

REVIEW

Development of a Site-Specific Nitrogen Management System for Paddy Rice

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Abstract

Land consolidation involving the joining of small paddy fields to form a large-size field has been promoted recently in Japan in order to increase the efficiency of rice production. However, the variability in soil fertility within a large-size field causes problems for rice production such as late heading, lodging, and deterioration of rice quality. To address these problems, a site-specific nitrogen management system for paddy rice was developed. In this paper, we briefly review the concept and the achievement of precision agriculture, outline the site-specific management system which we developed, and present the results of the application of this system in a farmer's field.

Discipline: Agricultural machinery/ Crop production/ Soil science

Additional key words: precision agriculture, map, variable rate technology, yield-monitoring combine

Introduction

The average amount of arable land per farm is increasing in Japan as elderly farmers retire, with few successors to replace them. As a result, the number of large farms with more than 10 ha has been increasing recently. Conventionally sized paddy fields (0.1 to 0.3 ha) are small and too numerous for being managed by these large farms. Therefore, land consolidation by joining several small fields to form a large-size field (ca. 1 ha) in order to increase the efficiency of farm management has been carried out recently, resulting in a total area of about 163,000 ha, which accounted for 6.3% of the total area covered by paddy fields in 2002. However, land consolidation, which involves moving large amounts of soil in order to level fields on sloping terrain, has led to differences in the thickness of fertile topsoil or high fertility in the subsoil. Therefore, considerable growth variability is sometimes recognized in these large-size paddy fields (Fig. 1), due mainly to the difference in soil nitro-

gen fertility. Conventional uniform application of nitrogen fertilizer to such fields often results in very low yields at low-fertility sites, as well as late heading, lodging of rice plants⁶ or the production of grains with high nitrogen content at high-fertility sites, which consumers find undesirable. Therefore, high priority is given to research on the development of a site-specific nitrogen management system for paddy rice.

The objectives of this paper were as follows: (1) To outline a site-specific nitrogen management system for rice in large-size paddy fields, (2) To elucidate the effect of variable rate application of nitrogen fertilizer on the growth and yield of rice in a field trial, (3) To explore the possibility of adoption of the site-specific management system in Japan.

Brief review of site-specific crop management

Research on site-specific crop management or precision agriculture was initiated in the USA in the 1980s, and has since been developing as a new technology.

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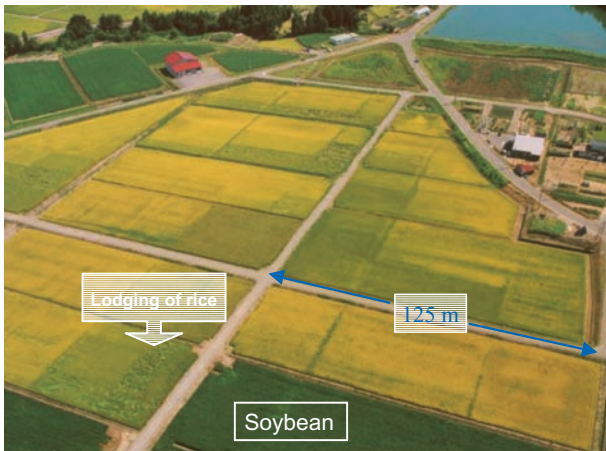


Fig. 1. Variability in rice growth in a large-size paddy field
Two weeks before harvest in 2002, Niigata Prefecture.

Regarding the adoption of precision agriculture technology, it was estimated that in the USA in 2003, the market area of soil sampling with GPS accounted for 19%, yield monitors for 22%, variable rate application of single fertilizer for 11%, and chemicals for 5%, with an upward trend¹².

The site-specific management system has many advantages over conventional uniform management in terms of uniformity in product quality and proper application rates of agricultural inputs, because inputs such as

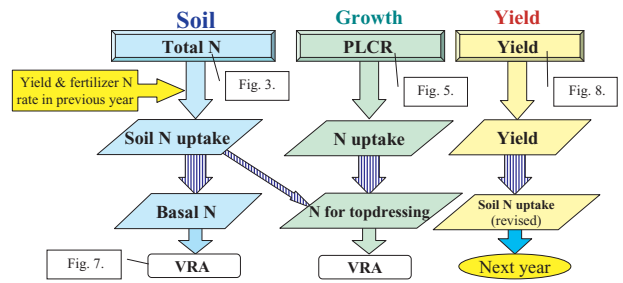


Fig. 2. Outline of the site-specific nitrogen management system for rice

▭ : measurement, ▭ : map.
PLCR: plant cover ratio, VRA: variable rate applicator.
➡ : Calculation by software “RiceNiSMo”.

