and February orchid was 60 kg ha^{-1} and 30 kg ha^{-1}, respectively. In mixture, sowing densities were half of the corresponding sole crop density of each species (50% hairy vetch: 50% February orchid). Seeds of both species were mixed before sowing to ensure that they were mixed in the row. Sowing was carried out with a row width of 20 cm and a sowing depth ranging from 1.5 to 2 cm on 22 September 2019. The proportion of each sown species was controlled during the cover crop emergence phase. No fertilizer, irrigation or herbicides were applied to CCs throughout their growing period. On bare soils, only manual weeding was performed.

Preparation and isotope labeling of fertilizer

The microplot experiment was set up within the respective treatments of the large-plot experiment (6×4 m per plot replicated in three blocks) on 21 October 2019. Galvanized metal frames confining an area of 1.0×1.2 m (1.2 m^2) were driven 20 cm into the soil leaving 3 cm above the ground. Six rows of catch crops were covered in each microplot. Each plot had one microplot, and hence there were four replicates for each type of CCs.

The ^{15}N-labeled urea (3.66 atom%^{15}N) was mixed with 1 kg of soil from each ^{15}N microplot and uniformly spread by hand; then the 0~20 cm soil layer was tilled using a shovel to achieve a uniform application of ^{15}N fertilizer. A ^{15}N-labeled urea (3.66 atom%^{15}N) solution was applied as a tracer to all microplots on the soil surface along the crop rows using a pipette. The total application of 10 kg N ha^{-1} was split into two doses applied on 20 March and 27 March 2020, respectively. This was done to maximize crop uptake and minimize leaching of ^{15}N. Weeds emerging in and around the microplot area were killed on several occasions but left on the soil surface. The CC tops in all microplots were harvested by hand-cutting at the soil surface on 4 May 2020 and then returned to the field area of metal frames on 15 May 2020.

Crop planting and fertilization

In the large-plot experiment, all CCs tops were manually returned to the field on 15 May 2020. Then all treatments were planted with spring maize. Before planting, 6-leaf (V6) stage to silking (R1), and R1 to physiological maturity (R6), optimal N rate was calculated by subtracting the measured soil nitrate content in the root zone (0–60 cm from V6 to R1 and 0–90 cm from R1 to R6) from the corresponding N target values (185 and 160 kg ha^{-1} for the two growing periods, respectively). When calculating optimal N rates, to ensure that each plot obtained sufficient N, replicated plots with too high NO_3^-–N were omitted. If the NO_3^-–N in all replication plots exceeded the target N, 30 kg ha^{-1} N fertilizer was applied to ensure normal maize growth. Nitrogen fertilizer for all treatments was applied in the form of urea in split doses, as described in Table 1. Together with the urea, 20 kg ha^{-1} P as superphosphate and 75 kg ha^{-1} K as potassium sulfate were broadcasted and incorporated into the upper 0–30 cm soil layer by rotary tillage before planting. At the V6 and R1 stages, urea was top-dressed by furrow application. The modern staygreen maize hybrid used was Denghai 605. Spring maize was sown on 25 May 2020, with a row spacing of 60 cm and plant spacing of 22.5 cm, ~75,000 plants ha^{-1}. The grains were harvested at the R6 stage when the black layer occurred; the harvest date was November 23 in 2020 for all treatment. Pesticides were applied in case there was a need for managing disease, weeds, and insects during the two growing seasons.

In the microplot experiment, the planting density and field management practice was consistent with the large-plot experiment.

Sampling and analyses

At the end of the growing season (5 May), the aboveground biomass of the CCs was sampled outside the microplots to determine dry matter yield. Here, three 80 cm×100 cm quadrats were collected from each

Table 1 Nitrogen (N)-fertilizer application rate (kg ha^{-1}) in four treatments

Treatment	Total	Before planting	V6	R1
Fal.	272	30	175	67
HV	191	30	161	0
OV	248	45	203	0
HO	197	30	167	0

Fal. fallow-spring maize cropping system, *HV* hairy vetch-spring maize cropping system, *OV* February orchid-spring maize cropping system, *HO* hairy vetch/ February orchid mixture-spring maize cropping system. V6, 6-leaf stage; R1, silking stage plot. In the microplots, all the CC tops were harvested and oven-dried at 40 °C (48 h) to determine dry matter content and then cut into small pieces (ca. 0.5 cm). The pieces were randomly sampled from each microplot to determine the ^{15}N content of CC biomass.

