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Depth of nitrogen fertiliser placement affects nitrogen accumulation, translocation and nitrate-nitrogen content in soil of rainfed wheat

W. Duan[a,b], Y. Shi[a,*], J. Zhao[c], Y. Zhang[a], Zh. Yu[a]

[a]*Key Laboratory of Crop Ecophysiology and Farming System, Ministry of Agriculture, Shandong Agricultural University, Tai'an 271018, China.*
[b]*Crop Research Institute, Shandong Academy of Agricultural Sciences, Jinan 250100, China.*
[c]*Agricultural Information Institute, Chinese Academy of Agricultural Sciences, Beijing 100081, China.*
*Corresponding author. E-mail: shiyu2013sdau@163.com

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Abstract

A field experiment was conducted to examine the effects of different depths of nitrogen (N) fertiliser placements on N accumulation, remobilisation and NO_3^--N content in soil of rainfed wheat. Nitrogen was applied on the surface (D_1) and in the 10 cm (D_2), 20 cm (D_3) and 30 cm (D_4) soil layers from 2010 to 2012. Compared with D_1 and D_2, D_3 and D_4 treatments obtained significant higher N distribution amounts in grain and N accumulation amounts at maturity. D_3 and D_4 treatments increased the N accumulation amount of vegetative organs at anthesis and at maturity. D_3 treatment resulted in significantly higher N translocation amounts from vegetative organs to grains compared with D_1 and D_2 treatments and had no significant difference with D_4 treatment. Compared with the D_1 and D_2, D_3 and D_4 treatments obtained significant higher NO_3^--N contents in the 20 cm to 120 cm soil layer at anthesis from 2011 to 2012. However, D_3 treatment showed no significant differences with D_1 and D_2 treatments at maturity in terms of the NO_3^--N contents in the 40 cm to 100 cm soil layer. D_4 treatment produced the highest NO_3^--N contents in the 40 cm to 140 cm soil layer. Grain yield, N uptake efficiency, apparent N recovery efficiency, N agronomic efficiency and N partial factor productivity were significantly increased by D_3 and D_4 treatments. These results suggest that the D_3 treatment facilitates the best wheat production and highest efficiency among all treatments.

Keywords: Nitrogen fertiliser placement; Nitrogen accumulation; Nitrogen translocation; Nitrate-nitrogen content; Grain yield; Rain-fed wheat.

Introduction

Different nitrogen (N) fertiliser placements affect crop yield and N fertiliser efficiency. Direct winter wheat seeding has rapidly become an accepted practice in the Chinook region of the South western Canadian prairies. Banded treatments have lower yields than 10% and 50% seed bed utilisation treatments; the yield of seed-placed treatments significantly increases with increasing N content (McKenzie et al., 2001). Compared with placement of N fertiliser on the soil surface, placement of N fertiliser below the soil surface improves winter wheat growth and grain yield in both years (Melander et al., 2003). Hou and Tsuruta (2003) reported that urea applied by banding increases grain yield by 22.8% compared with urea applied by broadcasting. Apparent fertiliser N recovery is consistently higher with fall- or spring-injected than with winter- or spring-broadcast urea-ammonium nitrate solution. The average grain yield of dryland winter wheat is 8% greater with spring-injected treatment than with spring-broadcast treatment (Schlegel et al., 2003). Deep N fertiliser placement elicits positive effects on the grain yield of wheat. Field studies were conducted for three seasons on a Palouse silt loam to evaluate the effects of broadcast and deep banding of N fertilizer on N uptake, dry matter production and grain yields of winter wheat. The result showed that wheat N uptake, growth and grain yields were consistently higher with band-applied N compared to broadcast N (Cochran et al., 1990). Fertilising with greater N rates applied as a subsurface band (especially if following grain sorghum) may be necessary to maximise the wheat yield potential of no-till systems in the eastern Great Plains (Kelley et al., 2007). In Shaanxi Province of Northwest China, field trials were conducted to determine the outcome of applying ^{15}N-labelled urea to summer maize and winter wheat in Loess soils. The recovery of fertiliser-derived N is considerably lower with surface applications than with mixed treatments and deep-band placements (Rees et al., 1997).

