J. ISSAAS Vol. 26, No. 2: 1-16 (2020)

EFFECTS OF LONG-TERM FERTILIZATION ON PADDY RICE YIELD AND NITROGEN USE EFFICIENCY IN ANDOSOL

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(Received: May 19, 2020; Accepted: September 18, 2020)

ABSTRACT

Exploiting a long-term fertilization study in Andosol, the effects of N, P, K, Si and compost (Co) on grain yield and nitrogen use efficiency (NUE) were investigated using two rice cultivars, Nipponbare and Koshihikari. The application rate for each element in a standard (NPK) plot was 7.5 g m^{-2}. Plots with no fertilizer, with a deficiency or double dose of N, P, and/or K, with Co, and with NPK plus calcium silicate or Co were investigated. Three NUE parameters (NUEs) were measured: N use efficiency for grain yield (NUEg), recovery efficiency of N (REN) and partial factor productivity of N (PFPN). P fertilizer had the most important role in rice growth in the Andosol paddy field. Grain yield increased in 2NPK, N2PK and NPKSi plots compared to the NPK plot. NK, 2NPK, NPKCo and 2N2P2K plots showed reduced NUEs. The N2PK plot had increased REN and PFPN, while the NPKSi plot showed increased NUEs in 2018. The NP plot had reduced grain yield and NUEg in Koshihikari. Grain yield and NUEs can be maintained by a decrease in fertilizer N combined with adequate P application. K fertilizer may not be required for Nipponbare but should be applied to Koshihikari. Si could improve grain yield and NUEs whilst Co was not effective.

Key words: calcium silicate, nitrogen, phosphorus, potassium, rice straw compost

INTRODUCTION

Rice (*Oryza sativa* L.) is the most important staple food in the world, feeding more than 50 % of the world's population (Gyaneshwar et al. 2001). Fageria (2007) estimated that by 2025 rice production needs to increase to approximately 60 % more than current levels, corresponding to annual yield increases of at least 1.2 % (Normile 2008), to meet the food demands of the growing world population. Increasing fertilizer nutrient input, especially N fertilizer, has contributed considerably to improved crop yields globally (Xue et al. 2013). However, overuse of fertilizer and unbalanced NPK application rates to increase rice production have resulted in soil-related problems, such as acidification, structure degradation and organic matter loss (Zhong and Cai 2007). This leads to a yield decrease in rice production systems. The increase in the rate of rice yield decreased gradually from 3.0 % in 1981-1985 to 1.8 % in 1986-1990 and less than 1 % in recent years (FAOSTAT). Appropriate nutrient management is one of the most important factors for improving rice yield and maintaining sustainability.

Nitrogen use efficiency (NUE) is the main index used to evaluate crop production systems and it is related both to production quantity and environmental safety (Cassman et al. 2002). NUE reflects the relative balance between the amount of fertilizer supplied and the amount absorbed or used by a crop to produce grain, biomass or other end-products (Dawson et al. 2008). NUE is a complex trait which is affected by several factors, such as N application management, soil characteristics and climatic conditions (Zheng et al. 2007). Trends in reduction of NUE have been reported (Ladha et al. 2005) due to poor synchrony between N application and crop demand, leading to N loss through denitrification, surface runoff, volatilization and leaching (Raun and Johnson 1999). Low NUE thus not only increases production costs but also causes environmental pollution. NUE is therefore as important a factor as water use efficiency in crop production (Hirel et al. 2011).

Numerous studies to estimate NUE in rice have been conducted but they were almost all based on short-term experiments (Huang et al. 2016; Koutroubas and Ntanos 2003; Kumar et al. 2015; Xie et al. 2007; Ye et al. 2007). Long-term experiments are important in order to gain an understanding of how yield trends, soil dynamics and nutrient cycling are affected by year (Miao et al. 2011). Most experiments conducted over long-term periods have focused on evaluating the effect of fertilization on alterations in rice yield or paddy soil fertility (Chen et al. 2017; Dawe et al. 2003; Dong et al. 2012; Manna et al. 2005; Watanabe et al. 2009). There are only a few studies which focused on NUE under long-term fertilization (Duan et al. 2014; Yadvinder et al. 2009) and they were conducted in rice-wheat systems. There is also a need to evaluate the effects of P and K on NUE in rice production systems using long-term experiments.

The long-term fertilization experiment described here has been carried out at a paddy field in University of Tsukuba, Japan since 1978 using the variety Nipponbare (Yonekawa et al. 2001). The experiment was conducted in Andosol, the typical soil developed from volcaniclastic material with high aluminum (Al) and organic matter contents (Shoji and Takahashi 2002). The Al-humus complexation strongly contributes to organic matter accumulation in Andosols, but it also delays the decomposition of organic matter due to Al toxicity to some microorganisms (Takahashi and Dahlgren 2016). Andosol has relatively high available Si content (Yanai et al. 2016), but rice, as a Si accumulator, removes more Si than essential nutrients (N, P and K) so continuous cropping can lead to a reduction in the level of available Si in the soil (Meunier et al. 2008). The objective of this experiment is to evaluate the effect of different fertilizers, include N, P, K, Si and compost on rice yield but not to look at NUE. Nipponbare was one of the most popular cultivars in Japan, but nowadays, Koshihikari is the most widely cultivated in the country, accounting for 36.2 % of the total paddy rice area in Japan (Kobayahi et al. 2018). We therefore conducted research based on this long-term fertilization experiment to evaluate the role of N, P, K, Si and compost on rice yield and NUE in two rice cultivars, Nipponbare and Koshihikari. Direct data on grain yield and NUE from this long-term fertilization experiment in the paddy field will contribute to improving the efficiency of fertilizer management.

