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Analysis of Optimum Spikelet Number and Plant N in Rice at Tanazawa Paddy Field

By

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Summary : The objective of this study is to clarify regional optimum spikelet number for maximum grain yield for each cultivar, and plant N for spikelet number to obtain stable yield in rice. We conducted field experiments in a paddy field at Tanazawa District as city agriculture in order to establish highly effective N application management regionally. We analyzed 180 sets of experimental data on yield and its component, and plant N at the late spikelet differentiation and heading stage, using three low land cultivars, Nipponbare, Koshihikari and Takanari, grown under different methods and levels of N application over 9 seasons from 1998 to 2008. We made use of variously different split application of N, including basal application only (B), light basal and heavy top-dressings from the panicle initiation stage onward (L), heavy basal and heavy top-dressings from the spikelet formation stage onward (V), and no applications (0) in 1998–2001. In 2002, and 2005–2008 we set up experimental plots of the timing of a N top-dressing both with and without basal application of N. We investigated yield and its components and plant N at the late spikelet differentiation stage and heading.

Takanari tended to have the largest spikelet number and grain yield averaged over all plots. Optimum spikelet number for maximum grain yield was about 35000 m^{-2} in Nipponbare and Koshihikari, and about 48000 m^{-2} in Takanari, respectively. The relationship between spikelet number per unit area and plant N at the late spikelet differentiation stage or heading stage was close. Plant N for optimum spikelet number determined by those relationships was 12.8, 11.4 and 12.3 g m^{-2} at the late differentiation stage, and 12.5, 16.0 and 17.2 g m^{-2} at heading, in Nipponabare, Koshihikari and Takanari, respectively. A grain yield of 600 g m^{-2} in Nipponbare and Koshihikari and 750 g m^{-2} in Takanari would require spikelet numbers per unit area of 32000, 32000 and 40000, respectively, assuming that the percentage of ripened spikelets is 85%. To obtain these spikelet numbers, plant N must reach 12.1, 11.0 and 9.1 g m^{-2} at the heading stage for these cultivars, respectively.

Plant N derived from natural supply of N was 50–60% of total plant N at the late spikelet differentiation stage or heading stage. Therefore, to optimize spikelet number, we should make use of application of N top-dressing for the early panicle development stage, since rice can absorb much nitrogen, especially the cultivar Takanari.

Key words : N application, Spikelet number, Plant N, Rice, Yield

Introduction

Nitrogen (N) is one of the most important nutrients for maximizing rice yield[1–3]. In the past, N has been applied in large amounts in rice production system and the methods of N application were improved in order to obtain stable high yield[4–6]. The wide spread use of N, however, has resulted in negative effects on the surrounding environment[7,8]. Even in paddy rice cultivation, N application also increases the quality of water and air[9]. Heavy nitrogen application also increases the cost of rice production. So we must develop efficient rice cultivation method with timely input in order to prevent negative effects on the environment and maintain stable high yield, especially in city agriculture.

Various studies have shown that spikelet number per unit area is closely related to grain yield in rice[6,10–14]. Since grain size is fairly constant[6], sink capacity is primarily limited by spikelet number, which is closely associated with N nutrition of the crop[15,16]. WADA (1969)[1]

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related spikelet number to plant N accumulated up to the late spikelet differentiation stage. Murayama (1969)[17] found a regional variation in the relationship between plant N and spikelet number, especially between the northern and southern parts of Japan. Therefore, increasing the spikelet number per unit area by means of crop management is essential for increasing rice grain yield.

Grain yield is determined by the following yield components : panicle number per unit area, spikelet number per panicle, percentage of ripened spikelet, and 1000-grain weight[18]. Spikelet number per unit area is calculated from panicle number per unit area and spikelet number per panicle. 1000-grain weight is almost constant[6], but spikelet number per unit area and percentage of ripened spikelet are changable[1]. Excess spikelet number tends to result in low percentage of ripened spikelet, and the relationship between spikelet number and percentage of ripened spikelet is generally negative[1,15]. Some studies have shown the optimum spikelet number for grain yield, and the varietal differences in this number. In order to maximize the yield of each cultivar[19,20], we have to know the optimum spikelet number and plant N of each cultivar.

In this study, to determine the regional optimum spikelet number and plant N, and to establish more efficient N management for each cultivar, experiments were conducted in the paddy field at Tanazawa, which is known as a district of city agriculture.

Materials and Methods

Field experiments were carried out at Tanazawa paddy field of Tokyo University of Agriculture. This field in the northern district of Atsugi City, Kanagawa Prefecture, is located at latitude 35°30′N and longitude 139°21′E. The irrigation water was drawn sufficiently from Nakatsu River. The seasonal changes of mean temperature, accumulated sunshine duration and rainfall at Tanazawa over the rice growing period, from May to September are shown in Table 1.

