Moving towards low-input rice cropping practices: past experiences and future challenges for Japan

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Abstract: *Rice is one of the most widely produced cereals in the world and is the staple food of more than half of the global population. In order to reduce the impact of rice production on the surrounding local and global environment while maintaining yield, nitrogen (N) application should be optimized to avoid N contamination. Taking Japan as an example, this study describes some of the implications of the transition toward low-input agricultural practices in rice cultivation. Not too long ago, high-input practice was the dominant approach for paddy rice cultivation in Japan. However, since the 1990s, N fertilizer input per area has declined significantly and yields have been maintained, resulting in high N application efficiency. By focusing on N fertilizer management, this study examines the technical developments in low-input practices and socio-economic changes in the agro-food system, which have enhanced the relative advantages of low-input practices for rice farmers. These relative advantages include better palatability, habitat restoration for endangered species, work efficiency improvements, and higher resilience of the farming system against cold temperatures as well as pests and diseases. Without stringent regulations on N being imposed, the increase in the relative advantages has motivated farmers to adopt low-input practices. This study highlights the importance of clarifying the merits of low-input practices with regard to social and economic aspects. The awareness of the merits of low-input practices will lead to more farmers adopting these practices.*

Keywords: *rice, fertilizer management, conservation practices, sustainable agriculture, Japan, agro-food system, resilience*

Introduction

Nitrogen (N) is one of the most essential nutrients in agricultural production. Over the past several decades, the intensive use of synthetic N fertilizers combined with high-yielding varieties, irrigation, and agrochemicals for plant protection has resulted in a significant increase in productivity of major cereal crops such as rice (*Oryza sativa* L.), wheat (*Triticum spp.*), and maize (*Zea mays* L.) (Evans, 1993). However, as the N application volume increased, the excess N from agricultural systems began to contaminate the environment. The result was the deterioration of downstream water quality and eutrophication of estuaries and nearshore ecosystems, leading to loss of biological diversity and an increase in atmospheric nitrous oxide (Vitousek et al., 1997). Because synthetic N fertilizer is the major source of excess N in the terrestrial biosphere (Galloway et al., 2003), the outflow of excessive N from agricultural systems has been recognized as an international problem for the last 40 years (Commoner, 1975; Robertson and Vitousek, 2009). Since rice is the second most planted crop after maize (Maclean et al., 2002) and is the staple food of more than half of the world's population (FAO, 2004), the optimization of fertilizer management is an important issue to prevent N contamination while maintaining production yields.

From an agronomic aspect, N is a critical element for promoting growth and tillering during the vegetative stage and enhancing spikelet production during the early panicle formation stage in rice plants. If properly applied, N also contributes to grain filling by improving the photosynthetic capacity and enhancing carbohydrate accumulation in culms and leaf sheaths (Mae, 1997). Thus, N has been recommended as a core fertilizer for rice in order to improve yields. However, mere increases in N applications do not guarantee yield improvement. A decrease in crop N use efficiency has been observed with increasing N input (Fageria and Baligar, 2001; Jiang et al., 2004; Peng et al., 2006). N fertilizer costs constitute a considerable share of the total rice production costs (Tirol-Padre et al., 1996). The recent rise in synthetic fertilizer prices and future uncertainty of the price stability emphasize the importance of better fertilizer management to secure economic viability.

A general principle in optimizing fertilizer management is to balance the supply of available N input with plant biological N requirements (Robertson and Vitousek, 2009). Although this principle is clear, its practical application and implementation are difficult and not straightforward (Shepherd and Chambers, 2007). Taking Japan as an example, this study describes some of the implications of moving toward low-input agricultural practices in rice cultivation. Not too long ago, paddy rice farming in Japan was characterized as a high-input practice. However, since the 1990s, N fertilizer inputs per area have been declining significantly while yields have been maintained, resulting in high N input efficiency. Focusing on N fertilizer management, this study examines the technical developments behind the N input reductions as well as the socioeconomic changes in the Japanese agro-food system that stimulated the rice farmers' adoption of low-input practices. After substantial reductions of N inputs in rice production have been realized, the challenge is to achieve N load reductions in wider agricultural systems to remedy water contamination conditions originating from agricultural production.