The effect of N fertiliser placement on N accumulation and translocation in plants has produced conflicting results in different environments. Wang et al. (2007) conducted pot experiments and showed that placing fertilizer at one side of the plants could increase nutrient uptake and plants in the patchy fertilizer treatments obtained higher leaf N concentrations than plants in the uniform fertilizer treatments. Zhang et al. (2009) showed that the deep N placement significantly increased total N accumulation in wheat under pot experiments. According to Petersen (2001), the uptake fate of applied N was unaffected by placement geometry for spring wheat. Wuest and Cassman

(1992) conducted a two-year field experiment and found that translocation of N to grain after anthesis from deep placement was higher than that from the shallow placement. Prasertsak et al. (2002) found that the leaves, stalks and roots in the subsurface treatment contained significantly more fertilizer N than the corresponding parts in the surface treatment. A experiment on the effect of N placement on wheat under ridge culture condition with different depth fertilisation were conducted in field by Ai et al. (1997). They concluded that the N accumulation in root and leaf under surface treatment showed a downward trend while those under deep placement showed a upward trend from trefoil stage to jointing stage. The deep N placement increased the N translocation amount after booting stage. In the Loess Plateau, China, the wholly deep dressing of N fertiliser to wheat before sowing could increase N accumulation in plant at various stages as compared with that by split N dressing (Lǚ, 1983). In sandy soil area of eastern Henan province, China, Wang et al. (2006) suggested that ammonium N fertiliser topdressing in deep significantly significantly increased nitrogen accumulation in leaf, stem and grain in wheat. However, on red-brown earth soils in South Australia, Adjetey et al. (1999) conducted both field and greenhouse experiments and showed that N placement at a depth of 15 cm slightly delayed the accessibility of N to the wheat only in the early stages of growth. Large differences in shoot N content observed as a result of placement was only transient and disappeared later in the season. Deep N placement may not be an important strategy for increasing N accumulation over a conventional shallow depth of 3-5 cm in wheat. Similar results were found by Waddell et al. (2006) in a ridge-till system on a Monmouth fine sandy loam in Maryland.

Placement of N fertiliser is crucial in minimising residual soil nitrate, which reduces ammonia volatilisation and nitrous oxide (N_2O) emission. A previous research found that N_2O emissions are higher when urea is applied on the soil surface than when urea is applied in a band below the seed row (Hultgreen and Leduc, 2003). According to Rochette et al. (2009), incorporating urea in bands in a dry acidic soil can increase NH_3 volatilisation compared with broadcasting urea before incorporation. White et al. (2002) found that the N loss by NH_3 volatilisation from surface-broadcast urea is significantly higher than that from deep point-placed urea. Venterea and Stanenas (2008) conducted a modelling study using silt loam from a field experiment and reported no increase in potential N_2O emission production rate with increasing soil depth to 30 cm under aerobic conditions. Drury et al. (2006) found that zone tillage and shallow N placement reduce N_2O

emissions from corn on fine-textured soils under humid conditions. Potential benefits of urea placement in concentrated zones to crop fertiliser use efficiency may enhance N_2O production (Engel et al., 2010).

Many studies showed that N fertiliser placement affects the root distribution at soil layers and delays the root senescence of wheat. Vyn (2008) revealed that N placement is important for root zone optimisation, especially in no-till and strip-till systems. Chassot et al. (2001) showed that the length density of roots increases in the zone enriched by side-banded fertilisers. The root length and weight density of wheat increase with deep placement compared with surface mixing of N fertiliser. The deep placement of N fertiliser under non-irrigation conditions promotes root growth (Sharma and Chauhhary, 1983). Similar results were observed by Shi et al. (2001) and Zhang et al. (2006) in the soil column experiments.

The flat terrain of the North China Plain is ideally suited for crop production and has one of the highest potentials for grain production in China; this terrain can accommodate approximately half the wheat produced in China (Zhang et al., 2009; National Bureau of Statistics of China, 2012). However, this region contains large rain-fed planting areas; for example, approximately 133×10^4 ha of rainfed wheat planting areas is available in Shandong Province (Wang et al., 2003). Deep fertiliser placement is commonly used in rainfed areas because it can effectively increase crop yield and fertiliser efficiency (Li et al., 2009). Spreading the fertiliser on the surface soil with subsequent fertiliser rotary in the soil layer less than 15 cm is the most popular fertiliser placement in the North China Plain. In the current field experiment, we examined the effects of different N fertiliser placements on N accumulation, N remobilisation and NO_3^--N contents in soil. This study aims to provide a theoretical basis for rational N fertiliser management and propose a suitable placement of N fertiliser for rainfed wheat in the North China Plain.

Materials and Methods

Experimental site

The field experiments were conducted in a hilly rainfed area in Bianhe Village (36° 7′ N, 118° 2′ E), Linzi, Shandong Province, China, in the 2010 to 2011 and 2011 to 2012 growth seasons. This village is located near the centre of the Huang-Huai-Hai Plain and the environment is typical and representative of the plain. The area has a warm temperate semi-humid continental monsoon climate. The top 0 cm to 20 cm soil layer of the experimental field contained 12.5 g kg^{-1} organic matter, 1.1 g kg^{-1} total N, 83.7 mg kg^{-1} alkali-hydrolysable N, 27.1 mg kg^{-1} available phosphate and 115.5 mg kg^{-1} available potassium in the 2010 to 2011 growth season. The precipitation amounts at different wheat growth periods are shown in Table 1.