MATERIALS AND METHODS

Study site and weather conditions. The experiment was conducted at the long-term fertilization experiment site in Tsukuba-Plant Innovation Research Center, University of Tsukuba, Ibaraki, Japan (36°12'N, 140°09'E, 25 m above sea level). The site has been in operation since 1978. The soil was classified as Andosol (IUSS Working Group WRB 2015). The soil chemical properties before starting the long-term experiment were pH (H_2O) 5.12, humus 8.3 %, total nitrogen 0.3 %, available phosphorus 3.6 mg $100g^{-1}$, exchangeable K 20.3 mg $100g^{-1}$, exchangeable Ca 58.8 mg $100g^{-1}$ and exchangeable Mg 13.6 mg $100g^{-1}$.

The weather data were collected at Tsukuba (Tateno) Weather Station, which is located at a distance of 10 km from the site (Japan Meteorological Agency) (Fig.1). The temperature from late June to the middle of July in 2019 (21.1-22.5 ˚C) was much lower than that in 2018 (24.2-28.8 ˚C), while temperature in early and middle of August in 2019 (29.3 and 27.7 ˚C) was higher than those in both 2018 (27.4 and 25.6 ˚C) and the 30-year average (25.8 and 25.6 ˚C) respectively. Total precipitation in June, July, and August in 2018 and 2019 was 265 mm and 359 mm respectively. This was less than the 30-year average, 388 mm (data not shown). However, it did not affect rice growth because the paddy field is well irrigated.

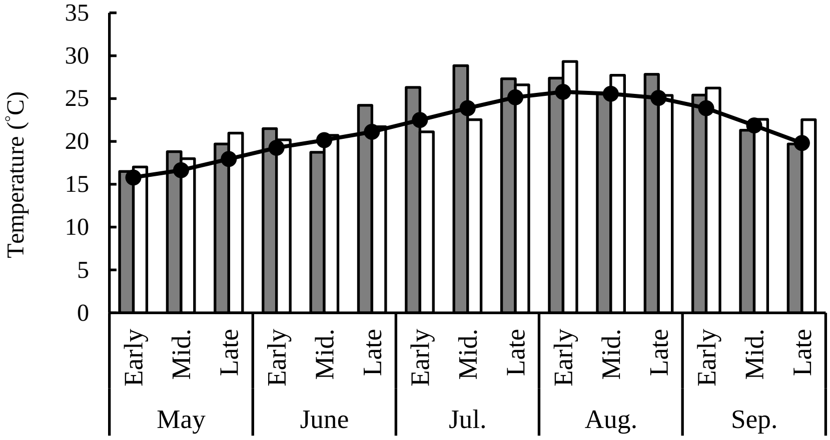


Fig. 1. Average ten-day mean temperature during the rice growing season in Tsukuba. Grey and white bars represent the years 2018 and 2019 respectively. The solid line indicates averages for the 30 years from 1981 to 2010 (data from the Japan Meteorological Agency).

Experimental design and field management. The long-term experimental site was divided into 12 fertilization plots with different combinations of inorganic N, P, K, Si and compost (Co), or with no supplement (Zero) (Table 1). For N application, two-thirds was applied seven days before transplanting as a basal dressing, and one-third was divided into two equal parts, which were applied at 35 and 20 days before heading (DBH). All inputs of P, K, Si and Co were applied as a basal dressing, except in NP2K and 2N2P2K plots. In the latter plots, two-thirds of the K was applied as a basal dressing and one-third of it was applied as two equal treatments at 35 and 20 DBH. Ammonium sulfate (21 % N), superphosphate (34 % P_2O_5), potassium sulfate (50 % K_2O), and calcium silicate were used as, respectively, N, P_2O_5, K_2O, and Si fertilizer. Co was prepared from rice straw two years before use. Moisture content, N content (% dry weight), and C-N ratio of Co were, respectively, 84.3 %, 1.7 %, and 17.1 in 2018 and 80.5 %, 1.7 %, and 17.7 in 2019.

Table 1. Fertilizer application rates in the long-term experiment (g m^{-2})

Plot	N	P_2O_5	K_2O	Co [1]	Si [1]
Zero	0	0	0	0	0
PK	0	7.5	7.5	0	0
NK	7.5	0	7.5	0	0
NP	7.5	7.5	0	0	0
NPK	7.5	7.5	7.5	0	0
NPKCo	7.5	7.5	7.5	1000	0
Co	0	0	0	1000	0
2NPK	15	7.5	7.5	0	0
N2PK	7.5	15	7.5	0	0
NP2K	7.5	7.5	15	0	0
2N2P2K	15	15	15	0	0
NPKSi	7.5	7.5	7.5	0	100

[1] Co and Si mean the amount of rice straw compost and calcium silicate respectively.

The experiment was conducted in 2018 and 2019 using two rice cultivars, Nipponbare and Koshihikari with no replication. Each fertilization treatment plot was divided into two areas for the two cultivars. Each area for one cultivar was 25 m^2 (10 m x 2.5 m). The 21-day-old seedlings were transplanted by hand on May 28, 2018 and May 31, 2019. Transplanting density was 22.2 hills m^{-2} (30 cm x 15 cm) with four seedlings per hill. Midseason drainage was conducted for five days from 39 days after transplanting (DAT) in 2018 and 35 DAT in 2019. With exception of these drainage periods, the field was continuously flooded with water to a level of 2-3 cm above the soil surface until one week before the final harvest. Weeds, insects, and diseases were controlled using herbicides and pesticides based on the standard control guidelines for this area.