Trends of the nitrogen fertilizer application rate

Rice, the staple food of Japan, is grown throughout the country. Almost all rice is of the *japonica* variety—a short-grain variety widely planted in Northeast Asia. Rice occupies 38.1% of all planted area in 2008, followed by feed crops (23.7%) and vegetables (13.0%) (Ministry of Agriculture, Forestry and Fisheries [MAFF], 2009a). Since the late 19th century, the yield of cultivated rice has increased through fertilizer application and mechanization (Ikeda, 2002). However, the country did not achieve self-sufficiency until 1966, when high-yield and cold-tolerant cultivars were developed, agrochemicals were used to control pests, diseases, and weeds, and far-reaching mechanization and high inputs of synthetic fertilizers were applied (Ikeda, 2002). Figure 1 shows the changes in the N application rates and rice yields from 1960 to 2007. In 1966, the average application rate of synthetic N fertilizer per 1-ha paddy field was 91.8 kg N ha^{-1}. Throughout the 1970s and 1980s, the average N application rate was approximately 100 kg N ha^{-1}. However, in 1988, the N inputs started to decrease, and 10 kg N ha^{-1} was reduced every 2–3 years. The N application rate became less than 100 kg N ha^{-1} in 1989, less than 90 kg N ha^{-1} in 1995, less than 80 kg N ha^{-1} in 1997, and less than 70 kg N ha^{-1} in 2001. In 2007, the application rate was 62.7 kg N ha^{-1}, which was only 62.8% of the fertilizer application rate in 1989. On the other hand, rice yields have remained rather steady since 1985, at around 5,000 kg ha^{-1}. Occasional declines in rice yields such as in 1993 are due to the impact of adverse weather conditions.

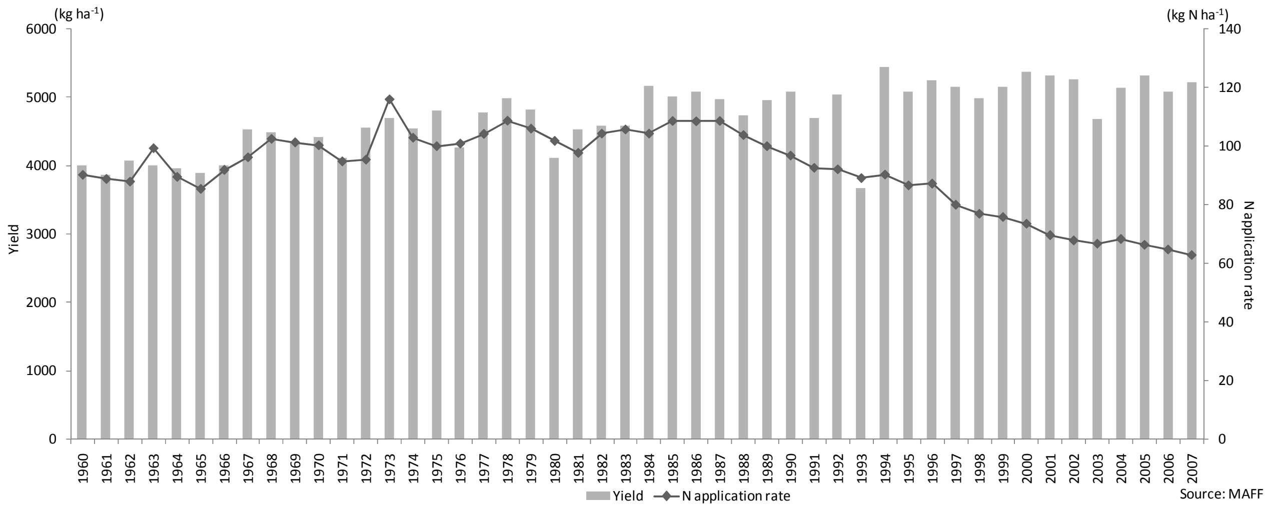

Figure 1. Rice yields and nitrogen application rates in Japan (1960–2007).