Three lowland cultivars, Nipponnbare (japonica) in 1998–2002, Koshihikari (japonica) in 2000–2002 and 2005–2008, and Takanari (indica) in 2001–2002 and 2005–2008 were grown under different cultivation methods and levels of N application over 9 seasons. 180 yield component data sets of field experiments were used. The plow layer of the paddy field consisted of about 50% clay. Paddy soil characteristics are shown in Table. 2.

Seeds were sown in nursery boxes in mid April, and two seedlings at the 4.5-leaf stage were transplanted to the paddy fields in mid May of each year. Planting density was 22.2 hills m^{-2}, with a hill spacing of 15×30 cm^2. The field was kept under submerged conditions throughout the course of the experiments.

In 1998–2000, N was applied in different spilt applications : basal dressing only (B), light basal and heavy top-dressings from the panicle initiation stage onward (L), heavy basal and heavy top-dressings from the spikelet formation stage onward (V), and no applications (0) (Table 3). Three or Four N levels were set for each of the B, L and V applications. In 2001–2008, experimental plots were set up to study the timing of a top-dressing of N both with and without N basal application of nitrogen (Table 4). The size of each plot was 20–54 m^2, and 8 g m^{-2} P_2O_5 and 8 g m^{-2} K_2O were applied as basal dressings each year.

The developmental stage of panicle initiation and heading were monitored by frequent inspections. Panicle initiation was defined as the first appearance of a differentiated apex when examined under a microscope. Heading was defined as 50% of panicles fully emerged from the flag-leaf sheath. Twelve to sixteen plants were harvested every 2 weeks from the panicle initiation stage to heading stage. Samples were dried for 5 or 6 days at 80℃ in a ventilated oven. After weighing, dried samples were powdered with a vibrating sample mill (TI-100, Heiko Co.Ltd.). N concentration of the samples was determined by an N-analysis sys-

Table 1 Seasonal changes of mean temperature, sunshine radiation and rainfall

	Dairy mean air tenperature (℃)						Accumulated sunshine duration (hrs)						Accumulated rainfall (mm)					
	May	Jun.	Jul.	Aug.	Sep.	Mean	May	Jun.	Jul.	Aug.	Sep.	Sum	May	Jun.	Jul.	Aug.	Sep.	Sum
1998	20.2	21.2	24.8	26.8	23.8	23.4	102	43	81	79	70	375	213	215	237	242	272	1179
1999	19.0	22.2	25.6	27.7	25.3	23.9	126	85	130	162	120	622	196	169	242	274	120	1001
2000	19.3	21.6	26.6	27.2	23.9	23.7	126	75	148	154	120	621	45	221	199	102	434	1001
2001	18.6	22.3	27.5	25.8	22.1	23.3	130	47	230	93	114	615	219	123	54	209	253	858
2002	17.7	20.8	27.1	27.4	22.1	23.0	129	108	154	227	120	738	121	222	150	173	294	960
2005	17.5	22.6	25.0	27.1	23.7	23.2	164	81	96	153	153	647	97	148	326	236	204	1011
2006	18.3	22.0	24.9	26.5	22.9	22.9	119	60	47	163	127	516	169	182	198	170	146	865
2007	18.8	22.4	23.8	28.0	24.2	23.4	211	169	69	245	121	815	144	69	408	75	300	996
2008	18.0	20.9	25.8	25.5	22.8	22.6	139	111	178	169	132	729	360	246	51	404	313	1373

Table 2 Physical and chemical properties of the paddy soil

Soil texture	Lic				
Bulk density (gcm^{-3})	1.07	Nitrate nitrogen ($mgkg^{-1}$)	23.2	Exchangeable K ($cmol(+)kg^{-1}$)	0.97
pH(H_2O)	6.3	Ammoniunm nitrogen ($mgkg^{-1}$)	11.5	Exchangeable Ca ($cmol(+)kg^{-1}$)	18
pH(KCl)	5.1	Organic carbon (gkg^{-1})	23.1	Exchangeable Mg ($cmol(+)kg^{-1}$)	3.38
Total nitrogen (gkg^{-1})	2.4	Available phosphoric acid ($mgkg^{-1}$)	75	Cation exchange capacity ($cmol(+)kg^{-1}$)	25.9