Table 1. Rainfall in the 2010 to 2011 and 2011 to 2012 growth periods of wheat (mm).

Growing seasons	Sowing to pre-winter	Pre-winter to revival	Revival to jointing	Jointing to anthesis	Anthesis to maturity	Total
2010-2011	5.0	0.0	20.0	9.5	71.1	105.6
2011-2012	105.6	12.7	23.2	25.1	11.6	178.2

Experimental design and crop management

In this experiment, the winter wheat Shannong 16 (a wheat cultivar suited for planting in high-fertility rainfed areas in Shandong Province) and Yannong 0428 (another wheat cultivar suited for planting in high-fertility rainfed areas in Shandong Province) were used for the 2010 to 2011 and 2011 to 2012 wheat growth seasons, respectively. With returing maize straw to the field and spreading total P, K fertiliser on the surface soil, we designed four treatments of different N application depths in the two years as follows: applied N on the surface (D_1) and in the 10 cm (D_2), 20 cm (D_3) and 30 cm (D_4) soil layers, respectively. For the D_1 treatment, we spread total N fertiliser on the surface soil. For the D_2, D_3 and D_4 treatments, we adjusted fertiliser tube to 10 cm, 20 cm and 30 cm below surface soil on the vibration subsoiler, respectively. And then vibration subsoiler was used to loosen the subsoil and rotary tillage was immediately by rotary cultivator for all the treatments. Seeding was carried out by common seeder after making surface soil smooth. The operation procedures of the four treatments are presented in Table 2. In 2011-2012, all of the treatments were carried out at the same plot. Each experimental plot was 3 m × 15 m and each treatment was replicated three times in randomised block designs.

Wheat was sown on 4 October 2010 and 3 October 2011 and then harvested on 11 June 2011 and 8 June 2012, respectively. The fertilisers used were urea (contained 46.4% N), calcium triple superphosphate (contained 46% P_2O_5) and potassium sulphate (contained 50% K_2O). In both cropping seasons, 150 kg ha^{-1} P_2O_5 and 150 kg ha^{-1} K_2O were added before sowing with 150 kg ha^{-1} N. Plant density was 225 plants m^{-2} at the four-leaf stage. Irrigation was not provided in both cropping seasons.

Table 2. N fertiliser placements and operation procedure.

N fertiliser placements	Operation procedure
Spreading N fertiliser on surface soil (D_1)	Total N fertiliser spreading→Subsoiling once with the vibration subsoiler→Rotary cultivating two times→Making surface soil smooth→Seeding with common seeder
Applying N fertiliser in the 10 cm soil layer (D_2)	Adjusting the fertiliser tube on the vibration subsoiler to 10 cm below surface soil→Subsoiling and applying N fertiliser simultaneously→Rotary cultivating two times→Making surface soil smooth→Seeding with common seeder
Applying N fertiliser in the 20 cm soil layer (D_3)	Adjusting the fertiliser tube on the vibration subsoiler to 20 cm below surface soil→Subsoiling and applying N fertiliser simultaneously→Rotary cultivating two times→Making surface soil smooth→Seeding with common seeder
Applying N fertilizer in the 30 cm soil layer (D_4)	Adjusting the fertiliser tube on the vibration subsoiler to 30 cm below surface soil→Subsoiling and applying N fertiliser simultaneously→Rotary cultivating two times→Making surface soil smooth→Seeding with common seeder

Variable measurements

Plant samples from two 1 m row segments from each plot were obtained at the key growth stages (i.e., pre-wintering, revival, jointing, anthesis and maturity). Dates of anthesis and maturity were recorded. Anthesis was defined as the period when the anthers of the central spikelets of 50% of spikes in a plot had extruded. Maturity was defined as the period when almost all spikes in a plot showed complete loss of green colour. At anthesis and maturity, plants samples were separated into stems + sheaths, leaves, glumes (spike axis and kernel husks) and grains (only at maturity) (Xu et al., 2005). All plant samples were oven-dried at 70 °C to constant weight to determine the above ground biomass. The plant samples were analysed for N concentration (micro-Kjeldahl) and N content was calculated by multiplying the element concentration by the dry weight according to Papakosta and Gagianas (1991).