The total N and atom fraction ^{15}N of plant samples were analyzed at UC Davis Stable Isotope Facility, using a PDZ Europa ANCA-GSL elemental analyzer interfaced to a PDZ Europa 20–20 isotope ratio mass spectrometer (Sercon Ltd., Cheshire, UK).

At the R6 stage of spring maize, plants in an area of 5.4 m^2 (3×1.8 m [three rows]) in the middle of each plot were harvested and threshed, and the grains were dried to determine the grain dry matter. At the V6, R2, and R6 stages, three representative adjacent plants from each plot were cut at the soil surface and separated into leaves, stems (leaf sheaths, tassels, husks and either cobs at R6 or ear shoots at R1), and grains (at R6) to determine the aboveground biomass. All plant samples were dried at 70 °C in a forced-draft oven until they reached a constant weight and then weighed to calculate the biomass.

Indicators used to characterize N recovery from fertilizers in the soil-plant system

The recovery rate of the applied ^{15}N enriched fertilizer, RF (%), in the above- or belowground biomass of a CC was calculated as follows (Li et al. 2015):

$$\mathrm{RF}\ (\%) = \left[\left(\frac{\mathrm{EA\ of\ CC}}{\mathrm{EA\ of\ fertilizer}}\right) \times \mathrm{CC}-\mathrm{N/fertilizer\ N}\right] \times 100 \quad (1)$$

where EA is the excess atom fraction ^{15}N of a sample; CC-N is the total N uptake in aboveground biomass or roots (kg N ha^{-1}) and the fertilizer N was 10 kg N ha^{-1}.

The N fixation by CCs was calculated by referring the EA of the OV. Therefore, the percentage of N in CC derived from the atmosphere, Ndfa (%), was calculated using the following equation (Huss-Danell and Chaia 2005):

$$\mathrm{Ndfa}\ (\%) = \left[1-\left(\frac{\mathrm{EA\ of\ CC}}{\mathrm{mean\ EA\ of\ non}-\mathrm{CC}}\right)\right] \times 100 \quad (2)$$

and the amount of biologically fixed N allocated in CC aboveground biomass or roots, N fixation (kg N ha^{-1}), was:

$$\mathrm{N\ fixation} = \mathrm{Ndfa}\ (\%)/100 \times \mathrm{CC}-\mathrm{N} \quad (3)$$

The amount of plant N derived from the soil N pool, Nds (kg N ha^{-1}) represents the ability of a CC to uptake N from the soil. The Nds included N taken up from both the applied ^{15}N fertilizer and the native soil N pool. Thus, Nds of the non-CC was identical to the total N uptake, while for CCs it was calculated as:

$$\mathrm{Nds} = \left[1\text{–}\mathrm{Ndfa}\ (\%)/100\right] \times \mathrm{CC}-\mathrm{N} \quad (4)$$

Calculation of N surplus and NUE

For N input, six indicators were considered: N from fertilizer and irrigation, atmospheric deposition, non-biological fixation, and seeds.

N fertilizer (urea- 46% N) application is shown in Table 1. The amount of irrigation water (1.35 mg L^{-1}) was 269.6 mm in all cropping systems.

Atmospheric N deposition (dry and wet): This refers to the process of gaseous and particulate N components transported from air to the surfaces of aquatic and terrestrial landscapes (Anderson and Downing 2006). The samples of atmospheric N deposition were collected by an APS-II sampler, and then measured in the lab. During the whole growth period, the atmospheric N deposition was 60.9 kg N ha^{-1}.

Non-biological fixation: For nonlegume crops, the value ranges from 4.5 to 20 kg ha^{-1} yr^{-1} (Bouwman et al. 2005). In this study, we used a value of 15 kg ha^{-1} yr^{-1} for non-biological fixation (Liu et al. 2008b).

Seeds The maize and CCs samples were collected and weighed. The N content was analyzed by an elemental analyzer (Flash 2000; Thermo, Waltham, MA, USA). N input from seeds was calculated according to the sowing amount (kg ha^{-1}) and N content (g kg^{-1}).

N output includes the N harvested in cereal grain. Maize was harvested, and the grain was separated from the straw. Crop N uptake by maize was calculated according to the grain/straw yield (kg ha^{-1}) and N content (g kg^{-1}).