Trends in N application rates and rice yields show that reduced N fertilizer input was not a limiting factor in maintaining yields. Figure 2 shows the N application efficiency (NAE) over the same period from 1960 to 2007. The NAE is the ratio of rice yield per unit of applied N fertilizer. Between 1960 and 1989, NAE stagnated in the range of 40–49 kg, and increased in 1990. After the NAE first exceeded 50 kg (kg N)$^{-1}$ in 1990, it continued to rise, reaching 70 kg (kg N)$^{-1}$ in 2000 and 80 kg (kg N)$^{-1}$ in 2007. The NAE has almost doubled over the past 40 years. Owing to the decrease in N fertilizer application in rice cropping, there has been a constant decline in the total residual N from agricultural production in Japan (Mishima et al., 2009). Generally, nitrate contamination is rarely observed in paddy field areas (Kumazawa, 1999).

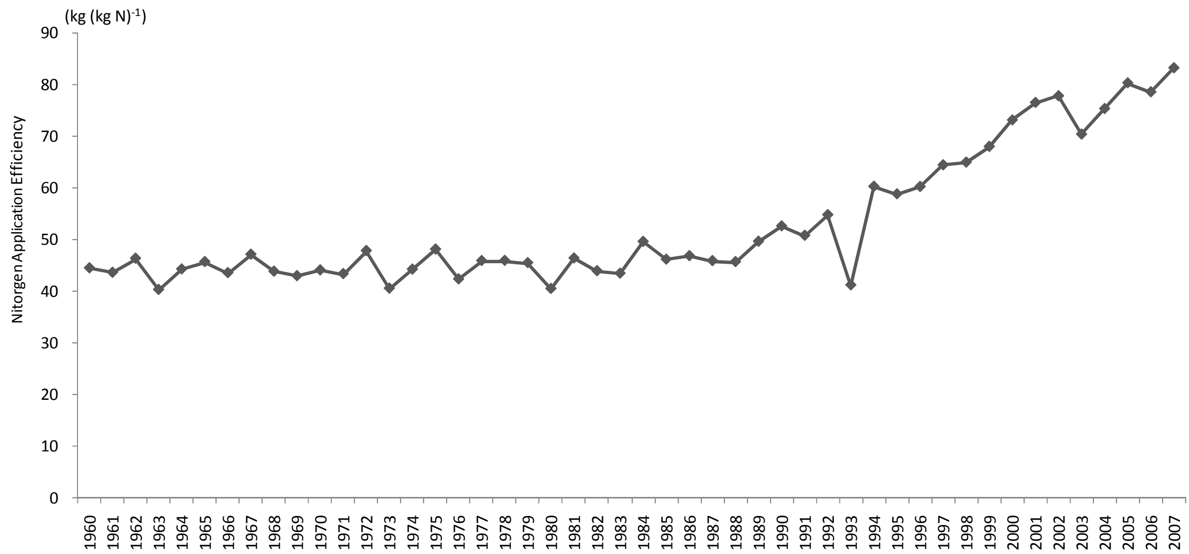

Figure 2. Nitrogen application efficiency (1960–2007).

Transition of nitrogen fertilizer management

How did this transition from high-input N practices to low-input N practices take place? This section examines the transition with regard to two developments: technical changes in rice farming practices and the drivers of the transition in the agro-food system that enhanced farmers' adoption of improved low-input N practices.

Technical aspects of nitrogen input reduction

Looking at the technical developments, the transition was undertaken mainly by three factors: varietal change; adjustment of fertilizer application timing and rates to improve resilience of rice cropping systems, and the technical development of N conservation practices.