In the current study, the various parameters that refer to N accumulation and translocation were calculated as follows (Papakosta and Gagianas, 1991):

N translocation amount = N accumulation amount of the vegetative organs at anthesis - N accumulation amount of the vegetative organs at maturity

N translocation efficiency = (N translocation amount / N accumulation amount of the vegetative organs at anthesis) × 100

Contribution of pre-anthesis N translocation to grain = (N translocation amount / N accumulation amount in grain at maturity) × 100

The following N efficiency parameters were calculated as follows (Delogu et al., 1998; Azam Shah et al., 2009; Baitilwake et al., 2011; Wang et al., 2011):

N utilisation efficiency as the ratio of grain yield to total plant N uptake

N harvest index as the ratio of N in grain to total plant N uptake

N uptake efficiency as the ratio of total plant N uptake to applied N fertiliser rate

Apparent N recovery efficiency as the ratio of (total plant N uptake of D_i - total plant N uptake of no N fertiliser treatment) to applied N fertiliser rate

N agronomic efficiency as the ratio of (yield of D_i - yield of no N fertiliser treatment) to applied N fertiliser rate

N partial factor productivity as the ratio of grain yield to applied N fertiliser rate,

where D_i is the different N fertiliser placements.

Soil samples were extracted in each field plot at anthesis and maturity at 0.20 m intervals from the soil surface to 2.00 m depths from 2011 to 2012. Soil water content was gravimetrically determined on a subsample by drying at 105 °C for 24 h. The remaining sample was stored in a freezer until further analysis. Unfreezed subsamples were extracted with 2 M KCl (20 g soil: 100 mL KCl), centrifuged and then decanted. Nitrate concentration in the extracts was determined using an AA3 Digital Colorimeter (BRAN+LUEBBE, Germany) (Wang et al., 2011).

Grain yield was calculated on 3 m^2 harvest areas in each plot and expressed at 12.5% grain moisture content (Xue et al., 2006).

Statistical analysis

Statistical analysis was performed using SPSS version 13.0 for Windows (SPSS, Chicago, Illinois, USA). All data presented are means over three replicates. Differences between means were analysed by ANOVA. Multiple comparisons were made using the least significant difference test at $P<0.05$ to determine significant effects.

Results

N accumulation amounts at various growth stages

Figure 1 shows the N accumulation amounts at various growth stages in 2010-2011 and 2011-2012. The D_1 treatment significantly increased the N accumulation amount at pre-wintering compared with the other treatments in both 2010 to 2011 and 2011 to 2012. No significant differences in N accumulation amount at revival were observed among the four treatments for cultivar Shannong 16 in 2010 to 2011; meanwhile, the D_1 treatment resulted in the highest N accumulation amount in for cultivar Yannong 0428 2011 to 2012. The D_3 and D_4 treatments slightly increased the N accumulation amount at jointing compared with the D_1 and D_2 treatments in both 2010 to 2011 and 2011 to 2012. The N accumulation amount at anthesis increased from the D_1 treatment to the D_4 treatment for cultivar Shannong 16 in 2010 to 2011; the D_3 and D_4 treatments resulted in significantly higher N accumulation amount compared with the D_1 and D_2 treatments for cultivar Yannong 0428 in 2011 to 2012. In addition, the D_3 and D_4 treatments resulted in significantly higher N accumulation amount at maturity compared with the D_1 and D_2 treatments in both 2010 to 2011 and 2011 to 2012.

N distribution amount and its ratio in different organs at maturity

Table 3 shows the N distribution amount and its ratio in different organs at maturity in 2010-2011 and 2011-2012. The different N fertiliser placements did not affect the N distribution ratio in different organs at maturity for cultivar Shannong 16 in 2010 to 2011. In 2011 to 2012 for cultivar Yannong 0428, the D_1 treatment caused the lowest N distribution ratio in the stem + sheath; the D_3 and D_4 treatments resulted in slightly lower N distribution ratio in the spike + axis and kernel husk than the D_1 and D_2 treatments. No significant differences in the N distribution ratio in the leaves and grain were noted among the four treatments. The D_3 and D_4 treatments resulted in significantly higher N distribution amount in the grain compared with the D_1 and D_2 treatments. No significant differences in the N distribution amount in the other organs were noted among the four treatments in both 2010 to 2011 and 2011 to 2012.

N translocation from vegetative organs to grain

Table 4 shows the N accumulation amount at vegetative organs at anthesis and N translocation amount from vegetative organs to grain after anthesis in 2010-2011 and 2011-2012. The N accumulation amount in the vegetative organs at anthesis slightly increased from the D_1 treatment to the D_4 treatment for cultivar Shannong 16 in 2010 to 2011; the D_3 and D_4 treatments resulted in significantly higher N accumulation amount in the vegetative organs compared with the D_1 and D_2 treatments for cultivar Yannong 0428 in 2011 to 2012. The D_3 and D_4 treatments numerically increased the N accumulation amount of vegetative organs at maturity in both 2010 to 2011 and 2011 to 2012. The D_3 and D_4 treatments resulted in significantly higher N translocation amount compared with the D_1 and D_2 treatments for cultivar Shannong 16 in 2010 to 2011. No significant differences in the N translocation amount were observed between the D_2 and D_4 treatments for cultivar Yannong 0428 in 2011 to 2012; the D_3 treatment resulted in significantly higher N translocation amount compared with the D_1 and D_2 treatments in this growth period. The different N fertiliser placements did not affect the translocation efficiency and contribution proportion in both 2010 to 2011 and 2011 to 2012.

