Effect of timing of additional N fertilization on spike number, grain yield, grain protein and N use efficiency of winter wheat cultivar “Kitahonami”

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A new leading cultivar of winter wheat in Hokkaido “Kitahonami” having a high-yield ability requires a suitable method of additional nitrogen (N) fertilization because it tends to lodge with overexuberant stems and have lower grain protein. Therefore, we compared the timing of additional N fertilization at the booting stage and the panicle formation stage with the aim of avoiding these problems. Additionally, we analyzed the difference of timing of additional N fertilization among the panicle formation stage, flag leaf stage and flowering stage.

Our results showed that additional N fertilization at the panicle formation stage rather than at the booting stage not only suppressed the overexuberance of stems and spikes but also increased the harvest index (HI), grain number per spike and grain protein without decreasing the grain yield. These results suggest that winter wheat cultivars having the tendencies of overexuberant stems and lower grain protein such as “Kitahonami” may prefer additional N fertilization at the panicle formation stage to at the booting stage.

Moreover, from the results of comparing the timing of N fertilization at the panicle formation stage, flag leaf stage and flowering stage, the following features of the response of “Kitahonami” to additional N fertilization timing were clarified: (1) earlier N fertilization tends to increase the risk of lodging through overexuberant stems and spikes, (2) later N fertilization does not tend to result in overexuberant stems and spikes, (3) later N fertilization tends to increase the 1000-grain weight, grain bulk density and grain protein through higher N efficiency.

The above results suggest means of ensuring the effective N fertilization of winter wheat cultivars with the tendency of overexuberance in later growth stages and lower grain protein such as “Kitahonami”.

Key words: grain protein, lodging, spike number, timing of additional N fertilization, winter wheat

INTRODUCTION

Wheat (*Triticum aestivum* L.) is one of the most important arable crops in Hokkaido, covering 120,000 ha, 10% of Hokkaido's total agricultural area (Watanabe 2010). Winter wheat accounts for more than 80% of the wheat cultivated in Hokkaido, which is mainly used for Japanese noodles, and the average grain yield has been approximately 5 Mg ha^{-1}.

The current leading variety, "Kitahonami", which is now grown throughout Hokkaido, has a high-yielding ability, producing 14-20% more grain than the previous leading variety "Hokushin" (Yanagisawa *et al*. 2007; Central Agricultural Experiment Station *et al*. 2008). In addition to its high yield, "Kitahonami" has good resistance to preharvest sprouting, good disease resistance, is suitable for milling and noodle-making and has a low ash content (Yanagisawa *et al*. 2007). Therefore, "Kitahonami" has become the most popular cultivar in Hokkaido.

However, previous experimental results found two major flaws of "Kitahonami" (Central Agricultural Experiment Station *et al*. 2008): (1) its spike number of "Kitahonami" tends to be more than that of "Hokushin" ; over 700 (per m^2) makes "Kitahonami" subject to the risk of lodging. (2) the grain protein tends to be lower than that required for high-quality flour (97-113 mg g^{-1}). In fact, excess additional N fertilization with the aim of increasing both the grain yield and grain protein of "Kitahonami" has caused considerable lodging in many commercial fields in Hokkaido. Therefore, it is essential to find a suitable method of additional N fertilization to avoid lodging and increase the grain protein.

The most common timing of N fertilization is the booting stage (after snowmelt) in the current conventional cultivation of winter wheat in Hokkaido (Suzuki *et al*. 1999; Tsuchiya *et al*. 2001). This is because N fertilization at the booting stage increases the grain yield of winter wheat more effectively than N fertilization at a later stage such as the flag leaf stage or flowering stage (Spratt and Gasser 1970; Shimono 1986; Watanabe 2010). However, too much N fertilization at the booting stage has a risk of inducing lodging as a result of an excessively high spike number (Watanabe 2010). Tsuchiya *et al*. (2001) reported that a split fertilization of N (30 kgN ha^{-1} at the booting stage and 30 kgN ha^{-1} at the panicle formation stage) was useful for mitigating lodging when the overexuberant growth of stems of "Hokushin" occurred. Therefore, for "Kitahonami" , whose spike number is apt to be higher than that of "Hokushin", clarification of the efficacy of N fertilization at the panicle formation stage is essential.

