JARQ 55 (SI), 489-500 (2021) https://www.jircas.go.jp

REVIEW

Contribution of Japanese Scientists to Global Agricultural Science and Production in Wheat and Maize at CIMMYT

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Abstract

The International Maize and Wheat Improvement Center (CIMMYT) aims to improve human livelihoods, especially smallholder farmers' livelihoods, through wheat and maize production mainly in the developing world. The first Japanese person to work at CIMMYT was an intern in 1970 according to existing CIMMYT documents. Since then, at least 10 interns or mid to long-term visiting students and 14 appointed or visiting researchers from Japanese institutes have worked on wheat and maize research at CIMMYT. Some Japanese board members and one Japanese Director General also contributed to the direction of CIMMYT's research. i The Japanese researchers and intern students have contributed greatly to CIMMYT research and to world food production. The research includes maize germplasm genebank, rapid breeding/doubled haploid technology for wheat, durable disease resistance in wheat, wheat wild relatives for heat/drought tolerance and a new trait of biological nitrification inhibition and wheat fusarium head blight resistance. The outlook for global wheat and maize supply has not been optimistic and will become worse in the future due to an increasing world population, the impacts of heat and drought and the spread of new diseases caused by climate change. The scientific achievements left by Japanese scientists at CIMMYT can play an important role in mitigating these problems.

Discipline: Crop Science
Additional key words: genetic resources, durable resistance, doubled haploid, wild species, biological nitrification inhibition

Introduction

The International Maize and Wheat Improvement Center (CIMMYT) aims to improve human livelihoods, especially smallholder farmers' livelihoods, through wheat (*Triticum aestivum* L.) and maize (*Zea mays* ssp. *mays* L.) production mainly in the developing world. CIMMYT research activities include wheat and maize breeding, agronomy, socioeconomics, agricultural extension, and capacity building. Current CIMMYT research is focused on nutritious, resilient, and productive maize and wheat production systems, using methods that nourish the environment and combat climate change, that will also improve global food security and reduce poverty. CIMMYT also has germplasm genebank which renowned as the world's largest collection of maize and wheat lines, freely available to scientists, researchers, and farmers around the world.

The origin of the institute can be traced back to the 1940s, funded by the Rockefeller Foundation, when Mexican government developed a pilot program aimed at raising farm productivity in Mexico. Under the scientific leadership of Dr. Norman E. Borlaug, the program developed higher yielding wheat varieties having resistance to wheat rust diseases, helping Mexico to be self-sufficient in wheat production in the 1950s, just one decade after its establishment. Then CIMMYT led the Green Revolution which helped India and Pakistan to stave off famine by doubling the countries' wheat production in the 1960s by providing high yielding semi-dwarf wheat (FAO 2004; Pingali 2012). Since the Green Revolution, CIMMYT has contributed to global wheat and maize production through improved wheat and maize varieties, new technologies, and capacity development, especially in developing countries. It is well-known that Japan indirectly contributed to the Green Revolution as the source of the semi-dwarf gene, however many Japanese people do not know that several Japanese researchers,

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Received 1 March 2021; accepted 25 August 2021.

scientists and students also contributed to wheat and maize production after the Green Revolution. The first Japanese person to work at CIMMYT was an intern from Hokkaido University in 1970, just four years after CIMMYT's establishment. Since then, at least 10 interns or mid to long-term visiting students have brought their scientific knowledge and techniques to CIMMYT research. The first Japanese appointed scientist joined CIMMYT in 1975. According to existing CIMMYT documents, an additional 13 appointed or visiting researchers from Japanese institutes have worked on wheat and maize research at CIMMYT (Appendix). Many of them have worked at CIMMYT for less than two years, which may be too short for their achievements to be visible. Mid to long term staff include only six researchers, and four of them seconded from Japan International Research Center for Agricultural Sciences (JIRCAS). Apart from the researchers, some Japanese individuals have served as board members,

Appendix. List of Japanese scientists worked at CIMMYT and CIMMYT board members.