A. Varietal change

Varietal change was one of the major factors that led to reductions in N input (Nishio, 2005). Around 1955, the recommended and preferred rice varieties were high-yield types with high adaptive capacities for fertilizer applications. Starting in the late 1960s, the short-culm and high panicle-number type was released nationwide. This variety was favoured due to its high lodging tolerance, suitability to machine planting, and high-yield ability (Higuchi, 2008). Nipponbare, the well known variety of this type, was the most planted cultivar in the 1970s. However, in 1979, Koshihikari became the most planted rice in Japan despite its low lodging resistance. Due to its eating quality, wide adaptability to different environmental conditions, sprouting resistance, and cold weather tolerance (Fujimaki, 1995), Koshihikari has been the most planted cultivar for the past 30 years (MAFF, 2009g). The changing of varieties has had a significant impact on fertilizer management. To overcome the low lodging resistance of Koshihikari, focus was shifted from basal fertilizer to top dressing along with total reductions in fertilizer applications. Though palatability is Koshihikari's varietal feature, its taste varies depending on the actual N application rates because the higher the protein content of rice grains – caused by high N uptake at ear emergence – the lower the palatability (Matsuhima and Matsuzaki, 1972). In the 1980s, several new premium quality varieties with high palatability were released: Akitakomachi in 1984, Hitomebore in 1987 and Hinohikari in 1989. All of these varieties are more than 50% related to the Koshihikari variety (Sakai, 1997). With a 66% share of the total paddy fields, Koshihikari and its related cultivars have a considerable impact on fertilizer management.

B. Nitrogen application adjustment to improve resilience

Another feature of low-input N management practices is related to its effects on farming system resilience against damage due to cold temperatures, pests, and diseases. By lowering N application rates and altering application timing, rice farming systems become less susceptible to these major production limiting factors.

Japan frequently experiences cold temperature damage to rice crops. Between 1880 and 1980, cold temperatures affected rice production once in every 4-year period (The Society of Agricultural Meteorology of Japan, 1994). Thus, minimizing the impact of cold summer weather has been one of the primary concerns of rice farmers. Apart from selecting a cultivar with high tolerance, it was found out that N fertilizer management effectively increases resilience against cold damage since rice plants with lower N contents show better responses to cold temperatures and have low sterility rates (Oota et al., 1994). To increase resilience against cold temperature, it is recommended that basal N applications be minimized and split fertilizer applications be adjusted accordingly (Nakahori, 2004). When one of the most serious cold temperature waves hit Japan in 1993, farmers who had lowered split application input or had not to applied top dressing at all suffered less pronounced production failure (Mayumi, 1995).

Regarding pests and diseases, excess N content during the initial vegetative stage makes rice plants more susceptible to infestation (Kiritani, 2004). In particular, high input of basal N application attracts ricehopper and leafhopper attacks as well as rice blast, sheath, and crown blight disease (Une, 1987). As part of initiatives to reduce application rates of pesticides and weedicides, fertilizer application rates were also revised to improve resilience (Kiritani, 2004). To facilitate changing fertilizer management, the development of tools to assess plant N status was important to allow farmers to adjust fertilizer application timing and amounts. Availability of an upgraded version of the leaf colour chart (Furuya, 1987) and commercialization of chlorophyll meters in the 1980s (Watanabe et al., 1980) enabled farmers to adopt more precise N applications.

C. Technical developments to reduce nitrogen input

In addition to varietal change and improved application rates and timing, technical development of new fertilizer types has contributed to the reductions of N inputs. These new fertilizer types include side-dressing fertilizers, controlled-release fertilizers, and fertilizers for single application in a nursery box. The side-dressing fertilizer can reduce N input by 10%–30% compared to conventional practices by using more specific N placement (Fertilizer Association, 1989). The development of rice planters equipped with a spreader unit for side-dressing fertilizer also has helped improve work efficiency. In 2007, the adoption rate of side- dressing fertilizer was 50.2% nationwide for rice planters with more than 6 rows. In some areas, such as the Kinki region (south-central region), the adoption rate was 85.8% (MAFF, 2009d). The N uptake ratio of controlled-release fertilizer is 50%–65%, while the N uptake ratio of conventional synthetic fertilizer is 20%–30% for basal fertilizer and 30%–50% for top dressing at the panicle formation stage (Toriyama and Sekiya, 2006). Thus, through use of the controlled-release fertilizer, N application rates can be reduced 20%–30% (Sato, 2007). In 2007, the national adoption rate of this fertilizer type was 34.9%. Through applying the controlled-release fertilizer in a nursery box, the N uptake ratio further increases to 60%–80% (Toriyama and Sekiya, 2006). As use of a single application of fertilizer in a nursery box is a relatively new method, the adoption rate of this practice is still limited. Even in the major rice production prefectures such as

Aomori Prefecture and Akita Prefecture (both of which are located in the north-central region), the adoption rate was 10% in 2008 (MAFF, 2009d).