Table 3 Nitrogen treatments for plots in 1998–2001

N application type	Plot	Basal dressing ($g\ m^{-2}$)	Top-dressing ($g\ m^{-2}$)						Amount of N ($g\ m^{-2}$)
			Tillering	Neck node differentiation	Early spikelet differentiation	Late spikelet differentiation	Reduction division	Full heading	
Nitrogen free, 0		—	—	—	—	—	—	—	0
Baisal application only, B	B09	9	—	—	—	—	—	—	9
	B14	14	—	—	—	—	—	—	14
	B19	19	—	—	—	—	—	—	19
Light basal and heavy top-dressing, L	L09	1	2	1	1	—	2	2	9
	L14	2	2	2	3	—	2	3	14
	L19	3	2	3	5	—	2	4	19
Heavy basal and heavy top-dressing, V	V09	3	2	—	—	2	—	2	9
	V14	5	3	—	—	3	—	3	14
	V19	7	4	—	—	4	—	4	19

Table 4 Nitrogen treatments for plots in 2002, and 2005–2008

Cultivar	Year	Applied N ($g\ m^{-2}$)			Experimental plots with and without basal application of N
		Basal dressing	Top-dressing	Sum of N	
Nipponbare	2002	0	4	4	Without basal: 0-0, 0-4(-50), 0-4(-40), 0-4(-30), 0-4(-20)
		4	4	8	With basal: 4-0, 4-4(-50), 4-4(-40), 4-4(-30), 4-4(-20)
Koshihikari	2002	0	4	4	Without basal: 0-0, 0-4(-37), 0-4(-27), 0-4(-17), 0-4(-7)
		4	4	8	With basal: 4-0, 4-4(-35), 4-4(-25), 4-4(-15), 4-4(-5)
	2005	0	4	4	Without basal: 0-0, 0-4(-28), 0-4(-21), 0-4(-14), 0-4(-7)
		0	8	8	〃 : 0-0, 0-8(-28), 0-8(-21), 0-8(-14), 0-8(-7)
		4	4	8	With basal: 4-0, 4-4(-28), 4-4(-21), 4-4(-14), 4-4(-7)
		4	8	12	〃 : 4-8(-28), 4-8(-21), 4-8(-14), 4-8(-7)
		8	4	12	〃 : 8-0, 8-4(-28), 8-4(-21), 8-4(-14), 8-4(-7)
		8	8	16	〃 : 8-8(-28), 8-8(-21), 8-8(-14), 8-8(-7)
	2006	0	4	4	Without basal: 0-0, 0-4(-43), 0-4(-29), 0-4(-15)
		4	4	8	With basal: 4-0, 4-4(-43), 4-4(-29), 4-4(-15)
	2007	0	4	4	Without basal: 0-0, 0-4(-27), 0-4(-10), 0-4(-4)
		4	4	8	With basal: 4-0, 4-4(-25), 4-4(-8), 4-4(-2)
	2008	0	4	4	Without basal: 0-0, 0-4(-30), 0-4(-20), 0-4(-10)
		4	4	8	With basal: 4-0, 4-4(-28), 4-4(-18), 4-4(-8)
Takanari	2002	0	4	4	Without basal: 0-0, 0-4(-50), 0-4(-40), 0-4(-30), 0-4(-20)
		4	4	8	With basal: 4-0, 4-4(-46), 4-4(-36), 4-4(-26), 4-4(-16)
	2005	0	4	4	Without basal: 0-0, 0-4(-30), 0-4(-23), 0-4(-16), 0-4(-9)
		0	8	8	〃 : 0-0, 0-8(-30), 0-8(-23), 0-8(-16), 0-8(-9)
		4	4	8	With basal: 4-0, 4-4(-30), 4-4(-23), 4-4(-16), 4-4(-9)
		4	8	12	〃 : 4-8(-30), 4-8(-23), 4-8(-16), 4-8(-9)
		8	4	12	〃 : 8-0, 8-4(-30), 8-4(-23), 8-4(-16), 8-4(-9)
		4	4	8	〃 : 8-8(-30), 8-8(-23), 8-8(-16), 8-8(-9)
	2006	0	4	4	Without basal: 0-0, 0-4(-48), 0-4(-34), 0-4(-20)
		4	4	8	With basal: 4-0, 4-4(-48), 4-4(-34), 4-4(-20)
	2007	0	4	4	Without basal: 0-0, 0-4(-32), 0-4(-15), 0-4(-11)
		4	4	8	With basal: 4-0, 4-4(-29), 4-4(-12), 4-4(-8)
	2008	0	4	4	Without basal: 0-0, 0-4(-35), 0-4(-25), 0-4(-15)
		4	4	8	With basal: 4-0, 4-4(-31), 4-4(-21), 4-4(-11)

Numbers in the bracket of experimental plots with and without basal application of N indicate the days before heading.

tem (Shibata Co. Ltd.) equipped with digester, B-435, distiller, B-323, and titrater, E-702. Total N content was expressed as the product of total above-ground dry weight and the nitrogen concentration. Since the dates of biomass measurements deviated from the intended stage on several occasions, we estimated the biomass at the exact stage (14 days before heading and heading) and interpolated observed data with a third order spline curve for the plot of each cultivar[21].