Sampling and measurements. Koshihikari and Nipponbare were harvested at the maturity stage, which was generally at 120 DAT and 126 DAT respectively. Due to their slower development, rice plants in Zero, NK and Co plots were harvested 10 days later for each cultivar. Above-ground parts of rice plants were sampled with 3 replications and dried at 80 ˚C for 72 h for measuring dry weight. Dried samples were then crushed to a fine powder (< 1 mm) with a cutting mill (SM-100, Retsch GmbH, Germany) and N content was determined by the dry-combustion method using an automatic NC analyzer (NC-220F, Sumika Chemical Analysis Service, Ltd., Japan). Nitrogen uptake was calculated by multiplying dry weight by the N content of the dry matter. Fifty hills in each plot were harvested to evaluate grain yield and yield components based on a standard procedure. Grain weight was expressed at 15 % moisture content. (Maruyama 2007; Yonekawa et al. 2001)

Nitrogen harvest index (NHI) and three NUE parameters (Yu et al. 2015) were calculated as follows:

$$\text{NHI (g g}^{-1}\text{)} = \text{N uptake in panicle / TN} \qquad (1)$$

$$\text{NUEg (g gN}^{-1}\text{)} = \text{GY / TN} \qquad (2)$$

$$\text{REN (\%)} = [(\text{TN}_f - \text{TN}_0) / \text{N}_f] \times 100 \qquad (3)$$

$$\text{PFPN (g gN}^{-1}\text{)} = \text{GY}_f / \text{N}_f \qquad (4)$$

where: GY is grain yield, GY_f is grain yield with N application, TN is total plant N uptake, TN_f is total plant N uptake with N application, TN_0 is total plant N uptake without N application, N_f is N fertilizer application rate. REN was calculated using the Zero treatment plot as being without N application.

NHI is the ratio of amount of N in the panicle to amount of N in aboveground plant biomass (Eq. (1)). Nitrogen use efficiency for grain yield (NUEg) describes the amount of grain yield produced per unit plant N uptake into aboveground dry matter (Eq. (2)). Recovery efficiency of nitrogen (REN) expresses the percentage of fertilizer N recovered in aboveground plant biomass (Eq. (3)). Partial factor productivity of nitrogen (PFPN) is an integration of N uptake efficiency and N utilization efficiency, calculated as the ratio of grain yield to amount of N applied (Eq. (4)).

Statistical analysis. Data processing and statistical analysis were performed using Microsoft Excel and JMP 8 software (SAS Institute Japan Inc., Japan). Analysis of variance (ANOVA) was used for analyzing the effects of factors. Differences between plots were identified by Tukey’s honest significant difference (HSD) test or a t-test with p = 0.05.

RESULTS AND DISCUSSION

Dry weight and nitrogen uptake by rice plants. In 2018, the 2N2P2K plot had significantly more dry weight of Nipponbare (1351 g m^{-2}) compared to the NPK plot (1122 g m^{-2}), while 2N2P2K and N2PK plots increased dry weight of Koshihikari to, respectively, 1376 g m^{-2} and 1350 g m^{-2} compared to 1084 g m^{-2} in the NPK plot (Fig.2a). In 2019, the highest biomass was 1326 g m^{-2} for Nipponbare in the N2PK plot and 1146 g m^{-2} for Koshihikari in the 2N2P2K plot, both 21 % higher than in the NPK plot (Fig.2b). Among the nutrient deficiency (Zero, PK, NK, NP and Co) plots, dry weights of the two cultivars in the NP plot were similar to those in the NPK plot, while dry weight in the PK plot was significantly less than that in the NPK plot but much greater than that in the Zero, NK and Co plots. NP2K, NPKCo and NPKSi plots did not show any increase in dry weight of Nipponbare and Koshihikari compared to the NPK plot. The biomasses of the two cultivars in the NPK plot in 2019 were lower than those in 2018. The other plots were similar except for the Co plot (Fig.2).

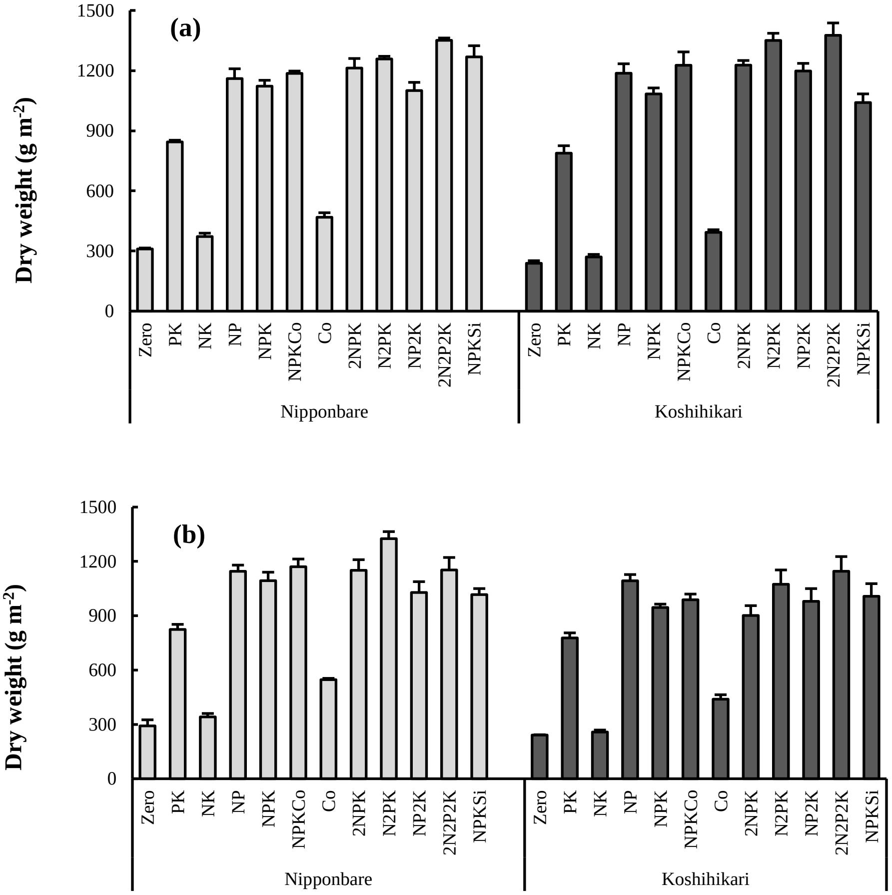
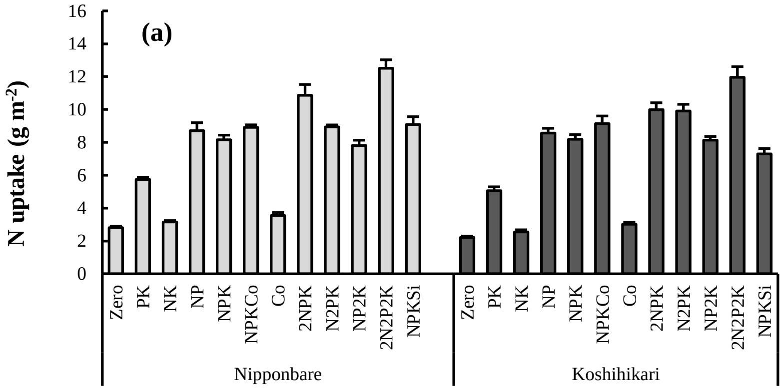


Fig. 2. Dry weight at maturity stage of the two rice cultivars as affected by fertilization conditions in 2018 (a) and 2019 (b). Vertical bars indicate standard error (SE).