On the other hand, "Kitahonami" requires additional N fertilization after the flag leaf stage to increase the grain protein (Central Agricultural Experiment Station *et al*. 2008), while the detailed features of the fertilization at this stage have still not yet been clarified sufficiently. Additional N fertilization at the flag leaf stage or heading stage tends to increase the grain number per spike and the 1000-grain weight in addition to the grain protein (Watanabe 2010). However, additional N fertilization at the flag leaf stage may also cause lodging when the wheat has overexuberant stems (Tsuchiya *et al*. 2001).

Foliar N application at the flowering stage is another technique of increasing the grain protein (Bly and Woodard 2003), but there has been no thorough comparison between N fertilization at the flag leaf stage and flowering stage.

Therefore, to find a suitable method of additional

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N fertilization for the winter wheat cultivar "Kitahonami", we compared the timing of additional N fertilization between the booting stage and panicle formation stage in terms of the spike number, grain yield, grain protein, and so forth. Moreover, we analyzed the difference between the effects of additional N fertilization among the panicle formation stage, flag leaf stage and flowering stage in terms of the spike number, grain yield, grain protein, N efficiency and so forth.

MATERIALS AND METHODS

Experimental Fields

In the eastern part of Hokkaido (Okhotsk area and Tokachi area), more than 100 field experiments were conducted from 2005 to 2008 as part of this study, as described in Tables 1-4. The studied fields consisted of several soil types, such as Andosol, Brown Lowland soil, Gray Lowland soil, Gray Upland soil and Wet Andosol, which are representative of the agricultural soils distributed in eastern Hokkaido. These soil types are classified in accordance with *Classification of Cultivated Soils in Japan, Third Approximation* (Cultivated Soil Classification Committee 1995).

The eastern part of Hokkaido (Okhotsk area and Tokachi area) is located between latitudes 42.2° and 44.7° north and longitudes 142.6° and 145.3° east; the annual average temperature ranges from 5 ° C to 7 ° C and the annual average precipitation is between 600 and 1,000 mm (Hokkaido Government Okhotsk General Subprefectural Bureau 2013; Hokkaido Government Tokachi General Subprefectural Bureau 2013).

The soil fertility in all the studied fields was high, as all the values obtained by soil chemical analysis satisfied the criteria authorized by the Department of Agriculture, Hokkaido Government (2010), such as the soil pH (5.5-6.5), available phosphate (Truog method, 100-300 $mgP_2O_5\ kg^{-1}$) and exchangeable potassium (150-300 $mgK_2O\ kg^{-1}$).

The topsoil (approximately 0-15 cm depth) of the studied fields was harrowed by a rotary harrow or vertical harrow- immediately before sowing the wheat seed (sowing date: 14th September to 5th October, see Tables 1-4). The seed was sown by hand. The amount of applied N fertilizer (ammonium sulfate) is given in Tables 1-4, and both phosphate and potassium fertilization were carried out by the conventional procedure employed by each farmer. Field management, including spraying (fungicides, herbicides and pesticides) and mechanical cultivation for weed control, was also carried out in the conventional manner.

Experimental Treatment

Firstly, to compare the timing of additional N fertilization at the booting stage and panicle formation stage, we prepared two types of experimental plots, in both of which N was fertilized intensively at the booting stage (B80-P0, B60-P0, B60-P30, see Table 1) and in which N was fertilized mainly at the panicle formation stage (B0-P80, B0-P60, B30-P60, see Table 1). A total of 31 fields were investigated. "B" denotes the booting stage, and "P" denotes the panicle formation stage. The numbers (0, 60, 80) indicate the amount of N fertilizer ($kgN\ ha^{-1}$) at each stage (B or P).

Secondly, to analyze the difference in the effect of additional N fertilization at the panicle formation stage, flag leaf stage and flowering stage, we arranged the experimental plots into those to which N was applied (30 or 40 $kgN\ ha^{-1}$) and not applied (control) in each stage. These experimental plot sets comprised 49 fields at the panicle formation stage (see Table 2), 36 fields at the flag leaf stage (see Table 3) and 24 fields at the flowering stage (see Table 4). To investigate the effect of foliar N application at the flowering stage, 0.1 $L\ m^{-2}$ of urea solution (10 $gN\ L^{-1}$) was sprayed three times using a handheld sprayer at the flowering stage and 1 week before and after the flowering stage. Every plot had an area of 6-14 m^2 and consisted of three replicates. The row width was 30 cm in every plot.