N surplus and NUE were calculated as follows (Zhang et al. 2019):

$$N_{sur} = N_{fer} + N_{see} + N_{irr} + N_{dep} + N_{fix} - N_{har} \quad (5)$$

$$NUE = N_{har} / \left(N_{fer} + N_{see} + N_{irr} + N_{dep} + N_{fix}\right) \quad (6)$$

where N_{sur} and NUE are N surplus and N use efficiency, respectively; N_{fer}, N_{see}, N_{irr}, N_{dep}, and N_{fix} represent the N input from fertilization, seed, irrigation, atmospheric deposition and non-symbiotic N fixation, respectively; and N_{har} is the N in harvested grain.

Statistical analyses

After verifying the homogeneity of error variances, analysis of variance (ANOVA) was performed using SAS software (ver. 6.12; SAS Institute, Cary, NC, USA). A one-way ANOVA model was used to assess the overall variability in grain yield, plant N uptake, the amount ($N_{plant\text{-}residue}$) and the proportion of N derived from residues, N surplus. Differences were compared using the least-significant difference (*LSD*) test at the 0.05 probability level in SAS.

Results

Dry matter and N uptake of cover crop yields

The treatments with hairy vetch (HV and HO) tended to produce more biomass than OV (Table 2). Hairy vetch and hairy vetch/ February orchid mixture had 10.0 and 8.4 t ha^{-1} (tops + roots), which were significantly more than that of the February orchid (7.4 t ha^{-1}). HV and HO had higher N concentrations in both tops and roots than OV, with highest concentrations of 23 mg g^{-1} in the tops of hairy vetch, which were significantly higher than those of OV (Table 2). The treatments with hairy vetch (HV and HO) contained 158–195 kg N ha^{-1} in tops + roots against 88 kg N^{-1} ha for OV (Table 2).

Grain yield and N uptake of spring maize

There were no significant differences in both dry matter of tops and grain yield among treatments. The grain yield with different winter cover crops was 11 ~ 12 t ha^{-1} (Table 3). Compared with the winter fallow, HV and OV significantly increased grain N uptake by 4% and 10%, respectively. OV had the highest N uptake of tops (290 kg N ha^{-1}), which were significantly higher than that of other treatments.

Table 3 Dry matter (DM) of tops, grain yield, grain nitrogen uptake and N uptake of tops of spring maize following different cover crops

Treatment	DM of tops (t ha^{-1})	Grain yield (t ha^{-1})	Grain N uptake (kg N ha^{-1})	N uptake of tops (kg ha^{-1})
Fal.	21 a	11 a	190 a	264 b
HV	21 a	12 a	199 a	273 b
OV	22 a	12 a	209 a	290 a
HO	20 a	12 a	182 a	258 b

Fal. fallow-spring maize cropping system, *HV* hairy vetch-spring maize cropping system, *OV* February orchid-spring maize cropping system, *HO* hairy vetch/ February orchid mixture-spring maize cropping system. Different letters indicate significant differences among treatments ($P<0.05$) (*LSD* test)

Table 2 Dry matter, nitrogen (N) concentration and N uptake in cover crop tops and root (0–20 cm) in large plots

Treatment	Dry matter (t ha^{-1})			N concentration (mg g^{-1})		N uptake (kg N ha^{-1})	
	Top	Expected Root[a]	Total	Top	Root	Top	Expected Root
HV	7.1 a	2.9 a	10.0 a	23 a	10 b	166 a	29 b
OV	4.2 c	3.2 c	7.4 b	10 b	12 a	50 b	38 a
HO	5.7 b	2.7 b	8.4 ab	23 a	10 b	130 a	28 b

HV hairy vetch-spring maize cropping system, *OV* February orchid-spring maize cropping system, *HO* hairy vetch/ February orchid mixture-spring maize cropping system. Different letters indicate significant differences among treatments ($P<0.05$) (*LSD* test)

[a]The DM and N uptake of Expected Root is calculated by the root to shoot ratio (Zhou et al. 2011)

Table 4 Dry matter (DM), nitrogen (N) concentration and N uptake in cover crop tops and root (0–20 cm) in microplots

Treatment	Dry matter (t ha^{-1})			N concentration (mg g^{-1})		N uptake (kg N ha^{-1})	
	Top	Expected Root[a]	Total	Top	Root	Top	Expected Root
HV	6.6 a	2.7 a	9.3 a	23 a	10 b	153 a	27 b
OV	4.3 c	3.4 c	7.7 b	10 b	12 a	43 b	39 a
HO	6.2 b	3.1 b	9.3 a	23 a	10 b	143 a	32 b