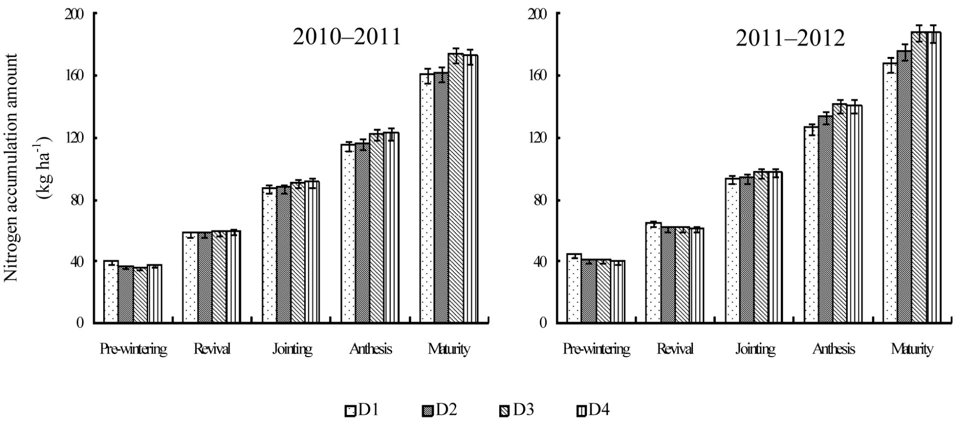

Figure 1. Effects of N fertiliser placements on N accumulation amount at various growth stages of wheat in 2010-2011 and 2011-2012. The cultivar Shannong 16 and Yannong 0248 was used in 2010-2011 and 2011-2012, respectively. D_1, D_2, D_3 and D_4 are applied N fertiliser on the surface, in the 10 cm, 20 cm and 30 cm below the surface soil, respectively.

Table 3. Effects of N fertiliser placements on N distribution at different organs at maturity in wheat.

Year	Cultivar	Treatment	Leaf		Stem+sheath		Spike axis+kernel husk		Grain	
			Amount ($kg\ ha^{-1}$)	Ratio (%)	Amount ($kg\ ha^{-1}$)	Ratio (%)	Amount ($kg\ ha^{-1}$)	Ratio (%)	Amount ($kg\ ha^{-1}$)	Ratio (%)
2010-2011	Shannong 16	D_1	9.15^a	5.72^a	12.57^a	7.86^a	11.76^a	7.36^a	126.36^b	79.06^a
		D_2	8.86^a	5.49^a	12.94^a	8.03^a	11.23^a	6.97^a	128.23^b	79.52^a
		D_3	9.48^a	5.47^a	13.16^a	7.60^a	12.07^a	6.97^a	138.57^a	79.97^a
		D_4	9.39^a	5.45^a	13.60^a	7.89^a	12.14^a	7.05^a	137.19^a	79.61^a
2011-2012	Yannong 0428	D_1	9.20^a	5.50^a	12.71^a	7.60^a	13.80^a	8.25^a	131.56^c	78.65^a
		D_2	8.64^a	4.92^a	11.78^a	6.71^b	14.04^a	8.00^{ab}	141.02^b	80.36^a
		D_3	9.41^a	5.01^a	12.83^a	6.83^b	14.27^a	7.60^b	151.18^a	80.55^a
		D_4	9.32^a	4.98^a	12.95^a	6.92^b	14.84^a	7.93^{ab}	150.05^a	80.17^a

D_1, D_2, D_3 and D_4 are applied N fertiliser on the surface, in the 10 cm, 20 cm and 30 cm below the surface soil, respectively.
Values with different letters within the same column in the same growing season indicate significant difference at the 5% level.

Table 4. Effects of N fertiliser placements on N translocation from vegetative organs to grain after anthesis.

