JAPANESE RICE-BREEDING RESEARCH APPROACH TO ADAPT TO GLOBAL WARMING

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ABSTRACT

In Japan, the impacts of global warming (GW) on agriculture have been observed over the past decade, especially on paddy rice. Injuries due to high temperatures to rice plants and increased incidences of infestations and infections by insects and pathogens (such as brown planthopper, rice stripe virus, blast, brown spot, and bacterial grain rot) have caused serious problems. Chalky rice grains, induced by high temperatures (≥27°C) during the ripening period, often cause a decrease in the rice grade (appearance grade) and also the eating quality. Brown planthopper caused serious yield reduction in the hot year, 2013, which incurred losses valued at 10 billion yen. Additionally, high-temperature-induced sterility has been predicted to occur in the near future. Some rice varieties with resistance to chalky grains have been bred; however, their cultivation area is limited. One of the reasons for the limited adoption of these varieties is that they carry almost no resistance genes to insects or pathogens. To adapt to the challenges of GW, the National Agriculture and Food Research Organization (NARO) recently bred two new varieties, 'Akiharuka' and 'Nijinokirameki', which exhibit good grain appearance under high temperatures and carry resistance genes against insects and pathogens exacerbated by GW. This report will introduce the breeding program that targets increased adaptation to GW and that is one of the four major breeding programs implemented by NARO.

Keywords: Global Warming, adaptation, rice-breeding program, chalky grains, high- temperature-induced sterility

INTRODUCTION

As a result of global warming (GW), temperatures in Japan have increased over the past century (1.19°C/100 years), and it is predicted that temperatures in 2100 will be 1.1°C–4.4°C higher than the current (2014) temperatures (JMA 2016). The frequency of heavy rain (>50 mm/h) in Japan has also increased (JMA 2016). GW is expected to have a serious impact on Japan's agriculture, especially on rice production. For instance, chalky grains, induced by high temperatures (>26°C) during the ripening period, is a serious problem affecting grain yield and quality, while cracked rice, where a mature rice grain cracks due to a rapid change in water content, is recognized as another high-temperature injury. In 2013, serious yield losses (valued at 10 billion yen) were reported due to brown planthopper. According to some prediction studies, the potential incidence of high-temperature-induced sterility will exceed 5% in the Chikushi (Saga prefecture), Wakayama (Wakayama prefecture) and Nobi (Aichi prefecture) Plains in 2090s. A study has reviewed the impact of GW on Japan's agriculture (MAFF 2007).

It is reasonably straightforward to breed rice varieties with increased tolerance to high temperatures (and consequent chalky grains) for adapting to GW. Some tolerant varieties, namely 'Kinumusume', 'Nikomaru,' and 'Tsuyahime', have been bred; however, the acreage planted to them is currently limited (6.6%, in 2016). One of the reasons why the cultivation area of these varieties is limited is that they have almost no resistance genes against pests and pathogens. Therefore, to breed rice varieties adapted to GW, breeding a variety with resistance to pests and pathogens and tolerance to high temperatures is necessary.

NARO recently breed two new varieties, 'Akiharuka' and 'Nijinokirameki,' both of which showed good grain appearance under high-temperature conditions and carried resistance genes to the main insects and pathogens diseases exacerbated by GW. This report introduces the breeding program concerning adaptation to GW, which is one of the four major rice-breeding programs implemented by NARO.

THE FOUR MAJOR RICE-BREEDING PROGRAMS IN NARO: THE 4th MID-TERM (2016-2020)

From April 1, 2016, NARO embarked on the fourth mid-term breeding programs for FY2016–2020, focusing on 1) commercial varieties for use in the food industry (high-yielding, high-quality, and/or suitable for rice flour); 2) the development of new resistant/tolerant varieties for adaptation to GW; 3) forage rice varieties; and 4) high-yielding varieties (more than 12 t/ha).

CHARACTERISTICS OF TWO NEW CHALKY GRAIN RESISTANCE VARIETIES, 'AKIHARUKA' AND 'NIJINOKIRAMEKI'

1. 'Akiharuka'; translation of Japanese name: "Landscape where rice grows far away in autumn"

'Akiharuka' was introduced by the Kyushu Okinawa Agricultural Research Center, NARO (KARC /NARO) in 2017 and is a non-glutinous rice variety, belonging to the moderate maturation group in Kyushu region. When grown under high temperatures, it exhibits an attractive grain appearance (Fig. 1) and is high yielding (Table 1). The consumption quality of cooked rice of 'Akiharuka' is comparable with that of 'Hinohikari,' which is one of the best varieties for high eating quality in western Japan. 'Akiharuka' carries four resistance genes, namely, *Bph11* against brown planthopper, *Pi39* and *Pb1* against rice blast, and *Stvb-i* against rice stripe virus (RSV). It was mainly planted in Saga prefecture (500 ha), and the rice products, i.e., rice balls and bento rice, were suitable for commercial use.