fertilizers and agricultural chemicals are applied based on site-specific information about the field conditions. However, the cost and benefits of adopting this system are a cause for concern since additional investment in terms of uniform management is required. According to the brochure titled “Practical guidelines for precision agriculture of cereals”⁵, it is recommended that farmers should adopt an appropriate level of investment depending on the farm scale and the area responding to the site-specific management. For example, targeted soil sampling is recommended after initial assessment of field variability that can be easily observed, such as waterlogging or drought. In this way, sampling sites as well as the

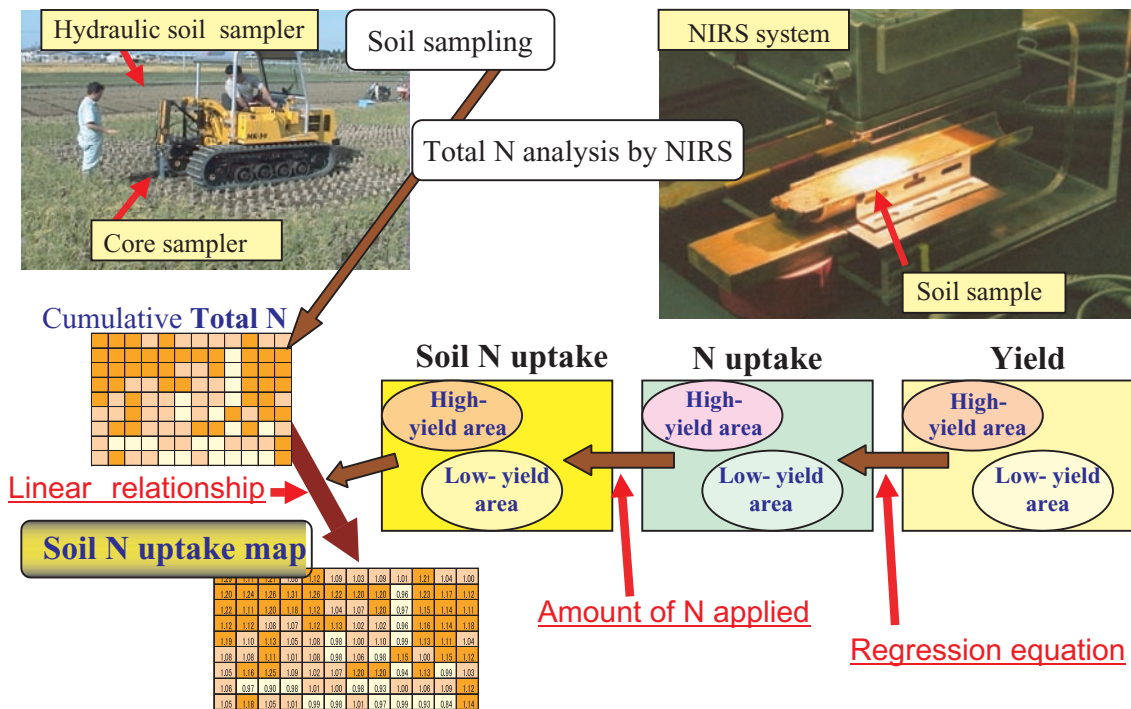


Fig. 3. Scheme for constructing the soil N uptake map

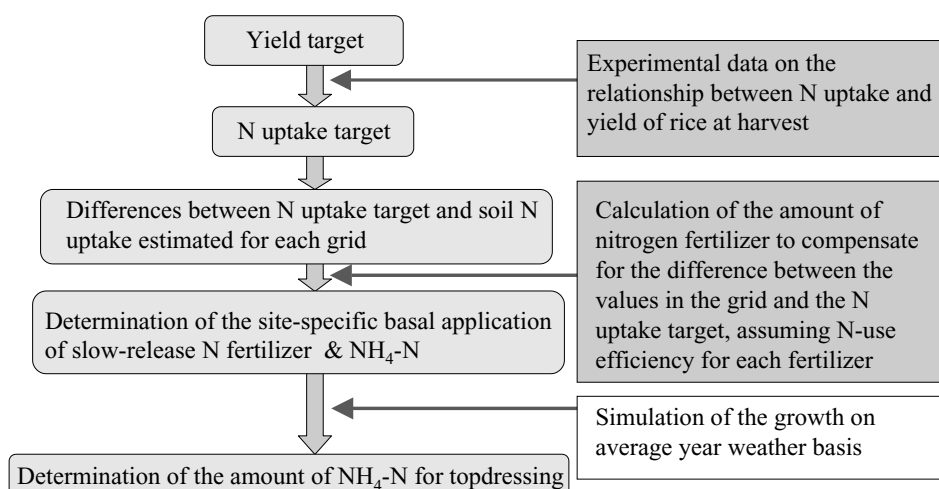


Fig. 4. Method for calculating the amount of fertilizer nitrogen for each grid by using the nitrogen management software “RiceNiSMo”

cost for sampling and analysis could be reduced.