Measurements

At the flag leaf stage, the stem number was counted by hand (0.3 m2, 1 m of a row). At the mature stage, 3.6 m^2 (1.2 m × 3 m) of wheat at the center of each experimental plot was cut and removed by hand using a sickle or handheld mechanical binder. Each sample of wheat was dried for at least 1 week before threshing. The spike number was counted for part of the wheat sample (approximately 300 stems/spikes), whose grain weight was measured by an electric

Table 1　Description of the experimental fields 1/4

Experimental treatment †	Area	Year	City/town	Soil type	Sowing date	Sowed seed (grain m^{-2})	N fertilization ($kg\ ha^{-1}$)	
							at sow	at flag leaf stage
B80-P 0 vs B 0-P80	Okhotsk	2006	Abashiri	Andosol	21.Sep	200	40	0
			Engaru	Brown Lowland soil	22.Sep	〃	〃	〃
			Kitami	〃	21.Sep	〃	〃	〃
			Ozora (Konan)	Andosol	〃	〃	48	〃
			Ozora (Nisshin)	〃	23.Sep	〃	〃	〃
			Saroma	Gray Upland soil	17.Sep	255	32	〃
			Takinoue	Brown Lowland soil	15.Sep	200	40	〃
		2007	Engaru	Brown Lowland soil	27.Sep	200	40	40
			Kunneppu	Wet Andosol	14.Sep	225	〃	〃
			〃	〃	20.Sep	〃	〃	〃
			〃	〃	〃	300	〃	〃
			Takinoue	Brown Lowland soil	15.Sep	200	〃	〃
		2008	Kunneppu	Wet Andosol	17.Sep	200	40	40
			〃	〃	17.Sep ‡	〃	〃	〃
			〃	〃	21.Sep	〃	〃	〃
			Ozora (Nisshin)	Andosol	30.Sep	255	50	〃
			Takinoue	Brown Lowland soil	16.Sep	200	40	〃
B60-P 0 vs B 0-P60	Okhotsk	2007	Abashiri	Andosol	25.Sep	200	40	40
			Kiyosato	〃	27.Sep	〃	48	〃
			〃	〃	27.Sep ‡	〃	〃	〃
			Ozora (Konan)	〃	20.Sep	〃	〃	〃
			〃	〃	20.Sep ‡	〃	〃	〃
			Ozora (Nisshin)	〃	25.Sep	〃	〃	〃
		2008	Abashiri	Andosol	24.Sep	200	40	40
			Ozora (Konan)	〃	22.Sep	〃	〃	〃
			〃	〃	22.Sep ‡	〃	〃	〃
B60-P30 vs B30-P60	Tokachi	2006	Shihoro	Brown Lowland soil	25.Sep	220	42	0
			Shikaoi	Wet Andosol	21.Sep	255	40	〃
			Shimizu	〃	17.Sep	210	32	〃
		2007	Shihoro	Brown Lowland soil	26.Sep	206	48	0
			Shimizu	Wet Andosol	23.Sep	240	32	〃

† B: booting stage, P: panicle formation stage, numbers (80, 60, 30, 0) indicate applied amount of N fertilizer ($kg\ ha^{-1}$).
‡ Sowed seeds were covered by unwoven fabric to accelerate germination and early growth of wheat.