Year	Cultivar	Treatment	N accumulation amount of vegetative organs		N translocation amount	Translocation efficiency	Contribution proportion
			Anthesis	Maturity			
			(kg ha^{-1})	(kg ha^{-1})	(kg ha^{-1})	(%)	(%)
2010-2011	Shannong 16	D_1	114.58^{b}	33.48^{bc}	81.11^{b}	70.78^{a}	64.18^{a}
		D_2	115.62^{ab}	33.03^{c}	82.59^{b}	71.43^{a}	64.43^{a}
		D_3	121.81^{a}	34.71^{ab}	87.10^{a}	71.48^{a}	62.84^{a}
		D_4	122.44^{a}	35.13^{a}	87.31^{a}	71.28^{a}	63.80^{a}
2011-2012	Yannong 0428	D_1	125.67^{c}	35.70^{ab}	89.97^{c}	71.57^{a}	68.43^{a}
		D_2	133.29^{b}	34.46^{b}	98.82^{b}	74.14^{a}	70.09^{a}
		D_3	140.63^{a}	36.50^{a}	104.12^{a}	74.03^{a}	68.90^{a}
		D_4	140.25^{a}	37.11^{a}	103.14^{ab}	73.54^{a}	68.75^{a}

D_1, D_2, D_3 and D_4 are applied N fertiliser on the surface, in the 10 cm, 20 cm and 30 cm below the surface soil, respectively.
Values with different letters within the same column in the same growing season indicate significant difference at the 5% level.

NO_3^--N contents in soil at anthesis and maturity

Figure 2 shows the NO_3^--N contents in the 0-200 cm soil layers at anthesis and maturity for cultivar Yannong 0428 in 2011-2012. The D_3 and D_4 treatments caused significantly lower NO_3^--N content in the 0 cm to 20 cm soil layer at anthesis compared with the D_1 and D_2 treatments; by contrast, the D_3 and D_4 treatments caused significantly higher NO_3^--N content in the 20 cm to 120 cm soil layer compared with the D_1 and D_2 treatments. No significant differences in the NO_3^--N content in the 120 cm to 200 cm soil layer were detected among the four treatments at anthesis. The D_3 and D_4 treatments caused significantly lower NO_3^--N content in the 0 cm to 20 cm soil layer compared with the D_1 and D_2 treatments at maturity. No significant differences in the NO_3^--N content in the 40 cm to 100 cm soil layer were observed at maturity between the D_1 and D_3 treatments or between the D_2 and D_3 treatments. The D_4 treatment significantly increased the NO_3^--N content in the 40 cm to 140 cm soil layer compared with the other treatments.

Grain yield and N utilisation efficiency

Significant differences were observed in grain yield among the different N placements in 2010-2011 and 2011-2012 (Table 5). The D_3 and D_4 treatments caused significantly higher grain yield, N uptake efficiency, apparent N recovery efficiency and N agronomy efficiency compared with the D_1 and D_2 treatments in both 2010 to 2011 and 2011 to 2012. No significant differences in N utilisation efficiency were detected between the four treatments in both 2010 to 2011 and 2011 to 2012. The different N fertiliser placements did not affect the N harvest index for cultivar Shannong 16 in 2010 to 2011. Meanwhile, the D_2, D_3 and D_4 treatments resulted in significantly higher N harvest index compared with the D_1 treatment for cultivar Yannong 0428 in 2011 to 2012. The D_3 and D_4 treatments caused significantly higher N partial factor productivity compared with the D_1 and D_2 treatments for cultivar Shannong 16 in 2010 to 2011. In addition the D_3 and D_4 treatments numerically but not statistically produced more N partial factor productivity than the D_1 or D_2 treatment for cultivar Yannong 0428 in 2011 to 2012.

Table 5. Effects of N fertiliser placements on grain yield and N utilisation efficiency in wheat.

Year	Cultivar	Treatment	Grain yield ($kg\ ha^{-1}$)	N utilisation efficiency ($kg\ kg^{-1}$)	N uptake efficiency ($kg\ kg^{-1}$)	N harvest index	Apparent N recovery efficiency (%)	N agronomy efficiency ($kg\ kg^{-1}$)	N partial factor productivity ($kg\ kg^{-1}$)
2010-2011	Shanong 16	D_1	4322.84^b	27.06^a	1.07^b	0.79^a	28.99^b	7.29^b	28.82^b
		D_2	4318.40^b	26.80^a	1.08^b	0.80^a	29.94^b	7.35^b	28.79^b
		D_3	4659.20^a	26.89^a	1.16^a	0.80^a	37.96^a	9.95^a	31.06^a
		D_4	4641.70^a	26.96^a	1.15^a	0.80^a	37.32^a	9.76^a	30.94^a
2011-2012	Yannong 0428	D_1	6340.54^c	37.92^a	1.12^b	0.79^b	29.47^c	13.68^c	42.27^b
		D_2	6675.59^b	38.06^a	1.17^b	0.80^a	34.95^b	15.91^b	44.50^{ab}
		D_3	7032.95^a	37.48^a	1.25^a	0.81^a	43.09^a	18.30^a	46.89^a
		D_4	7044.35^a	37.64^a	1.25^a	0.80^a	42.73^a	18.37^a	46.96^a

D_1, D_2, D_3 and D_4 are applied N fertiliser on the surface, in the 10 cm, 20 cm and 30 cm below the surface soil, respectively.