At maturity, for determinations of yield and its components, the plants in an area of 120 cm × 90 cm for each plot with 1〜3 replicates were harvested, and air-dried. After measuring of panicle number and threshing, spikelet number was measured. The percentage of ripened grain was determined from the number of unhusked kernels that sank in a saline solution with a specific gravity of 1.06, in relation to spikelet number[18]. The dry weight of husked grain that sank in the solution was measured, and moisture was adjusted to 14%. Grain yield per unit area was then determined.

Results

(1) Yield and its components

Yield and its components in all plots are shown in Table 5. Panicle numbers per unit area were 250–440, 170–460 and 150–310 m^{-2}, spikelet numbers per panicle were 67–104, 79–138 and 103–239, percentage of ripened spikelet were 46–93, 19–92 and 43–94%, and 1000-grain weights were 20.2–24.1, 18.3–23.9 and 17.6–23.8 g, in Nipponbare, Koshihikari and Takanari, respectively. Panicle numbers of Nipponbare and Koshihikari were higher than that of Takanari. Spikelet number per panicle of Takanari was clearly higher than those of the other two cultivars. Percentage of ripened spikelet varied widely under different cultivation conditions. 1000-grain weight was not constant, in contrast to the results of YOSHIDA (1981)[6], who showed a constant 1000-grain weight for each cultivar, that the differences in 1000-grain weight among years and cultivation methods were small, and that its coefficient of variation was very small. Spikelet number per unit area, determined from panicle number number per unit area and spikelet number per panicle, were 19,200–39,100, 15,700–45,600, and 20,300–56,700 m^{-2}, in Nipponbare, Koshihikari, and Takanari, respectively. Takanari clearly had many spikelets per panicle,which influenced spikelet number per unit area. Grain yield were 310–620, 120–640 and 320–810 g m^{-2}, in Nipponbare, Koshihikari and Takanari, respectively.

The low percentage of spikelet was caused by low solar radiation during ripening period in1998. In 2008, since the low air temperature during the early growing stage and low solar radiation during the later one affected the numbers of panicle and the percentage of ripened spikelet. And in 2005, the percentage of ripened spikelet of Koshihikari was low because of lodging by heavy wind after heading.

Table 6 shows correlation coefficient of panicle number per unit area, spikelet number per panicle percentage of ripened spikelet and 1000-grains weight to grain yield. The relationship between spikelet number per unit area and grain yield was strong, except in years with extraordinary weather conditions.

The changes with N top-dressing time of the spikelet

Table 5 Yield and its components of all plots in 1998–2002, and 2005–2008

Cultivar	Year	Plot number	Panicle number (m^{-2})	Spikelet number per panicle	Spikelet number per unit area (m^{-2})	Percentage of ripened spikelet (%)	1000-grains weight (g)	Grain yield ($g\,m^{-2}$)
Nipponbare	1998	10	280〜430	76〜102	22600〜39100	46〜92	20.2〜23.2	310〜600
〃	1999	10	330〜440	71〜 91	25600〜35100	72〜90	22.3〜23.7	470〜620
〃	2000	6	270〜350	67〜 88	19200〜26200	66〜93	21.3〜24.1	370〜540
〃	2001	11	250〜390	83〜102	20800〜35000	68〜82	21.2〜22.3	380〜530
〃	2002	10	260〜380	78〜104	21900〜39000	63〜89	21.2〜22.6	400〜520
Koshihikari	2000	6	250〜400	79〜 96	22400〜31300	75〜86	20.2〜22.2	380〜530
〃	2001	4	210〜320	88〜112	17800〜36300	47〜75	22.2〜23.9	300〜450
〃	2002	10	170〜320	88〜110	17200〜34100	63〜80	20.5〜23.7	240〜470
〃	2005	27	270〜460	79〜138	24800〜45600	19〜92	18.3〜23.8	120〜640
〃	2006	8	230〜340	98〜110	22300〜35100	59〜84	20.2〜21.6	320〜600
〃	2007	8	230〜340	87〜102	21800〜33200	79〜92	19.4〜21.1	380〜540
〃	2008	8	180〜290	87〜 97	15700〜26900	68〜86	20.9〜22.7	260〜490
Takanari	2001	3	240〜250	176〜204	42800〜50800	68〜75	22.5〜23.8	710〜770
〃	2002	10	160〜270	103〜180	20300〜38600	76〜90	19.0〜21.3	320〜620
〃	2005	27	200〜310	146〜239	32100〜56700	43〜91	17.6〜22.5	450〜810
〃	2006	8	150〜230	165〜221	25500〜45000	63〜92	20.6〜22.0	400〜770
〃	2007	8	170〜310	137〜179	28300〜46000	67〜94	19.6〜21.2	440〜810
〃	2008	8	180〜270	122〜205	27500〜44700	68〜80	20.0〜20.9	430〜630