Nipponbare in the 2N2P2K plot had the highest N uptake (12.5 g m^{-2} in 2018 and 13.6 g m^{-2} in 2019, values which were respectively 53 % and 51 % higher than that from the NPK plot). The application of 2NPK in 2018, and 2NPK and N2PK in 2019, also enhanced N uptake by Nipponbare compared to the NPK plot. In the case of Koshihikari, only the 2N2P2K plot increased N uptake significantly, to 12.0 g m^{-2}, 46 % higher than the NPK plot in 2018, and 14.3 g m^{-2}, which was 58 % higher than the NPK plot, in 2019 (Fig.3). Among the nutrient deficiency plots, N uptake in the NP plot was not significantly different from that in the NPK plot, while N uptake values in the PK plot were significantly lower than those in the NPK plot and much higher than those in the Zero, NK and Co plots. N uptake values by the two cultivars in 2019 were higher than those in 2018, except for Nipponbare in the NPKSi plot and Koshihikari in the 2NPK plot (Fig.3).



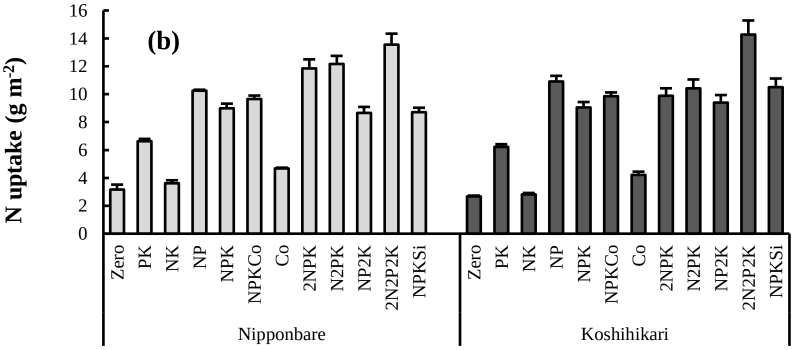


Fig. 3. Nitrogen uptake at maturity stage of the two rice cultivars as affected by fertilization conditions in 2018 (a) and 2019 (b). Vertical bars indicate SE.

Grain yield and yield components. In general, the effects of fertilization conditions on grain yield of Nipponbare in the present study were similar to those in a previous report by Yonekawa et al. (2001). The grain yield of Nipponbare differed little between 2018 and 2019 and was almost same as the average grain yield during the period 1978 to 1999. Meanwhile, the grain yield of Koshihikari was less in 2019 than in 2018 under all fertilization conditions (Table 2). This reduction was caused mainly by a reduction in filled grain percentage. The heading stage for Koshihikari occurred 7-10 days earlier than that for Nipponbare, so the panicle development period in Koshihikari was affected by low temperature from late June to the middle of July (21.1-22.5 ˚C in 2019 compared to 24.2-28.8 ˚C in 2018). This indicates that low temperature affected the early type, Koshihikari, but not the late type Nipponbare in our experimental years. However, the effect of fertilization conditions on grain yield was similar in the two years. Grain yield of the two cultivars was lowest in the Zero or NK plot, ranging from 92-106 g m^{-2} for Nipponbare and 63-93 g m^{-2} for Koshihikari, due to a marked decrease in panicle number and spikelet number per panicle. Andosol, known as volcanic ash soil, has a high aluminum content, and its reaction with inorganic phosphate renders the phosphate essentially insoluble and unavailable for plant uptake (Shoji and Takahashi 2002). P fertilization therefore is important for rice growth and development in Andosol. The lack of P fertilizer in the NK plot severely affected tiller number, resulting in decreases in dry weight, N uptake and grain yield of the two cultivars.

Table 2. Grain yield and yield components affected by fertilization conditions for the two cultivars

Cultivar	Plot	2018					2019				
		Panicle no. (hill^{-1})	Spikelet no. (panicle^{-1})	Filled grain (%)	1000-grain weight (g)	Yield (g m^{-2})	Panicle no. (hill^{-1})	Spikelet no. (panicle^{-1})	Filled grain (%)	1000-grain weight (g)	Yield (g m^{-2})
Nipponbare	Zero	4.8	53.0	79.7	20.8	94	5.0	44.4	85.6	22.2	94
	PK	9.2	74.0	81.2	22.8	280	8.4	84.1	64.9	21.5	219
	NK	5.4	52.8	77.3	21.6	106	5.2	44.4	79.5	22.5	92
	NP	12.2	75.7	66.9	23.6	324	11.1	86.6	71.8	22.1	339
	NPK	12.4	68.2	74.1	22.6	314	11.2	83.1	69.2	22.5	322
	NPKCo	12.5	68.9	76.7	23.4	343	11.9	81.5	63.5	22.4	306
	Co	6.6	60.1	70.6	21.8	136	8.0	56.4	76.4	23.7	181
	2NPK	13.3	83.4	67.8	22.6	377	13.4	87.6	76.7	21.7	434
	N2PK	14.9	71.4	78.5	22.2	412	14.1	84.2	62.9	22.6	375
	NP2K	13.0	70.3	67.6	22.7	311	11.2	90.9	64.4	22.6	329
	2N2P2K	17.2	71.4	73.2	21.8	435	16.8	85.9	56.8	21.6	393
	NPKSi	13.3	74.9	77.3	22.9	392	12.6	76.3	62.8	22.2	298
Koshihikari	Zero	4.5	57.9	80.8	19.9	93	5.5	38.1	69.1	19.5	63
	PK	9.6	86.7	82.6	21.6	330	8.6	95.1	67.1	21.6	263
	NK	4.3	54.3	83.5	20.2	88	5.4	41.0	69.3	19.5	66
	NP	11.9	91.5	73.5	22.2	395	11.0	95.0	56.7	22.2	292
	NPK	13.2	96.0	67.7	22.2	423	10.8	105.8	54.1	22.4	308
	NPKCo	13.5	92.9	71.1	22.3	441	11.6	100.5	60.9	22.3	352
	Co	5.9	59.7	78.5	20.7	127	7.2	65.0	58.6	20.4	124
	2NPK	12.2	102.2	74.6	21.3	440	12.1	106.6	46.6	22.5	300
	N2PK	15.8	81.1	69.5	22.3	441	13.6	98.6	52.7	22.0	345
	NP2K	13.0	88.7	74.0	22.0	417	11.2	92.1	63.6	22.2	323
	2N2P2K	17.5	79.0	41.6	21.1	269	14.9	105.6	18.4	21.2	136
	NPKSi	12.1	98.6	78.1	22.2	459	12.3	87.3	60.8	21.9	318