Name	Start year	End year	Role	(Note for visiting scientist and intern)
Junichi Yamaguchi	1970	1972	Intern	Intern from Hokkaido University
In-service trainees x 3[a]	1971	1975	Intern	
Suketoshi Taba	1975	2011	Maize scientist	
Umeo Koganemaru	1976	1976	Agronomy scientist	Visiting scientist
Junzo Fujigaki	1979	1980	Maize scientist	
Teruhiko Nibe	1982	1983	Trainer	
Mitsuru Osaki	1984	1984	Maize scientist	
Masao Yoshida	1984	1986	Wheat scientist	
Masaroni Inagaki	1993	1998	Wheat scientist	Visiting scientist from JIRCAS
Kazuhiro Suenaga	1998	2002	Wheat scientist	Visiting scientist from JIRCAS
Tomohiro Ban	2004	2007	Wheat scientist	Visiting scientist from JIRCAS
Masahiro Kishii	2004	present[c]	Wheat scientist	
Jiro Murakami	2005	2010	Wheat scientist	JIRCAS fellow
Hiro Nakamura	2005	2006	Wheat scientist	Visiting scientist from JIRCAS
Ryoko Machida-Hirano	2012	2012	Genetic resources scientist	Visiting scientist from Tsukuba University
Intern students x 7[b]	2004	2010	Intern	JIRCAS-CGIAR fellowship; others[d]
Masaru Iwanaga	2002	2008	Director General	
Kanichi Murakami	1983	1984	Board member	
Tomio Yoshida	1985	1985	Board member	
Hikoyuki Yamaguchi	1986	1991	Board member	
Hirofumi Uchimiya	1992	1996	Board member	
Atsushi Hirai	1997	2002	Board member	
Hisao Azuma	2002	2007	Board member	
Mutsuo Iwamoto	2008	2013	Board member	

[a] = the durations were unknown

[b] = the durations were around two months and their names were Yosuke Moritama, Maya Matsunami, Yohei Koide, Mayumi Egusa, Yohei Terasawa, Kento Oshima and Noriko Furuya

[c] = not worked for CIMMYT from 2009 to 2012

[d] = five out of seven were JIRCAS fellows

and had leading and management roles to determine and influence the direction of CIMMYT. In the early 2000s, CIMMYT had one Japanese Director General. It is also notable that funds from Japanese government (the Ministry of Foreign Affair and the Ministry of Agriculture, Forestry and Fisheries) have provided funds for research as well as infrastructures that have contributed significantly to the sustainability and level of research.

At present, the outlook for global wheat supplies has not been optimistic and is set to become worse in the future. The world population is still increasing, and the effects of climate change are expected to worsen, leading to drought and heat stress (Rosenzweig et al. 2014, Kelley et al. 2015; Zhao et al. 2017), as well as increasing the frequency of new disease emergence (Beddow et al. 2015; Singh et al. 2015). To meet population growth and global food demand, it is necessary to develop new high yielding wheat and maize varieties with higher drought and heat tolerance as well as resistance to new diseases. In this paper, I will describe some of the achievements of Japanese scientists who have worked at CIMMYT that will significantly contribute to current and future wheat and maize production, namely development of maize germplasm genebank, improvement of wheat doubled haploid technology for shortening a breeding cycle, contribution to wheat durable disease resistance, and utilization of wheat wild relatives for heat and drought tolerance as well as new trait of biological nitrification inhibition (BNI).

Maize germplasm genebank

A plant genebank is a place to store and maintain many plant lines for future purposes. It deposits all kind of plant materials, not only recent plant varieties but also old/ historical global varieties, wild relatives or any other kind of line that individual breeders or scientists cannot maintain in their labs or institutes. When new and better plant varieties are developed, old ones will be likely displaced by new ones and disappear from the farmer's field. However, this does not mean that the old ones will be useless to future breeding and science. The old varieties may have useful genes in the future. Breeders generally focus on current breeding targets and ignore non-essential traits due to limited funding. Yet breeding objectives have been changing over time. Wheat stem rust resistance was once removed from the priority list in 1960-1990, because good resistance genes for stem rust were incorporated in wheat varieties in 1950s and the problems caused by this disease disappeared (Singh et al. 2015). Suddenly in the 2000s, wheat breeders had to add stem rust resistance into their essential breeding traits, because a new wheat stem rust race (known as Ug99) emerged in 1999. At that time, about 80% of world wheat varieties did not have resistance against this disease, and the development of new stem rust resistance wheat became essential and a priority (Singh et al. 2015).