Table 6 Correlation coefficient of yield components to grain yield

Cultivar	Year	Panicle number per unit area	Spikelet number per panicle	Spikelet number per unit area	Percentage of ripened spikelet	1000-grains weight
Nipponbare	1998	-0.297	0.765**	0.293	0.673*	0.828**
〃	1999	0.651**	0.383	0.852**	-0.162	0.090
〃	2000	0.812**	-0.143	0.551**	0.350	0.206
〃	2001	0.966**	0.723**	0.996**	-0.964**	-0.185
〃	2002	0.879**	0.146	0.772**	-0.227	-0.420
Koshihikari	2000	0.624*	0.061	0.830**	-0.088	0.149
〃	2001	0.467	0.665*	0.518*	-0.178	0.734*
〃	2002	0.705**	0.428*	0.847**	0.133	0.253
〃	2005	-0.161	0.117	-0.014	0.909**	0.061
〃	2006	0.885**	-0.045	0.867**	0.748*	-0.232
〃	2007	0.833*	0.210	0.880**	0.111	-0.444
〃	2008	0.861**	0.491*	0.864**	0.358	0.273
Takanari	2001	0.882**	0.858*	0.862**	-0.668*	-0.347
〃	2002	0.786**	0.221	0.972**	-0.513	0.750**
〃	2005	0.418	0.055	0.391*	0.386	0.646*
〃	2006	0.676*	0.322	0.762**	0.338	0.661
〃	2007	0.945**	-0.270	0.814**	0.245	0.689
〃	2008	0.702	0.480	0.905**	-0.430	0.515

* and ** : significant at 0.05 and 0.01 probability level, respctively

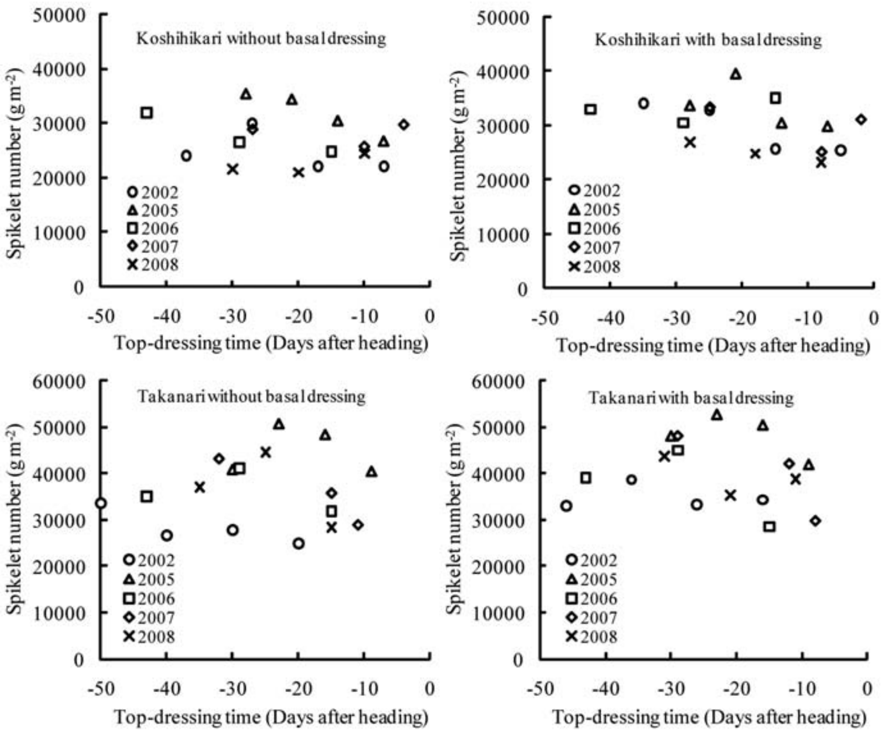

Fig. 1 Changes with N top-dressing time of spikelet number

number per unit area were shown in Fig. 1. The tendency was not clear, but generally the earlier N top-dressing led to increase of spikelet number per unit area of each cultivar. The difference of spikelet number between plots with and without basal dressing is not so large.