Values with different letters within the same column in the same growing season indicate significant difference at the 5% level.

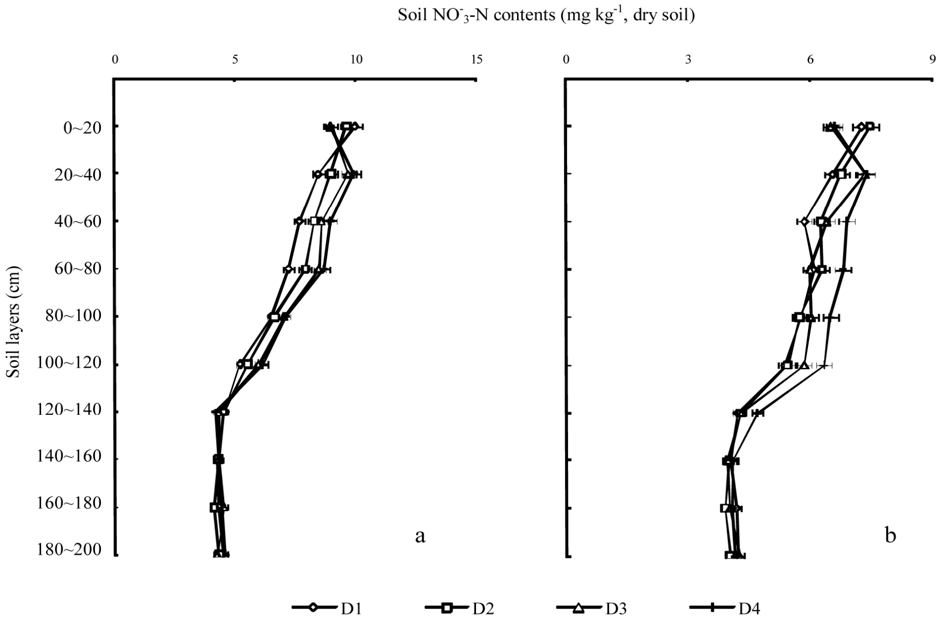

Figure 2. Effects of N fertiliser placements on NO_3^--N content in the 0 cm to 200 cm soil layer at anthesis (a) and at maturity (b) for cultivar Yannong 0428 in 2011 to 2012. D_1, D_2, D_3 and D_4 are applied N fertiliser on the surface, in the 10 cm, 20 cm and 30 cm below the surface soil, respectively.

Discussion

The efficiency of crop N uptake can be increased by improving the placement of N fertiliser in the soil (Zebarth et al., 2009). According to Kelley and Sweeney (2005), plant N uptake responds to better utilisation of subsurface-knifed N than surface-broadcast N. Under no-till systems, the grain N content of wheat is 33% higher with fertiliser banding (8 cm to 10 cm below the soil surface) below the seed row than with surface broadcasting (Rao and Dao, 1996). The application of N fertiliser in the 20 cm to 40 cm subsurface layer using the soil column method promotes the distribution of N in grains (Shi et al., 2001). Compared with the N fertiliser applied in surface soil, the N fertiliser applied in the 25 cm soil layer significantly increased the N accumulation amount of wheat plants and the grain at maturity under ridge-till field conditions. The two treatments show no significant differences in the N distribution ratio of grain N to total plant N. However, Adjetey et al. (1999) conducted a field experiment to examine the effect of depth of urea placement on N uptake in wheat grown on a red-brown soil in Australia. They found minimal advantage in the deep placement compared with the shallow placement. Waddell et al. (2006) conducted a two-year study in a ridge-till system on a Monmouth fine sandy loam in Maryland and found that fertiliser placement does not significantly affect N uptake. In the present study, no significant differences in the N distribution ratio in different vegetative organs were observed among the four treatments at maturity. The placement of N fertiliser in the 20 cm or 30 cm soil layer increased the N accumulation amount in the vegetative organs at anthesis. Such method also promoted N translocation to grains, which increased the N accumulation amount in grains at maturity. The total N accumulation in aerial wheat plants at maturity significantly increased when N fertiliser was applied in the 20 cm or 30 cm soil layer, which consequently increased the N uptake efficiency and apparent N recovery efficiency of wheat.