Table 2 Description of the experimental fields 2/4

Experimental treatment †	Area	Year	City/town	Soil type	Sowing date	Sowed seed (grain m^{-2})	N fertilization (kg ha^{-1})		
							at sow	at booting stage	at flag leaf stage
0 vs 30 at panicle formation stage	Tokachi	2006	Ikeda	Gray Lowland soil	25.Sep	255	64	30	0
			Shihoro	Brown Lowland soil	〃	220	42	90	〃
			Shimizu	Wet Andosol	17.Sep	210	32	〃	〃
		2007	Ikeda	Gray Lowland soil	26.Sep	284	64	60	0
			〃	〃	〃	〃	〃	30	〃
			〃	〃	〃	〃	〃	0	〃
			Shihoro	Brown Lowland soil	〃	206	48	90	〃
			Shimizu	Wet Andosol	23.Sep	240	32	〃	〃
0 vs 40 at panicle formation stage	Okhotsk	2005	Kunneppu	Wet Andosol	20.Sep	170	56	60	0
			〃	〃	〃	255	〃	〃	〃
			Shari	Andosol	26.Sep	170	40	〃	〃
			〃	〃	〃	255	〃	〃	〃
		2006	Kiyosato	Andosol	26.Sep	170	40	80	0
			〃	〃	〃	〃	〃	〃	40
			〃	〃	〃	255	〃	〃	〃
		2007	Kiyosato	Andosol	26.Sep	255	40	80	0
		2008	Engaru	Brown Lowland soil	27.Sep	200	40	40	40
			Yubetsu	Gray Upland soil	25.Sep	〃	〃	〃	〃
	Tokachi	2004	Memuro	Andosol	29.Sep	255	40	80	0
		2005	Honbetsu	Brown Lowland soil	27.Sep	255	30	30	0
			Makubetsu	〃	26.Sep	〃	40	40	〃
			Memuro	Andosol	23.Sep	170	30	80	〃
			〃	〃	〃	255	〃	〃	〃
			〃	〃	〃	〃	〃	〃	40
			〃	〃	5.Oct	〃	〃	〃	0
			Obihiro	〃	26.Sep	〃	40	60	〃
			〃	〃	〃	〃	〃	〃	40
			Otofuke	Wet Andosol	22.Sep	〃	〃	40	0
			〃	〃	〃	〃	〃	〃	40
			Shikaoi	〃	20.Sep	170	〃	20	〃
			〃	〃	〃	255	〃	〃	0
			〃	〃	〃	〃	〃	〃	40
			Taiki	〃	21.Sep	〃	〃	60	0
			〃	〃	〃	〃	〃	〃	40
		2006	Honbetsu	Brown Lowland soil	26.Sep	255	40	60	0
			〃	〃	〃	〃	〃	〃	40
			Makubetsu	〃	25.Sep	〃	〃	40	0
			〃	〃	〃	〃	〃	〃	40
			Memuro	Andosol	〃	170	〃	80	0
			〃	〃	〃	255	〃	〃	〃
			〃	〃	〃	〃	〃	〃	40
			〃	〃	5.Oct	〃	〃	〃	0
			Obihiro	〃	22.Sep	〃	〃	40	〃
			〃	〃	〃	〃	〃	〃	40
			Shikaoi	Wet Andosol	21.Sep	170	〃	〃	〃
			〃	〃	〃	255	〃	〃	0
			〃	〃	〃	〃	〃	〃	40
			Taiki	〃	25.Sep	〃	〃	60	0
			〃	〃	〃	〃	〃	〃	40

† Numbers (0, 30, 40) indicate applied amount of N fertilizer (kg ha^{-1}) .

Table 3 Description of the experimental fields 3/4

Experimental treatment †	Area	Year	City/town	Soil type	Sowing date	Sowed seed (grain m^{-2})	N fertilization (kg ha^{-1})		
							at sow	at booting stage	at panicle formation stage
0 vs 30 at flag leaf stage	Tokachi	2006	Ikeda	Gray Lowland soil	25.Sep	255	6.4	3	0
			Shihoro	Brown Lowland soil	〃	220	4.2	9	〃
			〃	〃	〃	〃	〃	6	3
			Shimizu	Wet Andosol	17.Sep	210	3.2	9	0
			〃	〃	〃	〃	〃	6	3
		2007	Ikeda	Gray Lowland soil	26.Sep	284	6.4	6	0
			〃	〃	〃	〃	〃	3	〃
			〃	〃	〃	〃	〃	〃	3
			〃	〃	〃	〃	〃	0	0
			Shihoro	Brown Lowland soil	〃	206	4.8	9	〃
			〃	〃	〃	〃	〃	6	3
			Shimizu	Wet Andosol	23.Sep	240	3.2	9	0
			〃	〃	〃	〃	〃	6	3
		2008	Shihoro	Gray Lowland soil	26.Sep	294	5.3	6	0
			〃	〃	〃	〃	〃	3	〃
			〃	〃	〃	〃	〃	0	〃
			Shikaoi	Wet Andosol	18.Sep	189	4	3	〃
			〃	〃	〃	〃	〃	0	〃
			Shimizu	〃	19.Sep	251	3.2	6	〃
			〃	〃	〃	〃	〃	3	〃
0 vs 40 at flag leaf stage	Okhotsk	2005	Kunneppu	Wet Andosol	20.Sep	170	5.6	6	0
			〃	〃	〃	255	〃	〃	〃
			Shari	Andosol	26.Sep	170	4	〃	〃
			〃	〃	〃	255	〃	〃	〃
		2006	Kiyosato	Andosol	26.Sep	170	4	8	0
			〃	〃	〃	〃	〃	〃	4
			〃	〃	〃	255	〃	〃	〃
		2007	Kiyosato	Andosol	26.Sep	255	4	8	0
		2008	Ozora	Andosol	22.Sep	200	4	6	0
			〃	〃	22.Sep ‡	〃	〃	〃	〃
	Tokachi	2003	Memuro	Andosol	24.Sep	255	4	8	2
		2004	Memuro	Andosol	29.Sep	255	4	8	0
		2005	Honbetsu	Brown Lowland soil	27.Sep	255	3	3	0
			〃	〃	〃	〃	〃	〃	4
			Makubetsu	〃	26.Sep	〃	4	4	0
			〃	〃	〃	〃	〃	〃	4
			Memuro	Andosol	23.Sep	〃	3	8	〃
			Obihiro	〃	26.Sep	〃	4	6	0
			〃	〃	〃	〃	〃	〃	4
			Otofuke	Wet Andosol	22.Sep	〃	〃	4	0
			〃	〃	〃	〃	〃	〃	4
			Shikaoi	〃	20.Sep	〃	〃	2	0
			〃	〃	〃	〃	〃	〃	4
			Taiki	〃	21.Sep	〃	〃	6	0
			〃	〃	〃	〃	〃	〃	4
		2006	Honbetsu	Brown Lowland soil	26.Sep	255	4	6	0
			〃	〃	〃	〃	〃	〃	4
			Makubetsu	〃	25.Sep	〃	〃	4	0
			〃	〃	〃	〃	〃	〃	4
			Memuro	Andosol	〃	〃	〃	8	〃
			Obihiro	〃	22.Sep	〃	〃	4	0
			〃	〃	〃	〃	〃	〃	4
			Shikaoi	Wet Andosol	21.Sep	〃	〃	〃	0
			〃	〃	〃	〃	〃	〃	4
			Taiki	〃	25.Sep	〃	〃	6	0
			〃	〃	〃	〃	〃	〃	4