(2) **Nitrogen content**

Interpolated N concentration and content at the late spikelet differentiation stage (14 days before heading) and the heading stage were shown in Table 7. Plant N concentration at the late spikelet differentiation stage did not depend on basal dressing application but did depend on top-dressing application up to spikelet differentiation. There were slight decreases in plant N

Table 7 Nitrogen concentration and content

Cultivar	Year	Plot number	N concentration (%)		N content (g m^{-2})	
			-14	0	-14	0
Nipponbare	1999	10	0.89～1.70	0.81～1.25	5.3～13.7	7.6～12.6
〃	2000	6	0.93～1.35	0.89～2.00	4.5～ 8.3	7.5～17.7
〃	2001	11	1.31～1.65	1.03～1.21	7.3～10.8	9.1～ 9.6
〃	2002	10	0.99～1.37	0.72～1.08	3.9～10.3	4.2～11.1
Koshihikari	2001	4	1.30～1.31	1.03～1.31	5.3～ 7.6	8.1～ 9.1
〃	2005	27	1.20～2.57	0.96～1.97	4.6～15.6	6.8～19.1
〃	2006	8	1.44～2.49	1.01～1.75	4.9～13.1	7.7～14.6
〃	2007	8	1.22～1.78	1.01～1.34	3.7～ 8.0	6.2～11.5
〃	2008	8	1.13～2.35	0.70～1.39	2.7～ 8.7	4.3～ 9.1
Takanari	2002	10	0.88～1.39	0.70～1.39	2.8～ 7.8	4.4～12.1
〃	2005	27	0.95～2.42	0.89～1.78	3.8～19.3	6.8～20.3
〃	2006	8	0.97～2.37	0.74～1.58	3.5～12.5	5.0～11.8
〃	2007	8	1.17～2.07	0.68～1.27	3.2～ 8.4	3.7～ 9.6
〃	2008	8	0.80～2.10	0.62～1.29	1.8～11.4	3.5～ 7.4

-14 and 0 indicate 14 days before heading and heading, respectively.

concentration in most plots from the late spikelet differentiation stage to heading stage.

Plant N content at the late spikelet differentiation stage and heading stage in Nipponbare was 3.9–13.7 and 4.2–17.7, and 2.7–15.6 and 4.3–19.1 g m^{-2}, respectively. Plant N in Takanari varied widely, ranging from 1.8 to 19.3 at the late spikelet differentiation stage, and from 3.5 to 20.3 g m^{-2} at the heading stage, respectively (Table 7).

Discussion

Concerning city agriculture, we must pay attention to the surrounding environment, controlling the quality of grain and maintaining stable high yield. Tanazawa District is a typical city rice farming area of Atsugi City. In this district most of the rice farmers can only work in the paddy field on holidays. Therefore, N application management should be assessed in a view to N efficiency. We discuss the effect of plant N on spikelet production.

In this study the maximum grain yield of Nipponbare, Koshihikari and Takanari were 620, 640 and 810 g m^{-2}, respectively. High-yielding rice cultivars produce many spikelets. Nipponbare and Koshihikari produced fewer spikelets than Takanari, because Takanari had a higher spikelet number per panicle, generally about 100 more than Nipponbare and Koshihikari. KROPFF *et al.* (1994)[22] reported that spikelet number is proportional to biomass production during the period from panicle initiation to heading. Furthermore, both plant N and biomass production during panicle development affect spikelet number[1]. Especially in Takanari, crop growth rate (CGR) would be markedly high, as shown by TYLARAN *et al.* (2009)[8].

As mentioned above, grain yield in rice was affected mainly by spikelet number per unit area. In this study the relationship between spikelet number per unit area and grain yield was strong, except in years with extraordinary weather conditions. Therefore, it is important to obtain a lot of spikelets with N top-dressing for the early panicle development stage. In this respect, some studies have demonstrated that grain yield is related positively to spikelet number[23,24], and others have shown that grain yield reaches a plateau or gradually declines to a certain spikelet number[19,20]. The relationship between spikelet number and grain yield of each cultivar is shown in detail in Fig. 2. The figure indicates that this tendency was clear in our study, which showed that each cultivar had an optimum spikelet number for maximum grain yield, which was cultivar-dependent[19,20]. Optimum spikelet number for maximum grain yield was about 35000 m^{-2} in Nipponbare and Koshihikari, and about 48000 m^{-2} in Takanari (Fig. 2). MIYAMA and OKABE (1984)[20] conducted paddy field experiments in Chiba and showed that optimum spikelet number in Koshihikari, Todorokiwase and Hayahikari was 33000, 35000, and 36000 m^{-2}, respectively. These values are almost the same as those for Nipponbare and Koshihikari in our study. All these results clearly show that optimum spikelet number of Japonica rice is about 35000 m^{-2}, and that for Takanari is clearly the largest.