A deficiency of N fertilizer did not affect rice yield as seriously as P deficiency. In the PK plot, the grain yield of Nipponbare was 219-280 g m^{-2}, representing 68-89 % of that in the NPK plot, while the grain yield of Koshihikari was 263-330 g m^{-2}, 78-86 % of the value for the NPK plot, resulting from a reduction in panicle number (Table 2). N can be supplied from natural N sources such as rainfall, irrigation and biological N fixation (BNF) (Ghosh and Saha 1997; Sinha and Hader 1996). Moreover, BNF is generally dependent on the available P content in soil (Ishii et al. 2011), so the N-deficient but P-sufficient conditions in the PK plot might increase BNF. Thus, since application of P not only improves rice yield but also promotes BNF activity, it can lead to a decrease in fertilizer N requirement. Compared to Nipponbare, Koshihikari had a higher grain yield in the PK plot but a lower grain yield in the NK plot, indicating that Koshihikari was more sensitive to P deficiency than N deficiency. Grain yield increased in the 2NPK and N2PK plots compared to the NPK plot, with the increase being greater in Nipponbare (16-35 %) than in Koshihikari (4-12 %).

Unlike N and P, K fertilizer had a negligible effect on rice yield in Andosol, although the grain yield of Koshihikari declined slightly (5-7 %) in the NP plot compared to the NPK plot (Table 2). Total K content in fresh volcanic ashes ranges from 0.5 to 4.0 % as K_2O, so only a small number of Andosols supply insufficient K for crops (Shoji and Takahashi 2002). Similarly, a long-term experiment conducted on a Pyeongtaeg series soil type in Korea indicated that grain yield in an NP plot was 96 % of that in an NPK plot due to the adequate amount of extractable K in the soil. An additional supply of K through the irrigation water would also provide adequate K in an irrigated rice system (Lee et al. 2008).

In the 2N2P2K plot, the grain yield of Nipponbare was 393-435 g m^{-2}, 22-38 % higher than in the NPK plot, while the grain yield of Koshihikari was 136-269 g m^{-2}, 36-56 % lower than in the NPK plot, because of lodging at the ripening stage. One of the disadvantages of Koshihikari is its low resistance to lodging (Kobayashi et al. 2018), therefore, the application of too much chemical fertilizer, for example in the 2N2P2K plot, was not beneficial for grain yield in Koshihikari.

Grain yield of Nipponbare in the NPKSi plot was 92-125 % of that in the NPK plot whilst that of Koshihikari was 103-109 % of the NPK plot value (Table 2). Si has a synergistic effect with N uptake, increasing leaf erectness and thus light interception in rice plants, thereby improving photosynthesis and grain yield (Pati et al. 2016; Savant et al. 1997). The co-application of Si with standard fertilization positively affected grain yield and N uptake in the BC15 cultivar grown in the city of Thanh Hoa, Vietnam (Cuong et al. 2017). The presence of silicate promotes the release of native inorganic phosphorus in Andosol (Hartono and Bilhaq 2014). In the present study, the combination of Si with NPK increased grain yield slightly in Koshihikari, but to a much greater extent in Nipponbare in 2018, suggesting that the effectiveness of Si fertilizer on grain yield depends on genotype.

For both cultivars, grain yield in the Co plot was higher than that in the Zero plot but grain yield in the NPKCo plot was similar to that in the NPK plot (Table 2). Recycling of rice straw can significantly reduce total N fertilizer requirements (Cassman et al. 1998) and maintain soil K and Si status in intensive rice systems (Dobermann and Fairhurst 2000). However, due to the low N content and high C-N ratio, the combination of rice straw compost with NPK did not lead to any considerable improvement in rice yield in our study. Similarly, rice straw had an insignificant effect on grain yield in long-term experiments in Asia (Dawe et al. 2003). A long-term field trial conducted on alluvial soil in the Mekong Delta showed that continuous application of rice straw compost did not significantly affect grain yield but had some positive impacts on soil physical properties (Watanabe et al. 2009).

Nitrogen use efficiency and its relationship with grain yield. The nitrogen harvest index (NHI) of Nipponbare in 2018 was highest in the Co plot (0.71), followed by the NK plot (0.67), and the PK and Zero plots (0.65). These values were significantly higher than that in the NPKCo plot (0.57), the 2NPK plot (0.56) and the 2N2P2K plot (0.54) (Fig.4a). In 2019, the highest NHI of Nipponbare was observed in the Co plot (0.64), but it was not significantly different from those in the NP2K, Zero, NP, NPK and NPKSi plots (Fig.4b). The NHI of Koshihikari ranged from 0.58 to 0.71 in 2018 and 0.43 to 0.65 in 2019. Zero, NK, Co and 2N2P2K plots in 2018, and the 2N2P2K plot in 2019, showed significantly lower NHI values than other plots (Fig.4).