HV hairy vetch-spring maize cropping system, *OV* February orchid-spring maize cropping system, *HO* hairy vetch/ February orchid mixture-spring maize cropping system. Different letters indicate significant differences among treatments (P<0.05) (*LSD* test)

[a]The DM and N uptake of Expected Root is calculated by the root to shoot ratio (Zhou et al. 2011)

Table 5 Differentiation of nitrogen (N) sources among biological N fixation and soil N uptake (including the applied ^{15}N-enriched urea) and recovery rate of ^{15}N in cover crops in the microplots

Treatment	Atom fraction ^{15}N (%)	Ndfa[a] (%)	N fixation (kg ha^{-1})	Nds[b] (kg ha^{-1})	RF[c] (%)
HV	0.7 b	78 b	119 a	34 b	29 a
OV	2.1 a	–	–	43 a	38 a
HO	0.8 b	88 a	110 a	32 b	34 a

HV hairy vetch-spring maize cropping system, *OV* February orchid-spring maize cropping system, *HO* hairy vetch/ February orchid mixture-spring maize cropping system. Different letters indicate significant differences among treatments (P<0.05) (*LSD* test)

[a]Ndfa is the percentage of N derived from the atmosphere in legume-based cover crops

[b]Nds is the amount of N derived from the soil (including the small amount of ^{15}N-enriched urea applied as a tracer)

[c]RF is the recovery rate of ^{15}N labeled fertilizer applied to cover crop

N recovery from fertilizers in the soil-plant system

In the ^{15}N microplots, the biomass of winter cover crops was 4.3 ~ 6.6 t ha^{-1}, N uptake was 43 ~ 153 kg ha^{-1} (Table 4). There was no significant difference in the biomass and N uptake of spring maize among the treatments incorporated with the aboveground residues of different winter cover crops.

The N fixation by CCs was calculated by referring the EA of the OV (non-legume cover crop). The result showed that the percentage of N derived from the atmosphere was 78 ~ 88% and the biological N fixation of legume cover crops was 110 ~ 119 kg ha^{-1} (Table 5). The recovery rate of ^{15}N fertilizer in all winter cover crops ranged from 29 to 38%, with no significant difference among treatments. The amount of N derived from the soil of HV and HO was 32–34 kg ha^{-1}, which was significantly lower than that of non-legume cover crop (February orchid: 43 kg/ha) (Table 5).

The total contribution to the N uptake of spring maize from the aboveground residues of hairy vetch and the mixture of hairy vetch and February orchid were 10.3% and 9.7% (Fig. 1a), respectively, which was 4.7 and 4.4 times as much as that of February orchid treatment, respectively, and the spring maize N derived from the residues was 27 and 22 kg ha^{-1}, respectively (Fig. 1b).

N surplus and N use efficiency

Here, we summarize the N inputs and outputs in the soil-plant system to calculate N surplus for the four cropping systems. Apart from fertilizer N, N from seed, irrigation, atmospheric deposition and non-biological fixation are also sources of N inputs. In the one-year rotation cycle, a highest N surplus (167 kg N ha^{-1}) was calculated in fallow-spring maize cropping system, while newly designed cropping systems significantly reduced them to 78, 127 and 102 kg N ha^{-1} in hairy vetch-spring maize cropping system (HO-M), February orchid-spring maize cropping system (OV-M) and hairy vetch/ February orchid mixture-spring maize cropping system (HV-M), respectively (Table 6). N use efficiency of different cover crop treatments were 64 ~ 72%, which were significantly higher than that of the fallow treatment (53%).

