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Appropriate dense planting with nitrogen fertilisation increased maize grain yield and soil organic carbon

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Abstract

Soil organic carbon (SOC) fractions and soil enzyme activities were effective indicators to represent C changes under different plant densities (PD) and nitrogen (N) application levels, which influenced crop yield in turn. The aim of the experiment was to investigate the impact of PD and N application levels on soil productivity. The experiment conducted in the North China Plain included three plant densities: 1) PD1 – 60,000 plants ha^{-1}, 2) PD2 – 67,500 plants ha^{-1}, and 3) PD3 – 75,000 plants ha^{-1}, and three N application levels: 1) N0 – 0 kg ha^{-1} N, 2) N1 – 220 kg ha^{-1} N, and 3) N2 – 290 kg ha^{-1} N. Maize (*Zea mays* L.) grain yield was higher when N was applied at the N1 and N2 application levels each year. Obviously, the grain yield and its components at the N1 and N2 application levels showed no difference at each PD, and *vice versa*. Plant densities and N fertilisation rates significantly affected the content of SOC, microbial biomass C (MBC), and dissolved organic C (DOC). Ranged from 1.85 to 1.98 mg d g^{-1}, the sucrase activity was larger in the treatment with a high PD and N fertilisation rate. Higher PD yielded the increase of grain yield (GY) by 19.38%, while the kernel number per ear (KN) and the 1,000-kernel weight (TKW) were decreased by 7.81% and 9.03%, respectively. In addition, the grain yield and yield components were dramatically increased at the N2 application level. The SOC content and its fractions and the sucrase activity were also increased with the PD and N fertilisation rate.

These results indicated that the optimum PD and N fertilisation rates were benefits for increasing the grain yield and soil C storage. Considering both soil parameters and grain yield, the PD of 75,000 plants ha^{-1} and the N fertilisation rate of 220 kg ha^{-1} N were benefits for crop production and soil sustainability.

Keywords: crop productivity, soil carbon fraction, sampling date, *Zea mays*.

Introduction

Appropriate planting density and fertilisation rate are vital for securing a high crop yield and soil carbon (C) accumulation (Xu et al., 2017; Zhao et al., 2021; Roussis et al., 2022). Plant density (PD), an effective agronomic strategy in increasing maize (*Zea mays* L.) yield, ranged largely among regions and seemed too low. The optimum PD was in a range of 35,900–46,600 plants ha^{-1} in dry areas, while in a range of 57,900–78,600 plants ha^{-1} in a wet area (Tokatlidis et al., 2011). However, a process-based model “hybrid-maize” indicated that the optimal PD could be more than 80,000 plants ha^{-1} (Liu et al., 2021). Generally, increases in PD would promote the allocation of organic C in soil, which in turn affected the nitrogen (N) transportation and absorption (Han et al., 2020). Nitrogen, an essential nutrient required for crop growth and grain yield (GY), is often applied in the chemical or organic form to soil. It is reported that a high maize GY can be realised by improving N fertiliser management (Xu et al., 2017). However, inappropriate N application level is a threat to maize yield, which also increased environmental costs (Chen et al., 2014). If overused, N leaching and lower GY would appear (Tang et al., 2021).

Changes in PD and N application level would affect the potential turnover rates of soil C and N, soil microorganisms being an important driving force (Li et al., 2020). It has been shown that N availability was associated with soil organic C (SOC) and microbial biomass carbon (MBC) (Li et al., 2018), which would affect soil enzyme activity in turn (Chen et al., 2021). Enzymes secreted by soil microorganisms are the catalyst for all biochemical reactions in soil (Kanté et al., 2021), conducive to soil fertility and GY (Asghar, Kataoka, 2022). Nitrogen fertilisation might decrease MBC content (Zang et al., 2016) and affect GY in turn. Therefore, a study of responses of soil C and related enzyme activity

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and their relationships to PD and N application level is needed.