† Numbers (0, 30, 40) indicate applied amount of N fertilizer (kg ha^{-1}) .
‡ Sowed seed were covered by unwoven fabric to accelerate germination and early growth of wheat.

Table 4 Description of the experimental fields 4/4

Experimental treatment†	Area	Year	City/town	Soil type	Sowing date	Sowed seed (grain m^{-2})	N fertilization ($kg\ ha^{-1}$)			
							at sow	at booting stage	at panicle formation stage	at flag leaf stage
0 vs 30 at flowering stage	Okhotsk	2005	Shari	Andosol	26.Sep	170	40	60	0	0
			〃	〃	〃	255	〃	〃	〃	〃
		2008	Engaru	Brown Lowland soil	27.Sep	200	40	80	0	40
			Kiyosato	Andosol	〃	〃	〃	60	〃	〃
			〃	〃	27.Sep ‡	〃	〃	〃	〃	〃
			Ozora(Konan)	〃	20.Sep	〃	〃	〃	〃	〃
			〃	〃	20.Sep ‡	〃	〃	〃	〃	〃
			Ozora(Nisshin)	〃	25.Sep	〃	48	〃	〃	〃
			〃	〃	〃	〃	〃	30	30	〃
	Tokachi	2004	Memuro	Andosol	29.Sep	255	40	80	0	0
		2005	Honbetsu	Brown Lowland soil	27.Sep	255	30	30	0	0
			Kunneppu	Wet Andosol	20.Sep	〃	56	60	〃	〃
			Makubetsu	Brown Lowland soil	26.Sep	〃	40	40	〃	〃
			Memuro	Andosol	23.Sep	〃	30	80	〃	〃
			Obihiro	〃	26.Sep	〃	40	60	〃	〃
			Otofuke	Wet Andosol	22.Sep	〃	〃	40	〃	〃
			Shikaoi	〃	20.Sep	〃	〃	20	〃	〃
			Taiki	〃	21.Sep	〃	〃	60	〃	〃
		2006	Honbetsu	Brown Lowland soil	26.Sep	255	40	60	0	0
			Makubetsu	〃	25.Sep	〃	〃	40	〃	〃
			Memuro	Andosol	〃	〃	〃	80	〃	〃
			Obihiro	〃	22.Sep	〃	〃	40	〃	〃
			Shikaoi	Wet Andosol	21.Sep	〃	〃	〃	〃	〃
			Taiki	〃	25.Sep	〃	〃	60	〃	〃

† Numbers (0, 30) indicate applied amount of N fertilizer ($kg\ ha^{-1}$) .
‡ Sowed seed were covered by unwoven fabric to accelerate germination and early growth of wheat.

balance after threshing. This value (spike number per grain weight) was used to calculate the spike number per square meter by multiplying by the grain yield ($kg\ ha^{-1}$). The grain yield and 1000-grain weight were corrected to a 0.135 g g^{-1} moisture basis. The harvest index (HI) was calculated as the ratio of the grain yield to the total weight (grain yield plus stem weight). The grain number per spike was calculated from the spike number (per m^2), 1000-grain weight (g) and grain yield (converted to g m^{-2}). The grain protein, grain bulk density and moisture of grain were measured using a near-infrared spectrometer (Infratec 1241 grain analyzer, Foss Co., Ltd.).