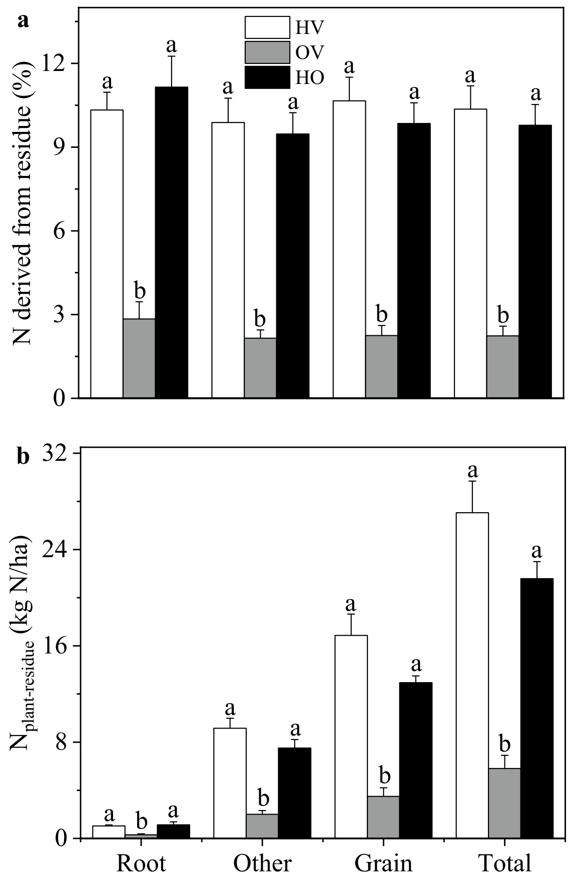

Fig. 1 **a** The proportion of N derived from residues (Ndfr) and **b** the amount ($N_{plant\text{-}residue}$) of nitrogen (N) derived from residues (Ndfr) of three cover crop tops in various parts of spring maize at maturity –grains, straw+husks+cobs (other), and roots (0–30 cm soil layer) in the microplots. Different letters indicate significant differences among cover crop roots/ grains/ others, respectively (P<0.05) (*LSD* test)

Discussion

Dry matter and N uptake of cover crop yields

Cover crops reduce soil mineral N residues and leaching losses, thereby sequestering N and making it available to subsequent crops, which have a positive relationship with the amounts of biomass accumulation and N absorption of CCs (Rinnofner et al. 2008). Previous research on the North China Plain showed that the biomass of OV ranged from 0.6 to 5.1 t ha^{-1}, the N concentration ranged from 1.5 to 2.9%, and the N absorption ranged from 9 to 145 kg ha^{-1} (Liu et al. 2015; Bai et al. 2018; Qin et al. 2015; Zhao et al. 2013). Therefore, compared with the results of studies with the same or similar sowing dates, the dry matter accumulation of OV in this study was higher but the N concentration and N absorption were lower. The preliminary analysis may be related to irrigation management and lower soil fertility. There are relatively few studies on HV on the North China Plain. Zhao et al. (2013) have found that the dry weight of HV was 3.4 t ha^{-1}, and the N absorption was 136 kg ha^{-1} at similar sowing date. The corresponding results of HV in this study are higher, which may be due to the difference in climate. For this experiment, the location was further south on the North China Plain with higher temperatures, which was more conducive for plant growth and allowed CC to take up more N and accumulate more biomass.

Grain yield and N uptake of spring maize

The spring maize had lower N fertilizer input and higher grain yield in the newly designed cropping

Table 6 Nitrogen surplus and nitrogen use efficiency (NUE) of different winter cover crops-spring maize rotation cropping systems

Treatment	N input		N harvest	N surpluses	NUE (%)
	fertilizer N	other N[a]			
Fal.	272	85	190 a	167 a	53 b
HV	191	85	199 a	78 c	72 a
OV	248	85	209 a	127 b	62 a
HO	197	85	182 a	102 c	64 a

Fal. fallow-spring maize cropping system, *HV* hairy vetch-spring maize cropping system, *OV* February orchid-spring maize cropping system, *HO* hairy vetch/ February orchid mixture-spring maize cropping system. Different letters indicate significant differences among treatments (P<0.05) (*LSD* test)

The unit for all the numbers except NUE is kg N ha^{-1}

[a]Including N inputs from seed, irrigation, atmospheric deposition and non-biological N fixation

[b]NUE = N harvest/N input × 100%.

systems than those in fallow treatment (Tables 1 and 3). This could be explained by a better synchronization between crop N demand and N supply as a consequence of soil testing and the use of estimated N fertilizer rates based on target N values at the critical growth stages (Meng et al. 2012), and also an additional N supply from CCs to maize (Zhang et al. 2022).

Hairy vetch (leguminous) and February orchid (non-leguminous) are two common winter cover crops which have been applied in the fallow period before planting main crops in China. Many previous studies showed that planting Hairy vetch and February orchid could increase the nutrient uptake and yield of subsequent crops (Bai et al. 2015; Wang et al. 2021). In long-term experiments of southern rice regions of Hunan and Jiangxi provinces in China, the application of green manure decreased chemical fertilizer requirements by 20 ~ 40%, while maintaining relatively high and stable grain yields (Xie et al. 2016; Zhou et al. 2019). In Hebei province on the North China Plain, compared with conventional fertilization, combining long-term planting of cover crops with 70% conventional N fertilizer has been reported to increase maize yield and N uptake (Bai et al. 2015).