We hypothesised that decreased N application level and increased PD would increase maize GY and promote SOC accumulation. To test this hypothesis, the effect of PD and N application level on GY, SOC, and sucrase activity was determined. The results of present experiment will provide technical support for high-efficiency agricultural management in the experimental area.

Material and methods

Experimental site description. The field experiment established in June 2018 was conducted in Xunxian County (114°40′ E, 34°40′ N; 72.3 m a. s. l.), Henan Province, the North China Plain. In the experimental area, the main crop was winter wheat (*Triticum aestivum* L.) → summer maize (*Zea mays* L.) rotation. The experimental field is in a warm, semi-humid region with an annual mean temperature of 13.7°C and a frost-free period of 220 days. The average annual rainfall is 647.8 mm and tended to be concentrated in summer, which is sufficient to meet the water demand of maize. The average rainfall and temperature each month across maize growing season in 2020 and 2021 are listed in Table 1. The soil is classified as *Fluvo-Aquic* (according to the Chinese Soil Taxonomic Classification) with 7.88 pH. It is a typical soil in this given region with a profile of sandy loams with a texture of 65% sand, 25% silt, and 10% clay. Before the experiment started in 2018, the basic properties of the topsoil (0–20 cm) layer were listed: soil organic carbon (SOC) 10.5 g kg^{-1}, total nitrogen (N) 1.1 g kg^{-1}, available phosphorous (P_2O_5) 15.9 mg kg^{-1}, and available potassium (K_2O) 109.1 mg kg^{-1}.

Experimental design and management. The experimental field was cultivated with a winter wheat–summer maize cropping system for more than 50 years before this experiment started. All the treatments of the field trail were laid out in a randomised complete block design, and the size of each plot was 30 m^2 (5 × 6 m). All treatments had alternating wide-narrow spacings (a wide row was 60 cm, and a narrow row was 40 cm). A 50 cm wide buffer plot was arranged between each plot to prevent N transporting from the neighbouring treatment to another. In this experiment, the summer maize was grown under the contrasting N and PD design. Maize seeds were sown manually at three densities: 1) 60,000 plants ha^{-1} (D1), 2) 67,500 plants ha^{-1} (D2), and 3) 75,000 plants ha^{-1} (D3). Nitrogen was applied at three levels: 1) 0 kg ha^{-1} N (N0), 2) 220 kg ha^{-1} N (N1), 3), and 290 kg ha^{-1} N (N2). As basal fertilisers, calcium superphosphate ($CaH_4P_2O_8$) and potassium sulphate (K_2SO_4) were applied to each plot to provide 90 kg ha^{-1} phosphorus (P) and 120 kg ha^{-1} potassium (K), respectively. Urea was applied as N fertiliser at a ratio of 4:3:3 for the stages of before planting, jointing stage, and silking stage, respectively. The basal fertiliser applied before planting was evenly applied on the formed land when sowing maize seeds. As experimental material, the summer maize cultivar ‘Xundan 20’ (plant height approximately 273 cm) was used, bought from Henan Agricultural High-Tech Group Co. Ltd. The ‘Xundan 20’ is lodging-susceptible, its parental lines were ‘Xun9058’ and ‘Xun928’. The hybrid was classified into the main heterotic group of Reid × Tang-SPT. The summer maize seeds were sown on 11 June 2020 and 12 June 2021, and harvested on 1 October 2020 and 2 October 2021 during two experimental years, respectively. In each plot, maize was irrigated according to the precipitation each year. Sufficient water was applied to prevent water stress. Flood irrigation of approximately 60 mm was applied to each plot one week before sowing, and a further 50 mm flood irrigation was applied at the later jointing stage after fertilisation. To assure that no factors other than PD and N supply affect maize growth during both years, both herbicides and pesticides were applied to inhibit weeds and insects during the entire growing season. All the above-ground biomass was cut and removed from the field, then the maize roots were also removed before ploughing.