After threshing, part of the grain sample and stem sample was powdered and used to measure the N content by the Kjeldahl method. The N uptake by the wheat ($kgN\ ha^{-1}$) was calculated by adding the N uptake by the grains to the N uptake by the stems, which were multiplied by their N contents and weights per square meter (grain yield, stem weight). The N efficiency (%) was calculated by the following equation:

$$\text{N efficiency (\%)} = (N_{app} - N_0) \div N_{fert} \times 100,$$

where

N_{app} : N uptake by wheat in the plot with additional N fertilization at the panicle formation stage, flag leaf stage or flowering stage

N_0 : N uptake by wheat at control plot for each stage

N_{fert} : amount of additional N fertilizer (30 or 40 kgN ha^{-1}).

RESULTS AND DISCUSSION

Effect of timing of additional N fertilization (booting or panicle formation stage) on several features of "Kitahonami"

The results of a comparison between intense N fertilization at the booting stage (B80-P0, B60-P0 and B60-P30) and panicle formation stage (B0-P80, B0-

Table 5　Effect of timing of additional N fertilization (booting or panicle formation stage) on stem number, spike number, grain yield, HI(harvest index), grain number per spike, 1000-grain weight, grain protein.

Data sets	N fertilization timing †	Stem number ‡ (m^{-2})	Spike number (m^{-2})	Grain yield (kg ha^{-1})	HI (%)	Grain number per spike	1000-grain weight(g)	Grain protein (g kg^{-1})
Okhotsk area, n=17	B80-P 0	1417a	665	7310	46.1b	28.2	39.0	98b
	B 0-P80	1232b	658	7350	47.8a	28.7	39.5	102a
Okhotsk area, n=9	B60-P 0	1773a	751a	8240	40.1b	26.1b	40.7	104
	B 0-P60	1527b	695b	8490	41.1a	28.6a	41.1	104
Tokachi area, n=5	B60-P30	1224a	659a	6990	46.7	28.4b	37.5	96
	B30-P60	1040b	621b	7070	46.8	30.0a	38.2	97

† B: booting stage, P: panicle formation stage, numbers (80, 60, 30, 0) indicate applied amount of N fertilizer (kg ha^{-1}).
‡ Measured at flag leaf stage. The other items were measured at or after mature stage.
Different letters (a-b) in each pair (B80-P0 vs B0-P80, B60-P0 vs B0-P60, B60-P30 vs B30-P60) indicate a significant difference between the pair using a paired T test ($P < 0.05$).

P60 and B30-P60) are shown in Table 5. The stem number (flag leaf stage) significantly decreased to approximately 200 m^{-2} or less when N fertilization was prioritized at the panicle formation stage. The spike number was also smaller at B0-P60 and B30-P60 than at B60-P0 and B60-P30, respectively. In particular, the average spike number at B60-P0 was 751 m^{-2}, which was over 700 m^{-2}, the criterion that must be satisfied to avoid lodging (Central Agricultural Experiment Station *et al*. 2008), while that at B0-P60 was 695 m^{-2}, less than 700 m^{-2}. The HI, grain number per spike and grain protein were also higher in the plots subjected to intense N fertilization at the panicle formation stage rather than at the booting stage, while the grain yield and 1000-grain weight exhibited no significant difference between them. These results suggest that greater N fertilization at the panicle formation stage than at the booting stage is preferable for the current leading cultivar "Kitahomani".

At first glance, this appears to contradict the previous conventional recommendation of prioritizing the booting stage over the panicle formation stage for additional N fertilization to obtain stable high yield of winter wheat (Suzuki *et al*. 1999; Tsuchiya *et al*. 2001). However, it is well known that early N fertilization after the snow melts boosts the stem number and spike number of winter wheat (Shimono 1986; Watanabe 2010). Moreover, Tsuchiya *et al*. (2001) reported that allocating 30 kgN ha^{-1} of N fertilizer to the booting stage and the same amount to the panicle formation stage was useful for mitigating the lodging of overexuberant winter wheat, even for the previous leading variety "Hokushin" in the case of overexuberant stems and spikes. "Kitahonami" has a greater risk of overexuberant stems and spikes than "Hokushin" (Central Agricultural Experiment Station *et al*. 2008); thus, greater care must be taken to avoid lodging due to overexuberant stems and spikes.