Changes in society

Technical developments in improved fertilizer management practices are essential for the reduction of N input. However, availability of technical solutions does not guarantee farmers' adoption of these new practices (Cassman et al., 2002). According to a recent review of adoption literature (Pannell et al., 2006), one of the important factors of adoption relates to whether farmers consider these new practices helpful for achieving their own economic, social, and environmental goals. Behind the trend of N input reduction in Japan, there have been societal changes that stimulated farmers' adoption of new practices and innovations to lower N input. This section looks at the changes of the agro-food system in the economic, social, and environmental dimensions that may have influenced individual farmers' decision-making processes to achieve their goals and/or respond to the external pressures.

A. Economic aspect

From the economic aspect, there was a considerable shift in the marketability of rice due to dietary changes caused by the westernization of food consumption patterns in which people started to consume less rice and cereals and eat more meat and dairy products (Ehara et al., 2009). After reaching its peak in the early 1960s, per-capita consumption of rice declined from 114.9 kg $year^{-1}$ in 1960 to 61.4 kg $year^{-1}$ in 2007 (MAFF, 2009c). Instead of quantity, people began to look for quality in rice such as better taste, food safety, and environmental soundness of farming practices. For instance, varieties with better taste have gained more popularity in the market. Due to its taste, lustre, fragrance, and texture, the market places a high premium on Koshihikari (Sakai, 1997). Also, consumers' concerns about various food safety and environmental issues have increased. To obtain rice produced using environmentally friendly methods, some consumer groups and cooperatives developed direct market channels with producers. With the strong support of consumers, farmers in various regions have adopted practices to reduce agrochemical input since the early 1990s (Yamaki, 1995).

Along with changing consumer preferences, rice market regulations were liberalized, which impacted both rice sales and farming practices. Marketing of rice in Japan had been under direct government control. However, after the excess of rice in stock turned into a social issue in the 1960s, "the self-marketing system" for rice was introduced in 1970 to partially allow sales of rice in other than government channels (Higuchi, 2008). Using this system, farmers were able to sell organic rice on the market (Yasuda, 1978). In 1987, "the specially grown rice system" was introduced to make direct sales between producers and consumers possible. In 1995, the marketing of rice was further liberalized to allow for multiple distribution channels (Ozawa and Suzuki, 2007).

B. Environmental aspect

With the increased intensification of agriculture, adverse impacts on the environment became apparent. Regarding N input to rice paddies, major environmental problems included water quality degradation and biodiversity loss. N contamination of underground water was noted in the 1970s and a number of studies indicated its close connection to agricultural production (Kobayashi, 1995). Also, eutrophication of enclosed waters turned into a serious problem. Lake Biwa, the largest lake in Japan, was no exception. In 1979, the Shiga prefectural government enacted an ordinance on eutrophication prevention in which the agriculture sector was mandated to follow appropriate fertilizer application rates and to control N outflow (Ministry of Land, Infrastructure, Transport and Tourism [MLIT], 2003). The other feature, biodiversity loss, is related to the fact that traditional rice farming nurtured rich flora and fauna. For instance, the rice paddies historically supported large predatory birds that fed on abundant and diverse aquatic life. As agricultural intensification proceeded and agrochemical input increased, species such as Oriental White Storks (*Ciconia boyciana*) became extinct in Japan (Okui, 2009). In response to these losses, a number of initiatives were undertaken to restore habitats. In the Toyooka Basin, Hyogo Prefecture, a project to bring back

Oriental White Storks was initiated. In addition to the restoration of fishways and shallow riverbeds, farming practices were revised to eliminate application of synthetic fertilizers during the production period and to reduce the use of pesticides and weedicides by at least 70% (Toyooka City, 2007). As a result of the increasing amount of rice paddies cultivated with conservation practice, there are currently 36 Oriental White Storks in the wild habitat (Toyooka City, 2009). Similar initiatives have been undertaken to restore and secure bird habitats through improving farming practices coupled with other measures. Examples of this include the Japanese Crested Ibis (*Nipponia Nippon*) in Sado city, Niigata Prefecture, and the White-fronted Goose (*Anser albifrons*) in the surrounding rice paddies of Kabukuri-numa, Miyagi Prefecture.