Siyal et al. (2012) demonstrated that placing N fertiliser on the sides of the furrow near the ridge top or on top of the furrow at the centre of the ridge maximises the retention of N fertiliser within the root zone. Lǚ et al. (1983) found high and small amounts of NO_3^--N in the 0 cm to 130 cm and 130 cm to 200 cm soil layers, respectively, after wheat harvesting with the deep N fertiliser placement before wheat sowing. The deep placement of N fertiliser can decrease NO_3^--N leaching in deep soil layers in the Loess Plateau of China. In the Weibei Tableland of Shaanxi Province, China, the NO_3^--N content in the 0 cm to 60 cm soil layer after wheat harvesting was the highest among the treatments of different N application depths. Moreover, the NO_3^--N content in the 0 cm to 100 cm soil layer with deep N fertiliser placement in the 20 cm soil layer increased by 17.37% compared with that with shallow N placement in the 6 cm soil layer. No significant differences in the NO_3^--N content in soil were observed between the two treatments (Lǚ et al., 2009). In the present study, applying the N fertiliser in the 20 cm soil layer promoted NO_3^--N utilization in the 0 cm to 100 cm soil layer from anthesis to maturity of wheat. However, the NO_3^--N content in the 100 cm to 140 cm soil layer after the second wheat harvesting significantly increased when N fertiliser was applied in the 30 cm soil layer. This result did not promote the NO_3^--N utilisation of wheat in the contemporary growth season.

The effectiveness of deep placement of fertilisers may be determined by soil texture, tillage, crop species and climatic condition (Ma et al., 2008).

Mahler et al. (1994) reported that grain yield and apparent N use efficiency differences that are attributable to N placement are not significant. Edwards et al. (2009) conducted a field experiment in the southern Great Plains and showed that the method of N application has no effect on the grain yield of winter wheat. In the Chinook Region of Southern Alberta, field experiments were conducted for 2 consecutive years. No difference in grain yield exists between fall-banded urea and spring-broadcast ammonium nitrate (Middleton et al., 2004). Petersen and Mortensen (2002) found a positive effect of increased depth for apparent N recovery in a pot experiment; the effects were more pronounced when the parameters were measured in the elongation phase of spring wheat. They also found that the distance from spring wheat row should not exceed 6 cm to 7 cm and that the depth below soil surface should exceed 4 cm to 5 cm to ensure a positive effect of N placement under low precipitation. Lin and Jin (1991) indicated that the agronomic efficiency of urea in wheat experiments is markedly higher when applied with deep placement than that when surface broadcasted. Rees et al. (1997) conducted a field experiment in the south edge of the Loess Plateau in China to study the effect of N fertiliser placement. They found that N recovery is significantly higher when N is applied in 15 cm depth than on the soil surface. In eastern areas of Weibei rainfed highland, China, compared with the conventional fertilisation, the deep fertiliser placement in the 20 cm soil layer before furrow sowing and flat sowing can improve wheat grain yield by 13.2% to 14.4% and by 9.2% to 10.8%, respectively (Fang et al., 2000). Compared with shallow N fertiliser placement, applying N fertiliser in the 20 cm soil layer increases grain yield by 11.95% and improves N fertiliser use efficiency by 7.33% in the Weibei Tableland of Shaanxi Province, China (Lǚ et al., 2009). In the present study, applying N fertiliser in the 20 cm soil layer improved grain yield, apparent N recovery efficiency and N agronomy efficiency by 7.22% to 9.85%, 22.63% to 31.61% and 25.25% to 26.73%, respectively, compared with spreading N fertiliser on surface soil. Deep N fertiliser placement can increase grain yield, apparent N recovery efficiency and N agronomy efficiency in the present experiment.

In the present study, although different cultivars were used between different years, the yield showed a similar changing trend with different N application depths in each year and the D_3 treatment showed the most advantages for yield increase for both cultivars. The long-term effects of N application depth on the same cultivar need to be further studied so as to provide a more reliable basic for the N managements in the said region.

Conclusion

Compared with spreading the N fertiliser in surface soil and applying N fertiliser in the 10 cm soil layer, applying the N fertiliser in the 20 cm soil layer improved the N accumulation amount in vegetative organs at anthesis. This process promoted the translocation of N to grains at maturity and significantly increased the N accumulation amount of aerial plants at maturity. As a result, the N uptake efficiency and apparent N recovery efficiency of wheat were improved. More NO_3^--N was also utilised from anthesis to maturity. The grain yield, apparent N recovery efficiency and N agronomy efficiency were significantly increased when N fertiliser was applied in the 20 cm soil layer. The NO_3^--N content in the 100 cm to 140 cm soil layer significantly increased when N fertiliser was applied in the 30 cm soil layer. Meanwhile, grain yield and N productive efficiency had no significant change. Application of N fertiliser in the 20 cm soil layer was suitable for increasing the yield and N efficiency of rainfed wheat.

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