In our study, CCs decreased the input of N fertilizer by 9 ~ 30% (Table 1) and resulted in a slightly increased grain yield of spring maize compared with the fallow treatment (Table 3). Compared with the same N fertilizer input of different CC treatment in previous studies, we considered the residual effect of CCs to the maize and further decreased the fertilizer N inputs, which will provide solutions to improve nitrogen use efficiency. But the benefit of increasing grain yield needs to be further tested through long-term experiments because of the soil properties can't be altered in short term.

Nitrogen recovery from fertilizers in the soil-crop system

The percentage of N derived from the atmosphere in legume-based cover crops (Ndfa) of HO was greater than that of sole HV (Table 5) which is consistent with the results of previous studies (Schipanski and Drinkwater 2012; Carlsson and Huss-Danell 2003; Rasmussen et al. 2012). The reason is that in the mixed treatment, the OV competed with HV for N uptake in the soil which in turn promoted the N-fixing ability of the symbiotic N-fixing rhizobia of HV (Rasmussen et al. 2012). Previous studies have shown that compared with leguminous CCs, cruciferous CCs can reduce N leaching losses more effectively (Tonitto et al. 2006; Askegaard and Eriksen 2007). The Nds of the cruciferous CC (OV) was greater than that of the leguminous CC (HV,) which means the N source provided by cruciferous CC could be more easily absorbed.

Fertilizer N is continually cascading through the soil-crop system. To avoid excessive N fertilization, we should recognize the fate of fertilizer N to understand the long-term effects of N fertilization on agronomic and environmental benefits. Previous studies have shown that fertilizer N recovery by the second crops is less than 10%, and large amounts of N transfers other forms and discharge to environment (Leip et al. 2011; Zhang et al. 2021a, b). Combining cover crop return and the use of estimated N fertilizer rates based on target N values at the critical growth stages has the potential to lower N losses. In this study, the total recovery amount of residual N in spring maize under the winter leguminous CCs treatments had a relatively higher recovery (9.7 ~ 10.3%) than that of winter non-leguminous CC treatment (2.2%), which explained the lower N input for spring maize in the winter leguminous CCs treatments. In addition, maximizing BNF of leguminous CCs will further reduce the input of inorganic N fertilizers. How to improve the BNF efficiency through agricultural management and technological innovations, and further realize fertilizer saving and stable yield is an issue that needs to be further studied in the future (Zhao et al. 2022).

N surplus and N use efficiency

There is no accepted and universally applied protocol for establishing soil surface balances and the N input items considered differ therefore between studies. For the soil surface N balance approach, N outputs are usually easy to obtain from grain and N concentration determinations. Nitrogen inputs include many items, including fertilizer, seed, irrigation, deposition, non-biological fixation etc. In usual, crucifers provide less green manure service than legumes due to their higher C:N ratio (range = 15 ~ 25), which induces slower mineralization of the cover crop residues after their incorporation into the soil compared with legumes (lower C:N ratio: range = 10 ~ 15) (Justes et al.

2009; Tonitto et al. 2006). That's why the CC-spring maize with leguminous CC had the lower N input than non-leguminous CC treatment (Table 6).

Cover-crop mixtures composed of legume and non-legume species could provide both catch crop and green manure services simultaneously by combining advantages of both sole crop species (Tosti et al. 2014; Tribouillois et al. 2016). Non-optimal crucifer density may lead to high competition with legumes and a non-optimal N green manure service. In our experiment, each mixture was sown with a 50%–50% density compared to those of its component in sole crop. We observed that mixtures and sole leguminous CC provided the higher level of nitrate catch crop service and green manure service than sole non-leguminous CC, which suggests that legume density should be increased in mixtures to improve NUE of the whole cropping system.

Conclusions

The results of this study emphasize that the nitrogen use efficiency of the CCs-spring maize rotation system were greater than those of the sole spring maize cropping system because of the residual effect of cover crop returns on the North China Plain. To summarize, the introduction of the legume cover crop hairy vetch, either sown alone or in a mixture with February orchid, in the rotation system of three crops across two years on the North China Plain had a better N-saving potential, and a lower N surplus, and a greater contribution to the N nutrition of the subsequent spring maize. We conclude that hairy vetch-spring maize cropping system and hairy vetch/ February orchid mixture-spring maize cropping system embedded to optimized N management (estimate N fertilizer rates based on target N values at the critical growth stages) offer viable alternative cropping systems for sustainable crop production in this intensive agricultural region.

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Declarations

Competing interests The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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