Table 1. The average rainfall and temperature each month during the maize growing season in the experimental years

	Year	June	July	August	September	October
Rainfall mm	2020	66.0	149.8	127.0	61.4	33.2
	2021	70.0	146.7	128.0	60.1	33.0
Temperature °C	2020	26.0	26.0	26.0	22.0	14.0
	2021	27.0	27.0	25.0	21.5	13.5

Soil sampling and analysis. Soil samples were collected from the topsoil (0–20 cm) layer after the maize harvest in October of each year. The composite soil samples were physically formed by five soil cores of each plot. All visible residues were clearly removed from the composite samples, and all the fresh samples were separated into two sets. One set was air-dried in the shade at room temperature and sieved through a 2-mm mesh screen. To determine the SOC content, the 2-mm screened soil samples were further meshed to pass through a 0.15-mm screen. The other set was immediately stored at 4°C in the laboratory until the samples were measured for soil microbial biomass carbon (MBC) and dissolved organic carbon (DOC) content, and sucrase activity.

To determine the SOC content in each soil sample, the Mebius (1960) dichromate oxidation method was used; the MBC content was determined according to Wu et al. (1990). Namely, six fresh soil subsamples equivalent to 20 g air-dried soil for each soil sample were fumigated in a vacuum chamber at 25°C for 24 h. The C of each sample was extracted from the fumigated and non-fumigated samples with 80 mL 0.5 mol L^{-1} K_2SO_4 solution for 1 h. Then, the filtered extracts of each subsample were analysed using a TOC analyser (Analytik Jena GmbH, Germany). Differently, DOC was extracted from a 10 g fresh soil sample with 50 mL 0.5 mol L^{-1} K_2SO_4 at 25°C. The mixture was shaken for 1 h at 220 r min^{-1} and filtered with a 0.45 µm membrane filter (Jones, Willett, 2006). The sucrase activity was determined using the soil samples stored at 4°C by the 3,5-dinitrosalicylic acid colorimetry method (Guan et al., 1986).

Crop yield and yield components. At harvest, grain yield (GY) was determined from each plot by collecting all maize in an area of 10 m^2 in the centre. The GY was assessed according to the average of three replications for each treatment. The dry matter of grain was obtained by drying the samples to a constant weight in an oven at 75°C. Then, 30 ears were selected in each plot and kernels were hand threshed and counted to test the kernel number per ear (KN), and 1000-kernel weight (TKW) was also assessed. The harvest index (HI) of maize was calculated as dry GY divided by the total aboveground biomass at maturity.

Statistical analysis. The effect of PD and N application levels and their interactions on each parameter (GY, KN, TKW, HI, SOC content and its fractions, and sucrase activity) was analysed using analysis of variance (ANOVA). Pairs of the mean values among the treatments were compared using the least significant difference (LSD) at 0.05 probability level. The Spearman correlation coefficient was calculated, and linear regressions were performed using the software SPSS, version 19.0 (IBM Incorp., USA).

Results

Maize grain yield (GY), yield components and harvest index (HI). Maize GY and its components were significantly influenced by sampling year, PD, and N application rate (Table 2).

Overall, the PD, N application level, and sampling year all had a significant effect on GY ($p < 0.001$), though the dyadic interaction of Y × N and the three-way interaction of Y × PD × N for GY were not significant. The GY and HI showed no difference across the sampling years, while KN and TKW were significantly lower in 2021 compared with those in 2020. GY was significantly increased by 19.38% at PD3 over PD1 across the experimental years and N fertilisation rates. No significant difference of GY was recorded between PD1 and PD2. KN showed a decrease trend as PD increased, and the decrease of 7.81% was significant at PD3 compared with PD1. No difference was observed between PD2 and PD3, but both significantly decreased TKW by 8.38% at PD2 and by 9.05% at PD3 compared with PD1 across the years and N fertilisation rates. The HI was significantly decreased by 3.61% at PD2 and by 7.31% at PD3 over PD1, respectively. With an increase in the N fertilisation rate, GY and its components were significantly increased by N fertilisation. No significant difference of GY at the N2 application level was observed when compared to N1 and N2 ones across the sampling years and PD.