Generally, early N fertilization after the snow melts increases the grain yield of winter wheat (Watanabe 2010). However, our comparison of N fertilization between the booting stage and panicle formation stage shows that N fertilization at the booting stage has no positive effect on increasing the grain yield, 1000-grain weight, HI, grain number per spike and grain protein compared with N fertilization at the panicle formation stage (Table 5). This discrepancy could be explained by the tendency of "Kitahonami" to have more void stems, which are unable to mature, in the case of N fertilization at the booting stage (Table 5).

The HI, grain number per spike and grain protein were increased more by intense N fertilization at the panicle formation stage than by intense N fertilization at the booting stage (Table 5). This finding is consistent with Shimono (1986) and Watanabe (2010), who also reported that later N fertilization (at the panicle formation stage, flag leaf stage, etc.) increased the grain number per spike and grain protein.
Therefore, these results suggest that suppressing the overexuberance of stems and spikes through N fertilization at the panicle formation stage rather than at the booting stage would improve the efficiency of both the grain production and N anabolism of grains of "Kitahonami".

Effect of additional N fertilization at each stage (panicle formation, flag leaf and flowering stages) on several features of "Kitahonami"

Table 6 Effect of additional N fertilization at panicle formation stage on spike number, grain yield, 1000-grain weight, grain bulk density, grain protein, N uptake by wheat and its N efficiency.

Treatment	Spike number (m^{-2})	Grain yield (kg ha^{-1})	1000-grain weight (g)	Grain bulk density (g L^{-1})	Grain protein (g kg^{-1})	N uptake by wheat (kg ha^{-1})	N efficiency (%)
N30 applied at panicle formation stage	728 a	832			10.7 a	19.2 a	57.9
Control	676 b	805			10.1 b	17.5 b	
n=	8	8			8	8	
N40 applied at panicle formation stage	754 a	759 a	40.0 b	835	10.5 a	18.6 a	56.1
Control	720 b	738 b	40.5 a	835	9.8 b	16.4 b	
n=	41	41	39	39	39	33	

Different letters (a-b) in each pair (N40 applied at panicle formation stage vs control) indicate a significant difference between the pair using a paired T test ($P < 0.05$).

Table 7 Effect of additional N fertilization at flag leaf stage on spike number, grain yield, 1000-grain weight, grain bulk density, grain protein, N uptake by wheat and its N efficiency.

Treatment	Spike number (m^{-2})	Grain yield (kg ha^{-1})	1000-grain weight (g)	Grain bulk density (g L^{-1})	Grain protein (g kg^{-1})	N uptake by wheat (kg ha^{-1})	N efficiency (%)
N30 applied at flag leaf stage	711 a	755 a			10.6 a	18.0 a	59.8
Control	680 b	723 b			10.0 b	16.2 b	
n=	20	20			20	20	
N40 applied at flag leaf stage	770	780 a	40.7 a	835 a	10.8 a	19.8 a	69.7
Control	755	734 b	40.0 b	832 b	9.9 b	17.0 b	
n=	36	36	34	34	34	30	

Different letters (a-b) in each pair (N40 applied at flag leaf stage vs control, N30 applied at flag leaf stage vs control) indicate a significant difference between the pair using a paired T test ($P < 0.05$).

Table 8 Effect of additional N fertilization at flowering stage on spike number, grain yield, 1000-grain weight, grain bulk density, grain protein, N uptake by wheat and its N efficiency.

Treatment	Spike number (m^{-2})	Grain yield (kg ha^{-1})	1000-grain weight (g)	Grain bulk density (g L^{-1})	Grain protein (g kg^{-1})	N uptake by wheat (kg ha^{-1})	N efficiency (%)
N30 applied at flowering stage	774	772 a	40.5	846 a	10.5 a	18.1 a	72.0
Control	773	746 b	40.0	841 b	9.7 b	16.0 b	
n=	24	24	23	23	23	19	

Different letters (a-b) in each pair (N30 applied at flowering stage vs control) indicate a significant difference between the pair using a paired T test ($P < 0.05$).