In 2018, the nitrogen use efficiency for grain yield (NUEg) of Nipponbare in the PK plot (48.7 g gN^{-1}), N2PK plot (46.1 g gN^{-1}) and NPKSi plot (43.1 g gN^{-1}) were much higher than that in the NPK plot (38.5 g gN^{-1}). For Koshihikari, NUEg values in the PK plot (65.2 g gN^{-1}) and NPKSi plot (62.9 g gN^{-1}) were greater than that in the NPK plot (51.6 g gN^{-1}). In 2019, only the NUEg of Koshihikari in the PK plot (42.3 g gN^{-1}) was markedly higher than that in the NPK plot (34.0 g gN^{-1}) (Table 3). The optimal NUEg for irrigated rice has been reported to be 68 g gN^{-1} (Witt et al. 1999). In both years, Zero, NK and 2N2P2K plots decreased NUEg in Nipponbare, while Zero, NK, NP, Co, 2NPK, N2PK and 2N2P2K plots decreased NUEg in Koshihikari, compared to the NPK plot. Recovery efficiency of nitrogen (REN) and partial factor productivity of nitrogen (PFPN) for the two cultivars were lowest in the NK plot, ranging from 1.9-6.0 % and 8.9-14.1 g gN^{-1} respectively. NPKCo, 2NPK and 2N2P2K plots also decreased these parameters compared to the NPK plot. Low REN but high PFPN was observed in the Co plot. In particular, the PFPN of Nipponbare was highest in the Co plot (56.5 g gN^{-1} in 2018 and 69.8 g gN^{-1} in 2019). Compared to the NPK plot, the N2PK plot increased REN and PFPN for both cultivars, while the NPKSi plot increased the REN and PFPN of Nipponbare and PFPN of Koshihikari in 2018, and the REN of Koshihikari in 2019 (Table 3).

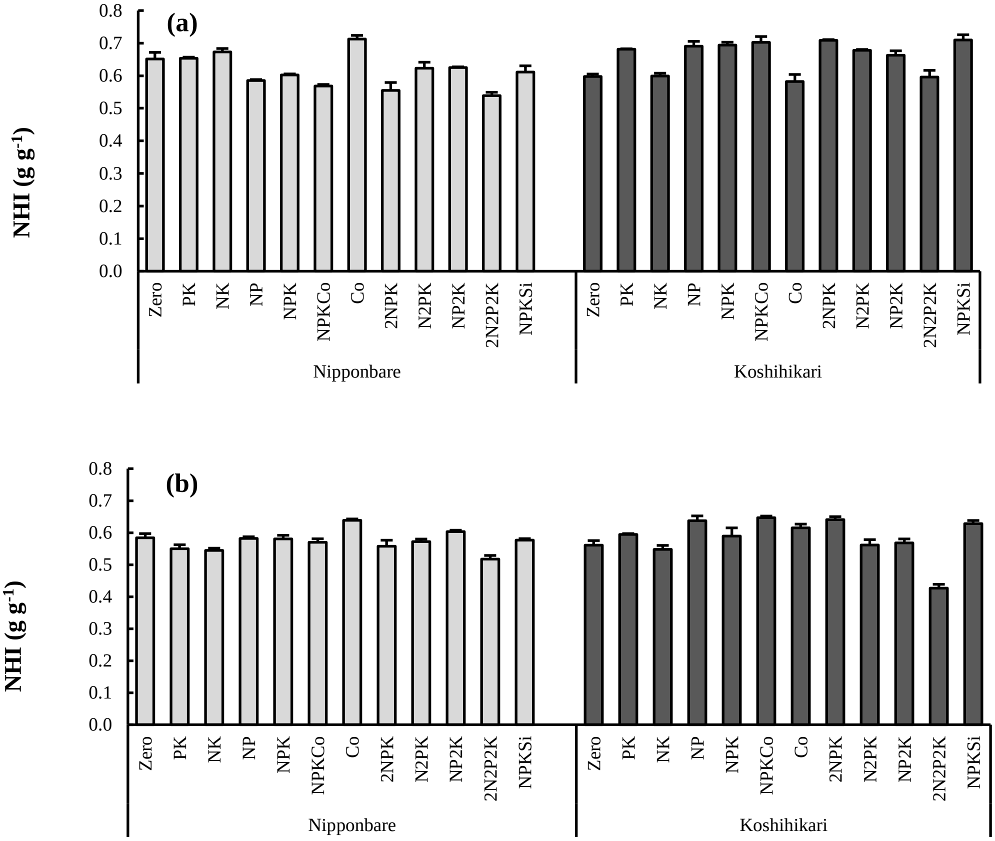
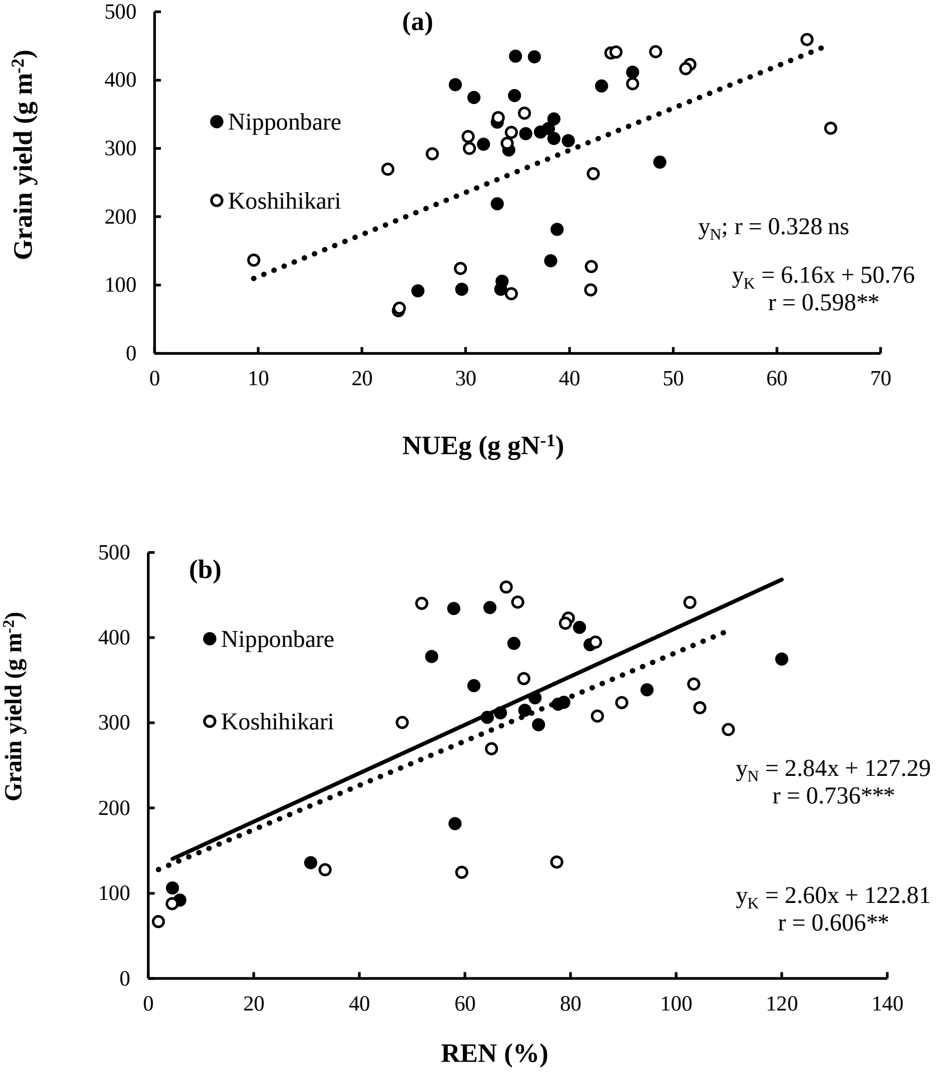