Table 2. Maize grain yield (GY), kernel number (KN), 1000-kernel weight (TKW), and harvest index (HI) of different treatments during the experimental years (2020–2021)

Treatment	GY Mg ha^{-1}	KN ear^{-1}	TKW g	HI %
Year (Y)				
2020	10.45 ± 1.53 a	458.96 ± 22.32 a	325.48 ± 28.15 a	52.76 ± 1.93 a
2021	9.92 ± 1.64 a	429.70 ± 54.42 b	302.22 ± 41.47 b	51.87 ± 2.61 a
Plant density (PD)				
PD1	9.34 ± 1.21 b	465.11 ± 38.30 a	333.22 ± 38.81 a	54.29 ± 1.20 a
PD2	10.06 ± 1.37 b	439.11 ± 36.55 ab	305.28 ± 29.89 b	52.33 ± 1.34 b
PD3	11.15 ± 1.68 a	428.78 ± 49.25 b	303.06 ± 35.69 b	50.32 ± 2.27 c
Nitrogen (N) application level				
N0	8.31 ± 0.62 b	401.22 ± 49.23 b	273.33 ± 30.20 b	50.54 ± 2.63 b
N1	11.19 ± 0.97 a	461.89 ± 14.95 a	333.89 ± 18.53 a	53.24 ± 1.58 a
N2	11.04 ± 1.02 a	469.89 ± 18.40 a	334.33 ± 20.24 a	53.16 ± 1.54 a
		Source of variation		
Y	42.51***	128.18***	86.28***	18.01***
PD	167.98***	69.97***	60.10***	122.26***
N	532.39***	281.46***	261.84***	72.70***
Y × PD	3.35*	3.06	9.85***	1.53
Y × N	0.58	113.56***	30.21***	4.39*
PD × N	7.25***	2.61	2.65*	3.32*
Y × PD × N	0.15	3.76*	0.29	4.82**

Note. Error bars indicate the standard deviation; different letters within a year, PD or N application level indicate significant differences at 5% under the same PD in the same year; *, **, *** – significant at 0.05, 0.01, and 0.001, respectively.

The relationships between the N fertilisation rate and GY under different PD were as follows:

$y = -6 \times 10^{-5}x^2 + 0.024x + 7.8$ ($R^2 = 0.889$, $p < 0.01$) for PD1, $y = -7 \times 10^{-5}x^2 + 0.028x + 8.266$ ($R^2 = 0.948$, $p < 0.01$) for PD2, and $y = -8 \times 10^{-5}x^2 + 0.034x + 8.866$ ($R^2 = 0.993$, $p < 0.01$) for PD3, respectively,

where y is GY (Mg ha^{-1}) and x is the N fertilisation rate.

The components of GY showed a consistent trend with GY, and increases of KN, TKW, and HI were 15.12–17.12%, 22.16–22.32%, and 5.34–5.18% over N0 application level, respectively.

Organic carbon fractions in soil. The PD and N fertilisation rate had a significant effect on the SOC content. The dyadic interaction of Y × N and DP × N also had a significant influence on the SOC content (Table 3). No significant difference of the SOC content was observed across years, though the SOC content in 2021 was slightly lower than that in 2020. As PD increased, the SOC content significantly increased by 11.84% at PD2 and 21.50% at PD3 over PD1, respectively. Across the sampling years and PD, the average content of SOC was ranked in an order of 8.36 g kg^{-1} at the N0 < 11.11 g kg^{-1} at the N1 < 11.23 g kg^{-1} at the N2 application levels. No difference of the SOC content was observed at the N1 and N2 application levels.

The sampling year, PD, and N fertilisation rate had a significant effect on the MBC content, while the PD and N fertilisation rate significantly affected the DOC content. The dyadic interaction of Y × N, PD × N, and Y × PD had no significant influence on the content of MBC and DOC. Significant increases of the MBC and DOC content were observed at the N2 and N3 application levels cross the sampling years and PD, though no difference was observed between N2 and N3 ones. The MBC content at the N2 and N3 application levels was 211.14 and 215.42 mg kg^{-1}, respectively, which displayed significant increases of 11.61% and 13.87%, respectively, when compared with N1 one. The DOC content at the N2 and N3 application levels was 25.28 and 26.73 mg kg^{-1}, respectively, which displayed significant increases of 33.12% and 40.76% over N1 one, respectively.