This system consists of two types; a sensor-based system and a map-based system. The map-based system requires the use of GPS (global positioning system), sensors and software for constructing management maps based on the acquired data. In general, it is important to identify the limiting factors for yield to construct a management map, and it is desirable to use maps which are stable over the years, such as an elevation map or total nitrogen map.

Site-specific nutrient management strategies were tested for rice in several Asian countries in cooperation with IRRI¹³, in areas where the management unit was as large as each field unit and thus GPS was not necessary. Because the investment was not costly, financial profitability of rice farming by site-specific nutrient management was found to be higher than that by farmer fertilizer practice⁴.

Development of a site-specific nitrogen management system for paddy rice at Hokuriku Research Center

We developed a site-specific nitrogen management system to overcome the growth and yield variability in large-size paddy fields. The system consists of four parts, namely (1) a sensing and mapping subsystem for soil nitrogen and plant nitrogen uptake, (2) a software for constructing the nitrogen application map, (3) a variable rate applicator, and (4) a yield monitoring combine. The outline of the system is described below and is shown in Fig. 2.

1. Constructing a soil nitrogen map

Soil sampling can be performed with a ca. 10 m-grid using a tractor-mounted hydraulic soil sampler (Fig. 3, top left). Total nitrogen content in both the plow layer soil and subsoil is measured by near-infrared spectroscopy (NIRS), which saves both the cost and time for chemical analysis of soil (Fig. 3, top right). Total nitrogen content of the plow layer and that of the subsoil are summed up to obtain the cumulative total nitrogen content in the root zone soil of each grid. Soil nitrogen uptake for high- and low-fertility sites in the field can be determined based on the nitrogen uptake of rice and nitrogen application data of the respective sites, and the nitrogen uptake is calculated in advance by the empirical regression equation between the yield and nitrogen uptake of a rice variety. The soil nitrogen uptake in other grids can be determined by assuming the existence of a linearity between the soil nitrogen uptake and cumulative total nitrogen content, because the soil nitrogen release capacity can be considered to be linearly correlated with the content of total nitrogen¹¹ in soil. The soil nitrogen uptake map can be constructed in this manner (Fig. 3, bottom). The amount of nitrogen uptake target is determined from the yield target by using the empirical regression equation between yield and nitrogen uptake. The amount of nitrogen fertilizer for basal application and topdressing for each grid is then calculated as shown in Fig. 4, using the nitrogen management software “RiceNiSMo” (Sasaki, R. et al., unpublished data).

2. Constructing a rice growth map

Nitrogen uptake and leaf area index (LAI) are used as indices of the growth status of rice plants. We thus

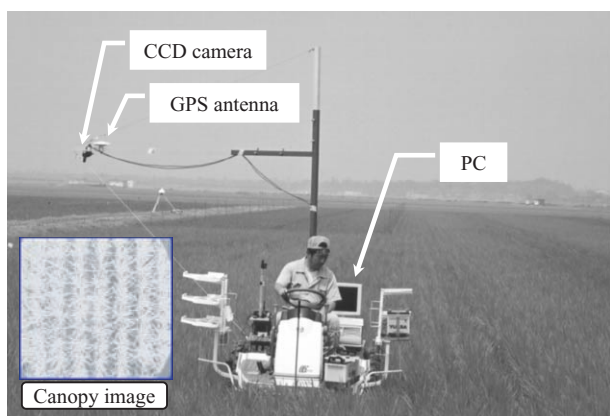


Fig. 5. Ground-based image mapping system (GIMS) for sensing and mapping of plant cover ratio (PLCR)

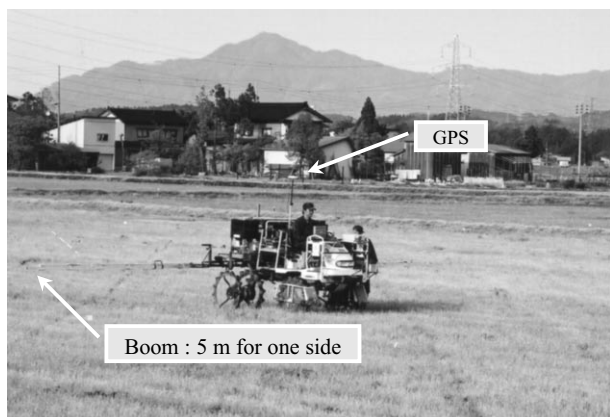


Fig. 7. Variable rate granular fertilizer applicator with a GPS and 10 m boom for applying coated urea as a basal nitrogen fertilizer