Figs 3 and 4 show the relation of plant N at the late spikelet differentiation stage and the heading stage to spikelet number of Nipponbare, Koshihikari and Takanari. Spikelet numbers of each cultivar were proportional to plant N at the late spikelet formation and the heading stage. Spikelet number in Takanari tended to be higher than in Nipponbare and Koshihikari at the same level of plant N. Many previous studies have

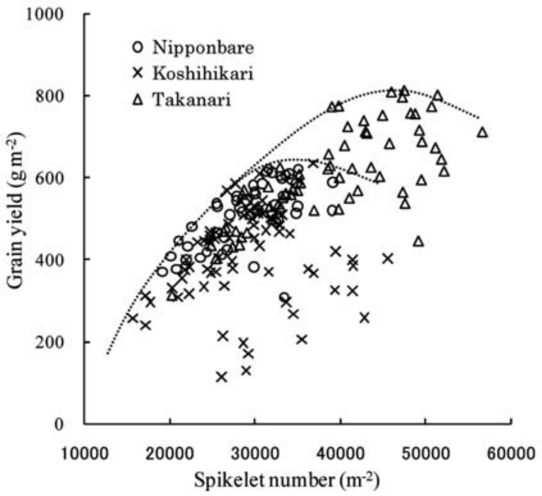

Fig. 2 Relationship between spikelet number and grain yield per unit area

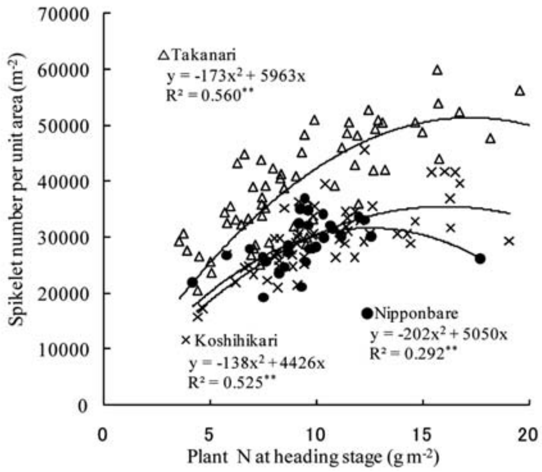

Fig. 4 Relationship between plant N at the heading stage and spikelet number
** : significant at 0.01 probability level

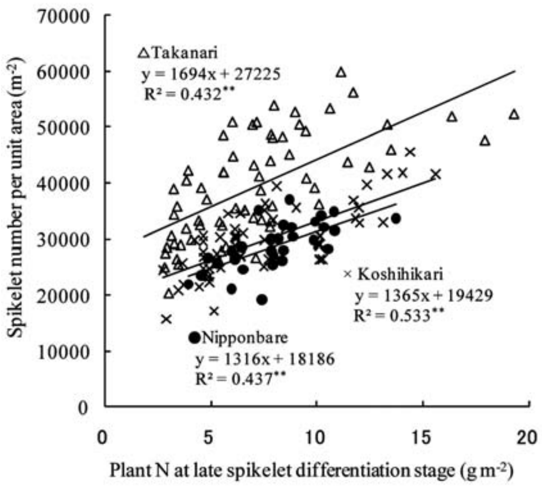

Fig. 3 Relationship between plant N at the late spikelet differentiation stage (14 days before heading) and spikelet number
** : significant at 0.01 probability level

shown that spikelet number is closely related to plant N content during the reproductive stage. Using N application experimental data for rice, WADA (1969)[1] found that spikelet number was linearly related to the amount of plant N at the late spikelet differentiation stage, while KAMIJI and HORIE (1988)[15] obtained a linear relationship between spikelet number and the amount of plant N at the panicle formation stage. MURAYAMA (1969)[17], however, showed that linear relationships between N content and spikelet number were location-specific. HASEGAWA *et al.* (1994)[25] extended MURAYAMA's study by hypothesizing that the number of spikelets is the product of a linear function of plant N concentration and a curvilinear function of crop dry weight. HORIE *et al* (1997)[26] obtained a relationship between plant N and spikelet number by the Michaelis-Menten equation, which indicated that spikelet number increased with an increase in crop biomass and plant N concentration, and that spikelet production efficiency per unit plant N declined as plant N increased. WADA (1969)[1] had already proposed that the number of spikelets generated was proportional to plant N content at the late spikelet differentiation stage, and suggested that the proportionality constant between degenerated and generated spikelet numbers was a function of CGR during the generation period, which closely corresponds to the 2-week period preceding heading. On the basis of these studies, YOSHIDA *et al.* (2006)[27] modeled spikelet number per area as a function of N content at the late spikelet differentiation stage and CGR during the generation period.