Soil sucrase activity was not affected by a sampling year ($F = 1.77$, $p = 0.19$), while it was significantly influenced by the PD ($F = 82.12$, $p < 0.001$) and N fertilisation rate ($F = 60.57$, $p < 0.001$). The interaction of Y × PD on the soil sucrase activity was also significant ($F = 3.89$, $p = 0.03$). However, the interaction of Y × N fertilisation rate ($F = 0.21$, $p = 0.82$)

Table 3. Soil organic carbon (SOC), microbial biomass carbon (MBC), and dissolved organic carbon (DOC) content in different treatments during the experimental years (2020–2021)

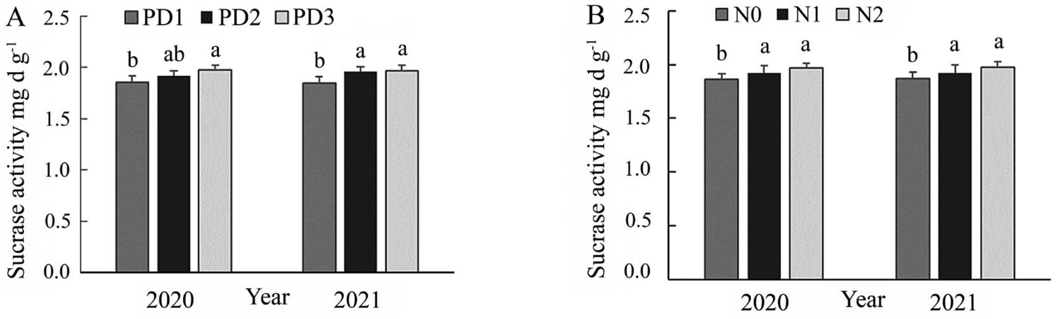
Treatment	SOC g kg^{-1}	MBC mg kg^{-1}	DOC mg kg^{-1}
Year (Y)			
2020	10.56 ± 0.64 a	207.64 ± 16.13 a	23.94 ± 3.32 a
2021	9.90 ± 0.65 a	202.85 ± 13.84 a	24.06 ± 3.37 a
Plant density (PD)			
PD1	9.21 ± 1.08 b	197.82 ± 13.26 b	22.47 ± 2.76 b
PD2	10.30 ± 1.53 a	203.43 ± 11.01 b	24.25 ± 3.39 ab
PD3	11.19 ± 1.74 a	214.49 ± 16.12 a	25.27 ± 3.30 a
Nitrogen (N) application level			
N0	8.36 ± 0.62 b	189.18 ± 7.28 b	19.99 ± 1.21 b
N1	11.11 ± 1.19 a	211.14 ± 9.79 a	25.28 ± 1.73 a
N2	11.23 ± 1.12 a	215.42 ± 11.85 a	26.73 ± 1.76 a
Source of variation			
Y	49.37***	7.03*	0.17
PD	147.81***	29.42***	30.60***
N	395.90***	81.02***	192.15***
Y × PD	1.68*	0.27	0.20
Y × N	0.53	1.02	0.42
PD × N	10.37***	1.26	1.09
Y × PD × N	0.60	0.56	1.52

Note. Error bars indicate the standard deviation; different letters within a year, PD or N application level indicate significant differences at 5% under the same PD in the same year; *, **, *** – significant at 0.05, 0.01, and 0.001, respectively.

and PD × N fertilisation rate ($F = 1.84$, $p = 0.14$), and the three-way interaction of Y × PD × N fertilisation rate ($F = 0.27$, $p = 0.89$) for the sucrase activity were not significant. As is shown in the Figure, it ranged from 1.85 to 1.98 mg d g^{-1}. A lower value of sucrase activity was observed at PD1, and a higher sucrase activity was recorded at PD3 irrespective of a sampling year. Similarly, a lower sucrase activity was recorded at the N0 application level, while N2 one yielded a higher value. The sucrase activity tended to increase with the increasing of PD and N fertilisation rate.