Fig. 4. Nitrogen harvest index (NHI) as affected by fertilization conditions in 2018 (a) and 2019 (b). Vertical bars indicate SE.

Increasing N application rate in NPKCo, 2NPK and 2N2P2K plots decreased all NUE parameters (NUEs) regardless of cultivar, a finding consistent with those of previous studies (Kumar et al. 2015; Xie et al. 2007; Ye et al. 2007). The application of P improved NUEs is consistent with a study by Duan et al. (2014). Increasing P application rate up to 15 g m^{-2} (N2PK) improved N uptake and grain yield, as a result of higher REN and PFPN values compared to standard fertilization (NPK). However, NUEg in the N2PK plot was usually less than that in the NPK plot, showing that N absorbed by plants was not always converted to grain efficiently. When increased N uptake by a crop is greater than the increase in grain yield, the phenomenon is often termed luxury absorption (Cui et al. 2009). The weaker effect of K fertilizer, compared with N and P fertilizers, on NUEs in rice may well be soil type dependent because of the relatively high level of available K in Andosol, as in the research of Duan et al. (2014). Nevertheless, K deficiency reduced NUEg in Koshihikari compared to the NPK plot, suggesting that K fertilizer should be applied to Koshihikari to enhance N utilization efficiency. The role of calcium silicate in the improvement of NUEs observed in 2018 was consistent with previous reports (Ku et al. 2017; Yogendra et al. 2013). A high PFPN was found in the Co plot because N supply was low relative to grain production. However, the low grain yield in the Co plot is not likely to benefit farmers. Increasing the amount of Co in order to enhance crop-available nutrients and yield might present difficulties in storing and transporting the compost as well as increasing labor costs (Gao et al. 2006).

The relationship between grain yield and NUE parameters affected by fertilization conditions was dependent on cultivar (Fig.5). For Nipponbare, significant correlation was observed only between grain yield and REN (r = 0.736***). On the other hand, correlation between grain yield and NUEg (r = 0.598**), REN (r = 0.606**) and PFPN (r = 0.620**) was observed in Koshihikari. Improving N uptake efficiency might increase grain yield in Nipponbare, while the grain yield of Koshihikari could be increased by improving both nitrogen uptake efficiency and nitrogen utilization efficiency.



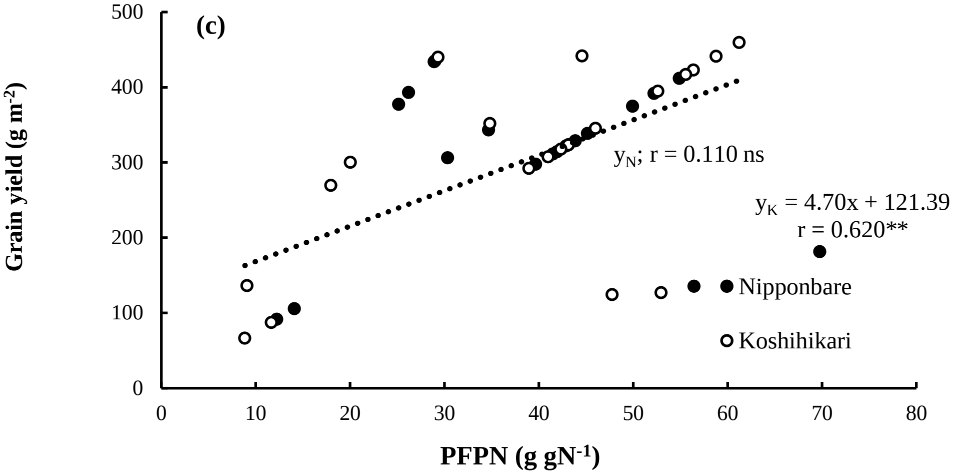


Fig. 5. Relationships between grain yield and nitrogen use efficiency for grain yield, NUEg (a); grain yield and recovery efficiency of nitrogen, REN (b); and grain yield and partial factor productivity of nitrogen, PFPN (c) as affected by fertilization conditions.

ns, ** and *** mean not significant, and significant at the 0.01 and 0.001 level respectively; y_N and y_K mean grain yield of Nipponbare and Koshihikari respectively; solid and dotted lines are regression for Nipponbare and Koshihikari respectively.