Table1. Yeild trial data of 'Akiharuka' (KARC/NARO：Chikugo, Fukuoka)

Fertilization levels (N: kg/10a)	Varieties	Days to Heading	Days to Maturity	Culm length (cm)	Panicle length (cm)	Panicle number (/m^2)	Lodging (0: No ～ 5: All)	Yield (Brown rice base) (t/ha)	Yield (Brown rice base) (%)	1000-grain weight (g)	Grain quality (1:Excellent～ 9:Unacceptable)	Eating quality
Medium	Akiharuka	95	140	87	20.1	322	0.2	5.7	115	22.9	4.5	Good
(N=8.0)	Hinohikari	92	137	83	19.0	343	0.6	4.8	100	22.6	6.3	Good
High	Akiharuka	89	143	94	20.6	350	0.9	59.8	112	22.3	4.3	Good
N=10.5～12.0	Hinohikari	93	142	88	18.9	385	1.2	53.6	100	22.3	5.8	Good

Akiharuka (Good) Hinohikari (Poor)

Fig. 1. Grain appearance of 'Akiharuka'.

Fig. 2. Commercially available lunch box (Bento) made using 'Akiharaka' rice.

2. 'Nijinokirameki'; translation of Japanese name: "Good grain appearance as the sparkle of rainbow"

'Nijinokirameki' was introduced by the Central Region Agricultural Research Center, NARO (CARC /NARO) in 2018, and is a non-glutinous rice variety, belonging to the moderate maturation group in Hokuriku region. It is dwarf variety and shows high lodging resistance with high yield (Table 2). The consumption quality of 'Nijinokirameki' cooked rice is comparable with that of 'Koshihikari' cooked rice, which is one of the best varieties for consumption in Japan. 'Nijinokirameki' possesses the Stvb-i gene and shows resistance to RSV. The cultivation of 'Nijinokirameki' may be suitable for areas where RSV is epidemic or for areas where rice is planted after winter wheat or barley.

Table2. Yeild trial data of 'Nijinokirameki' (CARC/NARO : Joetsu, Niigata)

Fertilization levels (N: kg/10a)	Varieties	Days to Heading	Days to Maturity	Culm length (cm)	Panicle length (cm)	Panicle number (/m^2)	Lodging (0: No ～ 5: All)	Yield (Brown rice base) (t/ha)	(%)	1000-grain weight (g)	Grain quality (1:Excellent～ 9:Unacceptable)	Eating quality
Medium	Nijinotirameki	109	153	71	19.6	416	0.0	71.9	115	24.6	4	Good
(N=6.0)	Koshihikari	108	149	96	19.0	399	4.2	62.7	100	22.4	5.8	Good
High	Nijinotirameki	109	153	74	20.4	474	0.0	75.8	129	23.9	4.4	-
(N=9.0)	Koshihikari	108	149	101	19.6	449	4.8	58.9	100	21.7	5.9	-

Nijinokirameki (Good) Koshihikari (Fair)

Fig. 2. Grain appearance of 'Nijinokirameki'.

Nijinokirameki Koshihikari (lodging)

Fig. 3. Plant habit of 'Nijinokirameki' in the field. 'Nijinokirameki' has a short culm and shows lodging resistance.

BASIC RESEARCH CONTRIBUTING TO RICE BREEDING FOR ADAPTATION TO GW

To develop rice varieties that are adapted to progressive GW at the earliest, it is necessary to obtain suitable genetic information, such as gene mapping and whole-genome survey. Basic genetic information helps the breeder to introduce new traits and/or to perform gene pyramiding, assembling multiple desirable genes, particularly disease-resistance genes, into one elite line using new genetic resources. Japanese rice researchers and breeders

cooperate and are striving to acquire genetic information on tolerance to heat-damage (chalky grains and sterility) and resistance to pests and pathogens that are exacerbated by GW.

1. Chalky grain tolerance

Kobayashi *et al*. (2007) performed quantitative traits locus (QTL) analysis using F_3 lines derived from a cross between 'Hana-echizen' (tolerant) and 'Niigata-wase' (susceptible). They detected four QTLs on chromosomes 3, 4, 6, and 9. Among them, three tolerance QTLs (*qWB3, qWB4, and qWB6*) were alleles from 'Hana- echizen' while the remaining *qWB9* was derived from 'Nigata-wase'. The *qWB6* was a major QTL and its additive effect was more than 30%. Another QTL for reducing the occurrence of chalky grains was identified in an *indica* rice variety, 'Habataki' (Murata *et al*. 2014). This QTL was named *Apq1* (*Appearance quality of brown rice 1*), and its candidate gene is *Sucrose synthase 3*. This gene was introduced into the famous Japanese variety, 'Koshihikari' by repeated backcrossing, and two varieties harboring *Apq1* were released in 2018 (Kojima 2018).