In view of the promotion of sustainable agricultural practices, the MAFF implemented several schemes. One of the first initiatives was the labelling guideline for environmentally friendly agricultural products established in 1992. In 1999, 3 environmental agriculture laws went into effect. Related to these laws, an “eco-farmers” scheme was introduced to certify those who improve soil fertility and reduce the application of synthetic fertilizers and pesticides. Rice farmers account for around 40% of the certified farmers (MAFF, 2009e). The Law on the Promotion of Organic Agriculture was enacted in 2006. The present scheme offers two types of low-input agricultural products: Specially Grown Agricultural Products and Organic Japanese Agricultural Standard certified products. For specially grown certification, farmers must reduce application of fertilizers by more than 50% compared to the standard application rates. For organic certification, farmers are required to plant on the land without applying any agrochemical inputs for more than 2 years.

C. Social aspect

During the phase of rapid economic growth, the agriculture sector has experienced major socio-demographic changes in Japan. Growing demand for workforce from other sectors and relatively cheap agricultural commodity prices had a considerable impact on the agricultural labour market. The number of commercial farm households has almost halved over the last 20 years from 332 million in 1985 to 175 million in 2008 (MAFF, 2009f). During the same period, the proportion of farmers more than 65 years of age has raised from 22.1% in 1985 to 46.7% in 2008 (MAFF, 2009f). For many commercial farming households, it became more common to engage in off-farm employment. Of all commercial farm households, business farm households, whose agricultural income makes up more than 50% of their total income, accounted for only 20.9% in 2008 (MAFF, 2009f). Confronted with these changes in farming communities, farmers sought more labour saving and cost effective techniques. For instance, controlled-release fertilizer was already developed around 1970. However, it was not until the 1990s that stakeholders showed interest and undertook trials (Ono, 1995). Together with the effects of other improved farming techniques such as mechanization, the average operation hours for rice farming has declined from 551 hours ha^{-1} in 1985 (MAFF, 1987) to 274 hours ha^{-1} in 2007 (MAFF, 2009b).

Implications from the transition

To increase N use efficiency, quite a few studies on technical development have been published (Cassman et al., 2002). However, adoption of these technologies and practices has been limited since they require some cost, additional skills, and behavioural changes of farmers. Hence, to promote conservation practices, policy instruments are often considered necessary for providing either disincentives through imposing direct regulations or incentives such as green payments (Robertson and Vitousek, 2009). Nonetheless, the example of rice cultivation in Japan shows that there is another pathway to transition instead of imposing regulations. In the case of N application reductions in Japan, policy instruments seem to have played a relatively small role because water regulations, which address nitrate and nitrite pollution, indicate the regulatory threshold of groundwater contamination but do not specify the upper limit of N application rates. From the incentive aspect, programs to promote N reduction were only recently introduced such as the Measures to Conserve and Improve Land, Water, and Environment in rural areas, which was implemented in 2007. Under this program, direct payments are provided for conservation practices including the reduction of fertilizer application by 50%.

Alternately, in this example, farmers' adoption of low-input practices has been driven by changes in society that seem to have enhanced the relative advantages of low-input practices. Relative advantages, the perceived net benefit brought about by farmers' behavioural changes, are one of the major determining factors for farmers' adoption decision-making (Rogers, 2003). Increased relative advantages of a technology or practice can facilitate farmers' uptake as a driver of adoption (Pannell, 2006). Through adopting low N fertilizer management practices, rice farmers in Japan have been able to improve agricultural performance to achieve their goals in different aspects. First, the reduction of fertilizer application gave farmers a marketing benefit in the form of improved rice palatability and a sales advantage as safe and environmentally friendly food. The second relative advantage was related to environmental benefits, which contribute to remedy the eutrophication of closed water areas and the restoration of wildlife habitats of endangered species. The third advantage of low-input rice farming was work efficiency improvement, which was urgently needed due to the social demographic changes in farming communities. The fourth advantage is connected to the strengthening of farming system resilience against damage due to cold, pests, and diseases. This example shows that the relative advantages of low-input practices are multiple rather than single. Since farming communities are heterogeneous in nature, each farmer has different goals and seeks diverse relative advantages in farming practices. Responding to different relative advantages, farmers decide whether to adopt practices or technologies. The findings from this study underpin the importance of clarifying positive merits of low-input practices in social, economic, and agronomic aspects. Revealing the benefits embedded in low-input practices through research and putting an emphasis on the merits during extension will increase farmers' adoptability of these practices.