As mentioned above, WADA (1969)[1] showed that plant N at the late spikelet differentiation stage or heading stage influenced spikelet number, and proposed a simple model involving these factors, assuming the same linear relationship between plant N and spikelet numbers in the same location, regardless of cultivar, season, or cultivation method. In our study, the relationship between plant N at the late spikelet differentiation stage and spikelet number of Nipponbare and Koshihikariwas was almost the same, but different from the relationship for Takanari (Fig. 3). This relationship at heading of these three cultivars was completely different (Fig. 4). The relationships shown in Figs. 3 and 4 indicate that optimum spikelet numbers of Nipponbare, Koshihikari and Takanari derived from Fig. 2 are 12.8, 11.4 and 12.3 g m^{-2} at the late spikelet differentiation stage, and 12.5, 16.0 and 17.2 g m^{-2} at heading, respectively. A grain yield of 600 g m^{-2} in Nipponbare and Koshihikari and 750 g m^{-2} in Takanari would require spikelet numbers per unit area of 32000, 32000 and 40000, respectively, assuming that the percentage of ripened spikelets is 85%. To obtain these spikelet numbers, plant N must reach 10.5, 9.2 and 7.5 g m^{-2} at the late spikelet stage for these cultivars, and 12.1, 11.0 and 9.1 g m^{-2} at the heading stage, respectively.

Averaged plant N in N-free plots of Koshihikari and Takanari are 4.0 and 3.5 g m^{-2} at the late spikelet differentiation stage, and 6.3 and 4.9 g m^{-2} at the heading stage, respectively, in 2005–2008. Kamiji (2006)[28] reported that Tanazawa paddy field could produce mineralized N of 6.5 g m^{-2}, and Kaneko *et al.* (2008)[29] showed that N supply by irrigation and rainfall averaged 2.0 g m^{-2} in the same paddy field under average weather conditions. These results show that rice could use N efficiently from natural supply of N, and that 40–50% of total plant N must depend upon N application. In this respect, we should make good use of N top-dressing during early panicle formation, since rice can absorb much N, as suggested by Wang *et al.* (1997)[30], Fukushima (2007)[31] and Tylaran (2009)[8].

In conclusion, it was clear that the relationship between spikelet number and grain yield was close, and that optimum spikelet number for maximum grain yield is cultivar-specific, 35000 in Nipponbare and Koshihikari, and 48000 in Takanari, in Tanazawa paddy field. Plant N derived from natural supply of N was 50–60% of total plant N at late spikelet differentiation stage or heading stage. Therefore, to optimize spikelet number, we should make use of application of nitrogen top-dressing for early panicle formation duration, since rice can absorb much nitrogen, especially the cultivar Takanari.

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棚沢水田における水稲の最適穎花数と体内窒素量の検討

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（平成22年11月18日受付/平成23年3月10日受理）

要約：本研究は都市型農業がおこなわれている神奈川県厚木市の棚沢地区において，高度効率化を目指した窒素施肥管理の確立のために行ったもので，ここでは水稲の収量を最大にする最適穎花数とそのために必要な体内窒素量を検討した。栽培試験は東京農業大学棚沢水田において1998年から2008年にかけて行った。供試品種は水稲日本晴，コシヒカリおよびタカナリとし，試験区は典型的に施肥法が異なるもの，および基肥施用の有無と異なる追肥時期の組み合わせたもので構成し，合計180区であった。調査項目は収量および収量構成要，体内窒素濃度および体内窒素量の経時変化であった。タカナリは日本晴やコシヒカリよりも一穂穎花数が多い傾向にあり，その結果，単位面積あたり穎花数および玄米収量が明らかに多かった。単位面積あたり穎花数と玄米収量の関係は日本晴およびコシヒカリの日本型品種とタカナリとは明らかに異なった。収量を最大にする最適穎花数は日本晴およびコシヒカリでは35,000，タカナリでは48,000 m^{-2}であった。また，単位面積あたり穎花数は穎化分化終期および出穂期における体内窒素量の間には品種ごとに密接な関係があった。それらの関係を用いて最適穎花数に到達するために必要な出穂期における体内窒素量は日本晴，コシヒカリ，タカナリのそれぞれ，12.5，16.0，17.2 g m^{-2}であった。一方，無窒素区から算出した天然供給由来の吸収窒素量は体内窒素量の50～60％であり，残りは施肥に依存することになる。したがって，棚沢水田における水稲栽培では，最適穎花数を確保するために吸収率が高い幼穂発育期を中心とした窒素追肥を積極的に行うことが推奨される。

キーワード：水稲，窒素施用，体内窒素量，穎花数，収量

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