Relationships between GY and soil parameters. Significant correlations were recorded between each indicator (Table 4).

The grain yield was positively related to the content of SOC, MBC, and DOC and the sucrase activity ($p < 0.01$). Similarly, the SOC content was positively related to the MBC and DOC one, and the sucrase activity. The MBC content was significantly correlated with the DOC one ($R = 0.84$, $p < 0.01$) and the sucrase activity ($R = 0.69$, $p < 0.01$). The DOC content was also positively correlated with the sucrase activity ($R = 0.74$, $p < 0.01$).



Note. Error bars depict the standard deviation; the lowercase letter within the same year indicated a significant difference at $p < 0.05$; PD1, PD2, and PD3 were 60,000, 67,500, and 75,000 plants ha^{-1}; N0, N1, and N2 – 0, 220, and 290 kg ha^{-1} N, respectively.

Figure. Soil sucrase activity under different treatments: plant density (PD) (A) and N application level (B) during the experimental years

Table 4. The correlations of each indicator under different treatments during the experimental years (2020–2021)

Indicator	GY	SOC	MBC	DOC
SOC	0.97**			
MBC	0.90**	0.89**		
DOC	0.89**	0.87**	0.84**	
Sucrase activity	0.71**	0.74**	0.69**	0.74**

Carbon: SOC – soil organic, MBC – microbial biomass, DOC – dissolved organic; GY – grain yield; ** – significant at $p < 0.01$

Discussion

Field management could affect soil physical and chemical properties, which plays a vital role in increasing crop GY and promoting soil processes. It has been shown that a high PD would contribute to the increase of maize GY (Xu et al., 2017). Generally, the appropriate PD will correspondingly promote the dry matter accumulation and GY and the suitable increased N fertiliser rates can promote the growth of maize, so as to obtain a higher dry matter accumulation and GY (Asibi et al., 2022). The higher GY can be attributed to a higher KN and TKW. In the present study, GY was higher when maize was planted at 75,000 plants ha^{-1}. However, the KN and

TKW were decreased under a higher PD, in line with the results of Xu et al. (2017). This might be because the competition among plants aggravated when PD increased (Boomsma et al., 2009). Therefore, a negative effect of the competition of plants was offset by the positive effect of high PD.

As another important factor affected the crop yield, the appropriate N fertilisation rate significantly increased the GY. The soil inherent N without extra N fertilisation rate was not enough to provide a large GY. Nitrogen affects the crop GY via influencing KN and TKW. In the present study, GY and its components were significantly increased at the N application levels (N1 220 kg ha^{-1} N and N2 290 kg ha^{-1} N), consistent with the results of Asibi et al. (2022). However, no difference of GY and its components was observed at the N1 and N2 application levels. Xu et al. (2017) also showed that no significant difference of GY and yield components was recorded when N fertilisation rates were 180 and 360 kg ha^{-1} N. It has been reported that the recommended N fertilisation rate was in a range of 200–285 kg ha^{-1} N, which would significantly affect the crop yield and its components (Wang et al., 2018a). This might be due to the threshold effect of N fertilisation confirming the fact that the relationship between the GY and N fertilisation rate was not linear but parabolic curvilinear.

The interaction of N fertilisation rate and PD effectively improved the GY and HI, in line with the results of Asibi et al. (2022). In the present study, a larger GY was recorded at a higher PD and a higher N fertilisation rate. Differently, Shi et al. (2016) showed a higher GY when maize was sown at a higher PD and soil was applied with a lower N fertilisation rate. Moreover, Belete et al. (2018) found that GY was directly related to the N fertilisation rate and the GY was lower in the first year, while Asibi et al. (2022) reported a lower GY in the second year, the main reason being irrigation. However, the results of current experiment showed no difference of GY during two experimental years, which might verify the effect of water, since no difference in the precipitation and irrigation between the two experimental years was recorded.