developed a growth mapping system according to a ground-based image mapping system (GIMS)⁸, which collects the canopy images of a paddy field sequentially, while the vehicle is traveling in the field (Fig. 5). The images are then synthesized and displayed as a map. The GIMS is composed of a GPS, CCD cameras with band-pass filter (800 ± 10 nm), and a software for image analysis^{8,9} and synthesis⁸. Plant cover ratio (PLCR) was defined as the area covered by rice plants when viewed from above the plant canopy through a camera. Nitrogen uptake and LAI increased exponentially with PLCR, and were calculated by the measured PLCR using image analysis. This estimation is valid until the PLCR value reaches 80%, beyond which the precision of the estimate decreases⁷ (Fig. 6). Field experiments over a period of two years showed that the values of nitrogen uptake estimated from PLCR were equivalent to those obtained by

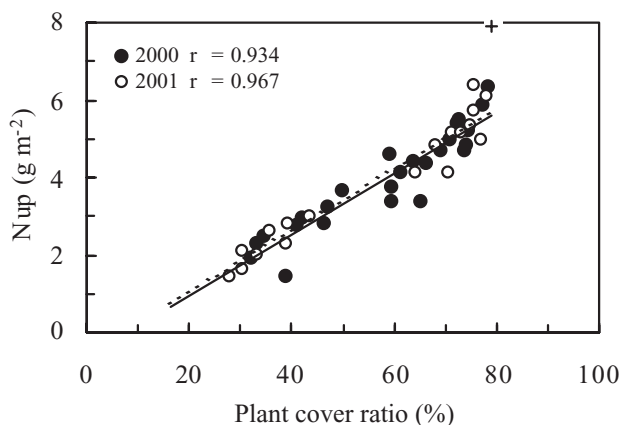


Fig. 6. Relationship between the plant cover ratio (PLCR) and nitrogen uptake (Nup), excluding the data for PLCR above 80%

Equations: $Nup = 0.079PLCR - 0.653$ (solid line, 2000). $Nup = 0.080PLCR - 0.549$ (broken line, 2001). “Plus” symbol indicates data for 2001 which were excluded in the equation.

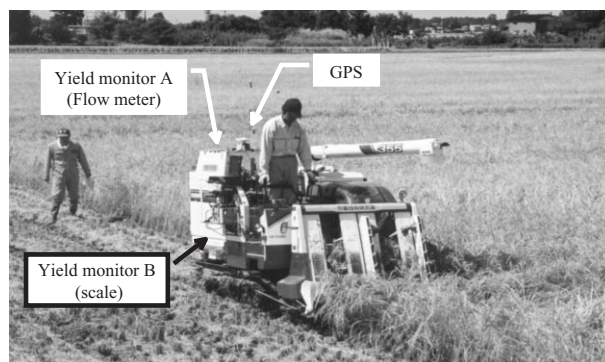


Fig. 8. Yield monitoring combine with GPS and dual yield monitoring system

the conventional method⁷.

3. Nitrogen uptake map before topdressing

As there are yearly fluctuations in the soil nitrogen supply, sensing of nitrogen uptake or LAI before nitrogen topdressing is important to control the growth of rice plants. The culm length at the ripening stage is positively correlated with the LAI and nitrogen accumulation at the panicle initiation stage¹². Lodging caused by a longer culm may also lead to a decrease in the percentage of ripened grains or associated with low grain quality. Therefore, if the nitrogen uptake or LAI at the panicle initiation stage exceeds the preset value, the rate of nitrogen topdressing at the panicle formation stage should be reduced to alleviate lodging at harvest. Also, it is possible to control the protein content of rice grains by determining the nitrogen uptake at the panicle initiation stage. Protein

content of brown rice is the index of palatability of rice, and in Niigata Prefecture, one of the areas that produce rice with the highest quality in Japan, the protein content should not exceed 6%.