The spike number significantly increased upon additional N fertilization at the panicle formation stage (Table 6) and flag leaf stage (Table 7), while it did not increase upon N fertilization at the flowering stage (Table 8). The grain yield significantly increased upon N fertilization at every experimental stage (Tables 6-8). These results suggest that N fertilization at all stages has a positive effect on increasing the grain yield, while N fertilization at later stages tends to alleviate the risk of overexuberant stems and spikes, especially foliar N application at the flowering stage. This is consistent with the reports of Shimono (1986) and Watanabe (2010), despite the fact that their studies were based on past cultivars. Therefore, the above findings are valid for both past cultivars and "Kitahonami" for the features mentioned above.

The grain protein significantly increased upon N fertilization at every experimental stage, with an increase in the N uptake by the wheat (Tables 6-8). Additionally, comparing the grain protein for different timings of N fertilization with the same amount of N fertilizer (30 kgN ha^{-1}), foliar N fertilization at the flowering stage increased the grain protein by an average of 0.8 g kg^{-1}, compared with 0.6 g kg^{-1} in the case of N fertilization at earlier stages. Moreover, the N efficiency ranged from 56.1 % to 72.0 %, and later N fertilization tended to raise the grain protein. Generally, later N fertilization raises the grain protein of wheat more effectively than earlier fertilization (Shimono 1986; Takebe *et al*. 2006; Watanabe 2010), which is consistent with our results (Tables 6-8). Therefore, it is suggested that the higher N efficiency in the case of later N fertilization increases the grain protein.

Furthermore, later N fertilization at the flag leaf stage significantly increased the 1000-grain weight (Table 7) while fertilization at the panicle formation stage decreased it (Table 6). The grain bulk density also increased upon later N fertilization (at the flag leaf stage and flowering stage, Tables 7 and 8), while N fertilization at the panicle formation stage had no effect (Table 6). This can also be attributed to the greater stuffing grains by the photosynthates, resulting from the higher grain yield with no increase or a small increase in the spike number upon later N fertilization such as at the flag leaf stage or flowering stage with higher N efficiency.

From these results, the following features of the response of “Kitahonami” to additional N fertilization were clarified: (1) earlier N fertilization tends to lead to a risk of lodging through overexuberant stems and spikes, (2) later N fertilization does not tend to result in overexuberant stems and spikes, (3) later N fertilization tends to increase the 1000-grain weight, grain bulk density and grain protein through higher N efficiency.

CONCLUSIONS

The features of N fertilization for the winter wheat cultivar “Kitahonami” were clarified to be as follows. Excess early N fertilization, such as at the booting stage, should be avoided because “Kitahonami” has a risk of lodging owing to the tendency of overexuberant stems and spikes. Regarding the timing of additional N fertilization, the panicle formation stage is better than the booting stage. N fertilization at the flag leaf stage should be carefully considered if the stem number exceeds. Instead, foliar N fertilization at the flowering stage is effective for ensuring a high 1000-grain weight, grain bulk density and grain protein through higher N efficiency without the risk of overexuberance.

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追肥窒素時期の違いが秋まき小麦「きたほなみ」の穂数・子実収量・子実タンパクおよび施肥窒素利用率に及ぼす影響

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Summery

北海道における秋まき小麦新品種「きたほなみ」は多収である一方，茎数過多によって倒伏しやすいことと，低タンパクとなりやすいことから，窒素追肥法の最適化を図る必要がある。したがって，著者らはこれらの問題の回避を主眼として，起生期および幼穂形成期について，窒素追肥時期の違いを比較した。さらに，幼穂形成期・止葉期・開花期について窒素追肥時期の違いを検討した。

幼穂形成期の窒素追肥は，起生期の窒素追肥に比べて茎数・穂数の増加を抑制するだけでなく，減収を伴わずに収穫指数（HI）や一穂粒数および子実タンパクを増加させた。このことから，「きたほなみ」のような茎数過多や低タンパクになりやすい秋まき小麦品種には，起生期追肥よりも幼穂形成期追肥がより適することが示唆された。

さらに，幼穂形成期・止葉期・開花期について窒素追肥時期の違いを比較した結果，「きたほなみ」の施肥反応の特徴として以下の３点が明らかになった。（１）早期の窒素追肥には茎数・穂数の過多を助長し倒伏のリスクを高める傾向がある。（２）後期の窒素追肥には過繁茂を助長する傾向はない。（３）後期の窒素追肥の窒素利用率は高く，千粒重，容積重および子実タンパクを高める傾向がある。

以上の結果は，「きたほなみ」のような生育後半の過繁茂と低タンパクを引き起こしやすい品種に対して効果的な窒素施肥法を構築する際の参考になると考えられる。

キーワード：子実タンパク，倒伏，穂数，窒素追肥時期，秋まき小麦