It has been shown that the N fertilisation could effectively affect the soil C content potentially regulating the crop GY (Sithole et al., 2019). The N application would cause diverse responses among soil C fractions according to their special properties (Song et al., 2014). The SOC content was higher in the treatments of PD3 and N2 application level because the SOC content increased the growth of root and plant biomass, which contributed to a higher GY (Brar et al., 2013). The content of soil C fraction was different from each other in response to the PD and N fertilisation rate. The higher sucrase activity in soil might be probably responsible for the higher MBC and DOC content in the N fertilisation treatments.

Compared with N0 application level, the DOC content was increased after N fertilisation in the two years. As was shown in the previous study (Mao et al., 2020), the N fertilisation had a promoting effect on the DOC content. Crop biomass and soil microorganisms promoted by N fertilisation and PD would accelerate the decomposition of soil organic matter (Brar et al., 2013). The positive correlation between the DOC content and GY reiterated the fact that the crop biomass was positively correlated with the GY (Li et al., 2018). However, the N fertilisation rate had an effect on the DOC content. Namely, when the N fertilisation rate increased at the N1 to N2 application levels, the DOC content would not ascend continuously, in line with the results of Wang et al. (2021). Excess N might have an inhibitory effect on the C-mediated microorganisms (Mao et al., 2020), which affected the increase of DOC content. Additionally, the GY did not benefit from the excess N fertilisation and indicated no increase in biomass and plant residues. Since the DOC content was regulated by N fertilisation, N applied at a medium rate could promote the accumulation of DOC content in soil.

As an important factor of soil fertility, MBC was also influenced by N fertilisation rate and PD (Ma et al., 2020). Generally, the high PD directly increased plant residues in soil and sucrase activity, and the increased PD resulted in a larger MBC in both years in the present study. MBC under the N fertilisation treatment was significantly higher relative to the N0 application level, and MBC was significantly positively correlated with GY. Soil N availability directly regulated MBC and enzyme activity (Li et al., 2018), thus, N fertilisation would not always increase MBC (Wang et al., 2018b). Studies have shown that sucrase activity significantly correlated with N availability (Song et al., 2019) and that a high or low N availability would inhibit soil sucrase activity. Thus, the optimum N fertilisation was benefit for promoting the soil sucrase activity.

Collectively, the results of the current experiment would guide reasonable N fertilisation and PD in agricultural management to increase crop yield and C storage. However, we did not explore the potential mechanism, and further study about the mechanism of optimised PD and N fertilisation to increase C accumulation and GY is required.

Conclusions

1. In the present experiment, the optimum plant density (PD) and N fertilisation rate were 75,000 plants ha^{-1} and 220 kg ha^{-1} N, respectively in the *Fluvo-Aquic* soil in Xunxian County, Henan Province, the North China Plain.

2. The high PD and optimum N fertilisation significantly increased the maize grain yield (GY), which was positively correlated with soil carbon fractions and sucrase activity. The relationships between the N fertilisation rate and GY under different plant densities were as follows: $y = -6 \times 10^{-5}x^2 + 0.024x + 7.8$ ($R^2 = 0.889$, $p < 0.01$) for 60,000 plants ha^{-1}, $y = -7 \times 10^{-5}x^2 + 0.028x + 8.266$ ($R^2 = 0.948$, $p < 0.01$) for 67,500 plants ha^{-1}, and $y = -8 \times 10^{-5}x^2 + 0.034x + 8.866$ ($R^2 = 0.993$, $p < 0.01$) for 75,000 plants ha^{-1}, respectively, where y is GY (Mg ha^{-1}) and x is the N fertilisation rate. Ranged from 1.85 to 1.98 mg d g^{-1}, the sucrase activity was affected by PD and N fertilisation rate.

3. The interaction of PD and N fertilisation rate on the soil C content and GY was significant, which indicated the synergistic effect of PD and N application level.

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