The finding that Koshihikari had a higher REN than Nipponbare under all fertilization conditions, excepting NK and 2NPK plots (Table 3), may be related to root architecture traits such as root length density and absorption area (Garnett et al. 2009). The lower REN of Koshihikari in the 2NPK plot may be due to greater losses from the system rather than a reduction in plant absorption. The unfavorable temperature adversely affected the panicle developing period in Koshihikari, hence inhibiting the translocation and mobilization of absorbed N for grain production. As a result, the NUEg of Koshihikari decreased considerably in 2019 and was lower than that of Nipponbare, although a higher value was observed in 2018 (Table 3). Thus, N utilization efficiency can be enhanced through genetic improvement but is also dependent on the constantly changing environment during the rice growing season, especially with respect to air temperature.

CONCLUSION

Understanding the various effects of long-term application N, P, K, Si, and compost on rice yield and NUEs is necessary to contribute the development of optimal fertilizer management. On Andosol, P fertilizer had the most important role for improving both yield and NUEs. With adequate P application, grain yield and NUEs of Nipponbare and Koshihikari can be maintained with a decrease in N fertilizer. Koshihikari was more sensitive to P deficiency than N deficiency. K fertilizer had negligible effect on yield and NUEs of Nipponbare but it should be applied to Koshihikari to enhance grain yield and NUEs. The effectiveness of Si fertilizer on grain yield and NUEs depends on genotype and environment. Nevertheless, as a Si accumulator, rice may need Si as a component of balance nutrition. Rice straw compost combined with standard fertilization did not lead to any considerable improvement in rice yield and NUEs.

Table 3. Nitrogen use efficiency parameters as affected by fertilization conditions.

Cultivar	Plot	2018			2019		
		NUEg (g gN^{-1})	REN (%)	PFPN (g gN^{-1})	NUEg (g gN^{-1})	REN (%)	PFPN (g gN^{-1})
Nipponbare	Zero	33.4 (87)	-	-	29.6 (83)	-	-
	PK	48.7 (126)	-	-	33.0 (92)	-	-
	NK	33.5 (87)	4.6 (6)	14.1 (34)	25.4 (71)	6.0 (8)	12.2 (29)
	NP	37.2 (96)	78.7 (110)	43.2 (103)	33.0 (92)	94.5 (122)	45.1 (105)
	NPK	38.5 (100)	71.3 (100)	41.9 (100)	35.8 (100)	77.7 (100)	42.9 (100)
	NPKCo	38.5 (100)	61.7 (86)	34.7 (83)	31.7 (89)	64.3 (83)	30.3 (71)
	Co	38.2 (99)	30.8 (43)	56.5 (135)	38.8 (108)	58.1 (75)	69.8 (163)
	2NPK	34.7 (90)	53.7 (75)	25.2 (60)	36.6 (102)	57.9 (75)	28.9 (67)
	N2PK	46.1 (119)	81.7 (115)	54.9 (131)	30.8 (86)	120.0 (155)	49.9 (116)
	NP2K	39.9 (103)	66.7 (94)	41.5 (99)	38.0 (106)	73.2 (94)	43.9 (102)
	2N2P2K	34.8 (90)	64.7 (91)	29.0 (69)	29.0 (81)	69.2 (89)	26.2 (61)
	NPKSi	43.1 (112)	83.7 (117)	52.2 (125)	34.2 (95)	74.0 (95)	39.7 (92)
Koshihikari	Zero	42.0 (81)	-	-	23.5 (69)	-	-
	PK	65.2 (126)	-	-	42.3 (124)	-	-
	NK	34.4 (67)	4.5 (6)	11.7 (21)	23.6 (69)	1.9 (2)	8.9 (22)
	NP	46.1 (89)	84.7 (106)	52.6 (93)	26.8 (79)	109.9 (129)	38.9 (95)
	NPK	51.6 (100)	79.6 (100)	56.4 (100)	34.0 (100)	85.1 (100)	41.0 (100)
	NPKCo	48.3 (94)	70.0 (88)	44.6 (79)	35.7 (105)	71.2 (84)	34.8 (85)
	Co	42.1 (82)	33.5 (42)	53.0 (94)	29.5 (87)	59.4 (70)	47.8 (117)
	2NPK	44.0 (85)	51.8 (65)	29.3 (52)	30.4 (89)	48.1 (57)	20.0 (49)
	N2PK	44.5 (86)	102.6 (129)	58.8 (104)	33.1 (97)	103.3 (121)	46.0 (112)
	NP2K	51.2 (99)	79.0 (99)	55.6 (99)	34.4 (101)	89.7 (105)	43.1 (105)
	2N2P2K	22.5 (44)	65.0 (82)	18.0 (32)	9.5 (28)	77.4 (91)	9.1 (22)
	NPKSi	62.9 (122)	67.8 (85)	61.2 (109)	30.2 (89)	104.5 (123)	42.3 (103)

NUEg, nitrogen use efficiency for grain yield, NUEg = Grain yield/total plant N uptake
REN, recovery efficiency of nitrogen, REN = (Total plant N uptake in N application plot - Total plant N uptake in Zero plot)/N applied rate x 100
PFPN, partial factor productivity of nitrogen, PFPN = Grain yield/N applied rate
Numerical values in parentheses are percentages of the value from the NPK plot for each cultivar; REN and PFPN were not calculated for Zero and PK plots because nitrogen fertilizer was not applied to these plots.

ACKNOWLEDGEMENT

We would like to express our great appreciation to Ms. Keiko Sugawara and Mr. Kazunori Yonekawa, technical staff of the Division of Crop Production, Tsukuba-Plant Innovation Research Center, University of Tsukuba, for supporting the field management. This research was partly supported by the "Sustainable Food Security Research Project" in the form of an operational grant from the National University Corporation.

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