Future Challenges

While N application rates in rice farming have declined over the past 20 years in Japan, residual N from the total agricultural production has also lessened (Mishima et al., 2009). However, although total residual N has declined, regional residual N levels differ widely depending on agricultural crop types (Mishima et al., 2009). In some areas, residual N is quite high, and this finding coincides with the fact that the nitrate and nitrite contamination levels exceeded the upper limits in 4.4% of wells in 2008; these water quality criteria are considered to be grave (Ministry of the Environment [MOE], 2009). Over-fertilization is the most common source of N contamination, followed by livestock waste and household drainage (MOE, 2008). Among the crop types, the residual N content for vegetables (454.4 kg N ha^{-1}) and industrial crops (388.5 kg N ha^{-1}) was notably higher than that for rice (10.3 kg N ha^{-1}) in 2002 (Mishima et al., 2006).

Thus, reductions of N input for these crops while maintaining yields is a major task in order to reduce environmental N load. One method to reduce N outflow involves the use of more efficient N materials such as controlled-release fertilizers. Another possible strategy is to use surplus N from vegetable and industrial crop production in rice cropping before releasing it into the ground water. Crop rotation is an effective approach to reduce N leaching to the environment. Vegetable farming, which involves heavy N input, often results in high levels of residual N in the soil. When rice is planted after the vegetables are harvested, residual N is taken up by the rice plants. For varieties such as Koshihikari, fertilizer management for crop rotation was technically difficult since high levels of residual N in soil enhance its lodging susceptibility (Hirota, 1992). However, newly emerging varieties of feed rice and flour rice require higher N application rates in order to attain higher yields. Crop rotation of vegetables and feed rice varieties could reduce excess N leaching due to vegetable farming. The other possibility for paddy fields to improve N use efficiency in the broader scope is connected to livestock operations, another major source of residual N leaching. For example, swine effluent, which contains N, can be applied instead of synthetic fertilizer (Anzai, 2005). Some regional initiatives have been undertaken through collaborations between swine farmers and rice farmers in Yamagata Prefecture (Chuuba and Niino, 2009). In view of the fact that feed rice could replace imported maize, increasing the domestic feed rice production would not only raise Japan's self-sufficiency rate but also contribute to the reduction of N overloading in other countries. Another approach to reducing N outflow from agricultural production involves connecting paddy fields with other farming systems with high residual N, for example, connecting paddy fields and tea plantations. When discharged water from tea plantations is rerouted as irrigation water to rice paddies, rice plants can uptake some of the N in the irrigation water (Toda, 2005). As tea plantations have one of the heaviest N fertilizer application rates (Nakashimada, 1995), the removal of N from discharged water will have a positive impact on overall water quality.

Conclusion

The application rate of N fertilizers in rice farming in Japan has declined considerably since the 1990s. With regard to technical aspects, varietal change, appropriate fertilization timing and rate, and the development of new fertilizer types have helped to increase N application efficiency. In addition to developments in technical aspects, the relative advantages of low-input practices have increased over the transition period. Owing to the number of different relative advantages of low-input practices, rice farmers have adopted these practices in order to improve their agricultural performance and work toward their personal goals. Since agricultural activities are closely connected to society, the latter's dynamic and heterogeneous nature determines the relative advantages of farmers. Thus, relative advantages of farming practices change over time and vary from farmer to farmer. The findings of this study indicate that spreading awareness of the advantages of conservation practices from multiple perspectives in research and extension programmes would enhance their adoptability.

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