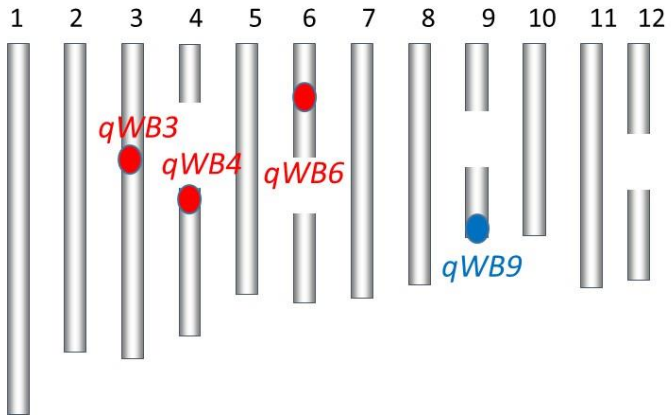

Fig. 4. QTLs for reducing chalky grain frequency at high temperatures. (Kobayashi *et al.* 2007)

2. High-temperature-sterility tolerance

Hakata *et al.* (2017) developed a novel assay system for high-temperature-sterility by using artificial rice paddies in phytotrons to conduct a highly reproducible assay throughout the year (involving a 3-d heat treatment of 35°C-day/29°C-night cycles). Using this system, they identified ten excellent heat-tolerant lines (exceed the tolerant variety, N22) from 116 accessions, which are being used to breed heat-tolerant varieties.

Fig. 5. Artificial rice paddies in phytotrons in KARC/NARO.
(Hakata *et al*. 2017)

3. Brown spot resistance

Brown spot of rice, which is caused by the fungus *Bipolaris oryzae*, is one of the most serious rice diseases worldwide. In temperate regions such as Japan, high temperatures during rice flowering and grain-filling stages tend to increase the severity of brown spot epidemics

Sato *et al*. (2015) performed QTL analysis on recombinant inbred lines from 'Tadukan' (resistant) × 'Hinohikari' (susceptible), and three resistance QTLs (*qBSfR1*, *qBSfR4*, and *qBSfR11*) were detected on chromosomes 1, 4, and 11, respectively. The 'Tadukan' alleles at *qBSfR1* and *qBSfR11* and the 'Hinohikari' allele at *qBSfR4* increased resistance. Near-isogenic lines with the major resistance QTL, *qBSfR11,* in a susceptible background ('Koshihikari') exhibited significant field resistance, confirming the effectiveness of *qBSfR11*. Genetic markers flanking *qBSfR11* will be powerful tools for marker-assisted selection to accelerate breeding for increased brown spot resistance.

4. Bacterial grain rot resistance

Bacterial grain rot, caused by the bacterial pathogen *Burkholderia glumae*, is a destructive disease of rice. At anthesis, rice panicles are attacked by the pathogen, and the infection causes unfilled or aborted grains, reducing grain yield and quality. Because the optimal temperature range for the growth of *B. glumae* is high (30–35°C), GW may cause bacterial grain rot to become even more destructive.

Mizobuchi *et al*. (2013) performed QTL analysis of backcrossed inbred lines from 'Kele' (resistant) × 'Hitomebore' (susceptible) and detected one major resistance QTL (*RBG2*) on chromosome 1. Recently, they have tried to conduct fine mapping of *RBG2* (Mizobuchi *et al.* 2015).

CONCLUSION

In Japan, obvious impacts of GW on agriculture has been observed over the past decade, especially in paddy field rice, High-temperature injury to rice plants and increased incidence of insects and pathogens (brown planthopper, RSV, blast, brown spot, and bacterial grain rot) have become major problems. NARO has embarked on the 4th mid-term breeding programs for FY2016-2020, focusing on the development of new pest- and disease-resistant varieties and high-temperature stress-tolerant varieties for adaptation to GW. The conclusions of this report are as follows:

1. It is necessary for us to breed rice varieties that adapt to progressive GW.
2. NARO has bred two new varieties ('Akiharuka'and 'Nijinokirameki;) with good grain appearance under high-temperature stress and with pest- and disease-resistance genes.
3. Basic research is also necessary to obtain the genetic information to facilitate breeding for adaptation to GW, enabling the breeder to introduce new traits and/or to perform gene pyramiding, using new plant genetic resources, in the future.

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