4. Software for the calculation of site-specific nitrogen application

The software “RiceNiSMo” for estimating the appropriate rate of fertilizer nitrogen application was developed for transplanted Koshihikari, which is the leading variety in Japan. This software can simulate the growth stages, nitrogen uptake, yield and the degree of lodging based on the parameters for soil nitrogen release and the weather in an average year. The optimal nitrogen fertilizer requirement based on the differences in soil nitrogen fertility could be calculated for the yield target. The calculation procedures are as follows: (1) Input the yield target and get the required nitrogen uptake at the panicle initiation stage and harvest stage, (2) Calculate the application rate of basal nitrogen by considering the soil nitrogen release pattern and the nitrogen use efficiency of both soil nitrogen and nitrogen from basal fertilizer to fulfill the nitrogen uptake requirement at the panicle initiation stage, (3) Calculate the application rate of nitrogen for topdressing by considering the soil nitrogen release pattern, the nitrogen use efficiency of nitrogen for topdressing, and the nitrogen uptake at the panicle formation stage to fulfill the nitrogen uptake requirement at the ripening stage. The parameters required for the calculations can be derived from field experiment data available at the regional agricultural experiment station.

5. Variable rate granular fertilizer applicator

Variable rate technology is essential for site-specific management. Thus a variable rate granular fertilizer applicator with a GPS and 10 m boom was developed² (Fig. 7). The application rate of the fertilizer was input into the software of the applicator, and then the motor control signal was automatically determined by considering the application rate and the velocity of the vehicle. The vehicle provides the power through PTO to the venti-

lation fan which blows the fertilizer to the nozzle on each 4×2.5 m boom and enables independent application at each 2.5 m interval. Coated urea, which is used as slow-release nitrogen fertilizer to compensate for the low nitrogen fertility of an area, was hardly damaged by using this applicator.

6. Yield-monitoring combine

A very important tool for site-specific management of rice is, however, the yield-monitoring combine^{1,3} (Fig. 8). The adoption of dual sensors, optical sensor and load cell as a yield monitor together with the recalculation algorithm of rough rice circulation in the combine contributed to the enhancement of the reliability of the yield map of rice. This combine could be used to monitor the results of site-specific management of rice for a particular field, following which the amount of nitrogen application for each grid could be revised by employing the software described above by using the yield data and the nitrogen application data of the corresponding grid.

Results of application of the developed site-specific management system in the field¹⁰

Field trials of the above site-specific nitrogen management system were conducted in a farmer’s field (1 ha) in Sanwa Village, Niigata Prefecture in 2002, and were compared with the results of uniform management carried out in 1998. The yield target in 2002 was 500 g m^{-2} and the nitrogen uptake target was 8.2 gN m^{-2} . As a result of the site-specific nitrogen management, mean nitrogen uptake was 7.5 gN m^{-2} with a standard deviation (SD) of 1.0 gN m^{-2} , while the mean uptake rate of soil nitrogen was 6.0 gN m^{-2} with a SD of 1.4 gN m^{-2} . The results showed that the variability in nitrogen uptake by rice plants at the harvest stage became lower than the variability in the soil nitrogen uptake. Also, the variability in grain yield was reduced, namely the area with mean yield $\pm 30 \text{ kg/10 a}$ accounted for 46% of the field in 1998, which increased to 71% in 2002.

As for the quality of rice, consumers prefer very sticky rice, and the stickiness increases with the decrease

Table 1. Improvement of the protein content of brown rice after adoption of site-specific nitrogen management

Treatment	Average	SD	Protein content of brown rice (%)					
			~5.0	~5.5	~6.0	~6.5	~7.0	~7.5
	Protein content (%)		Distribution of area in 1 ha field (%)					
Control in 1998	6.19	0.53	1.4	12.5	22.2	31.9	25.0	6.9
SSNM in 2002	5.06	0.29	48.1	43.5	8.3	0	0	0

SSNM: Site-specific nitrogen management.

in the protein content of brown rice. The palatability of rice is often evaluated by the protein content of brown rice. In Niigata Prefecture, for example, the recommended upper limit of protein content is 6.0% to guarantee rice quality. In our field experiment, in 64% of the field area, brown rice production exceeded the recommended upper limit in 1998 with an average protein content of 6.2%, which did not satisfy the farmers. However, the quality was considerably improved in the same field in 2002, since by the use of the site-specific management system, the average protein content reached 5.1% and no harvested area exceeded the upper limit of 6% (Table 1). Successful achievement of the quality target might be attributed to the use of slow-release nitrogen fertilizer to make up for the low soil N fertility, together with the low levels of nitrogen for topdressing. As mentioned above, the site-specific management system, which we developed, is effective for achieving uniform growth and yield of rice as well as high and uniform grain quality.

Adoption of the developed system

The farmers are concerned about the adoption of the above-mentioned system. Indeed, because of the cost of investment, organizations such as growers' cooperatives are the proper targets for the adoption of the above system. However, if the soil map could be constructed by using the yield monitoring combine and the software, the system might become more convenient and accessible to every grower. It is indispensable to analyze the cost and benefit relationships to determine the optimal investment level.

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