Dr. Suketoshi Taba worked for maize genetic resources and the maize genebank at CIMMYT for 36 years (Fig. 1). He joined CIMMYT as a post-doctoral fellow in 1975 and became the head of the maize genebank in 1986 and was dedicated to developing the maize genebank until his retirement in 2011. The genebank has three basic activities: storing of seeds, repropagation of new seeds and collecting new lines. Dr. Taba improved every genebank activity during his time, and one of his most important achievements was the enrichment of the genebank collection. In 2019, the CIMMYT genebank held about 25,000 maize lines, which is the largest maize collection in the world and includes local landraces (old/ historical varieties) and wild ancestors (direct ancestral species in wild form) of Teosinte (*Z. mays* ssp. *mexicana* and ssp. *Parviglumis*) and wild relatives of *Tripsacum* L (Matsuoka et al. 2002; Jaenicke-Despres et al. 2003).

Fig. 1. CIMMYT genebank

a) The view of CIMMYT genebank from the main entrance side.
b) The memorial plate on the left side of genebank entrance wall, describing that the genebank was built in 1996 through donations provided by the government of Japan.

The number was 10,000 in 1980, so it increased 2.5-fold during his time (Pardey et al. 2001). Mexico is the origin of maize domestication (Matsuoka et al. 2002), so the collected maize lines in Mexico and its neighboring countries are especially valuable in terms of saving unique genes for the present and for the future. The CIMMYT genebank has been functioning as one of the most important infrastructures for maize science and breeding in the world. CIMMYT distributes more than 10,000 maize seed packages worldwide annually. These genetic resources have been utilized not only for development of new maize varieties but have also contributed to some unique scientific findings. Illustrated below is one example of how a large number of maize lines from the genebank was utilized for a food crisis.

A quick reaction to prevent Maize Lethal Nercosis (MLN) pandemic is the best example how to utilize genebank for potential food crisis. MLN is a new and devastating disease in East Africa caused by an initial maize chlorotic mottle virus (MCMV) infection followed by some secondary fungal and bacterial infection, first found in 2011 in Kenya (Wangai et al. 2012; Redinbaugh & Stewart 2018). It was quickly realized that 100% of maize varieties in Kenya were susceptible to the disease. In 2012, MLN caused 30 to 100% yield loss depending on the severity, which led to a yield loss of 126 metric tons valued at U.S. $52 million in Kenya alone (Mahuku et al. 2015). Developing resistant maize varieties for sub-Saharan Africa became an urgent task. CIMMYT in partnership with Kenya Agricultural and Livestock Research Organization (KALRO) at Naivasha (Kenya) established a screen center in Kenya and conducted a large screening of maize lines, nearly 200,000 maize lines to find resistance sources from 2013 to 2020 (Boddupalli 2020). It included not only CIMMYT maize lines in the genebank (60% of the total number) but also maize lines from national agriculture research system (NARS) institutions in other countries (16%) and from the private sector (21%) (CIMMYT 2021a). The screening indicated that 90% of them were susceptible, but the remaining 10% of them showed some degree of resistance. Many of these varieties were traditional or historical lines, demonstrating the importance of maintaining old lines in genebanks. Traditional and historical lines have low yield potential compared to recent elite maize lines, so they cannot be used directly as varieties. It is therefore necessary to transfer the resistance genes into the elite maize background. The development of new elite maize lines was carried out quickly using molecular and rapid breeding technologies (which will be described in a later chapter), and finally some resistant maize varieties were released in East Africa (CIMMYT 2021b).

Wheat doubled haploid technology for shortening a breeding cycle

Plant breeding requires a long time to develop a new line and variety. In wheat and maize breeding, it takes several years to develop a new variety from F_1 to genetically fixed/ homologous advance lines those are usually F_6 or more advanced generations that are genetically. If we can obtain new varieties directly from F_1 to a homologous condition, skipping F_2-$_5$ segregating generations (Fig. 2), it can save years of breeding time, which can lead to a faster release of new varieties and bring a higher genetic gain or improvement in the same period. This is very important not only to achieve a faster yield increase but also to react to emergencies such as new disease races which we have seen in the previous paragraph. Doubled haploid (DH) is one such technology used to shorten a breeding cycle. In this method, haploid plants are induced in F_1, and then a genetically homogeneous plant is obtained in next generation by doubling chromosome numbers to be doubled haploid (Fig. 2).

Dr. Masanori Inagaki from JIRCAS contributed to the development of the maize-based wheat DH technology at CIMMYT in 1993-1998 when he was a visiting scientist. Before visiting CIMMYT, he had already developed the DH technology (Inagaki & Snape 1982; Inagaki 1985; Inagaki & Tahir 1990) and brought it to CIMMYT. Even though wheat haploid can be induced by several methods such as anther culture, irradiation, wide crosses with wheat wild relatives and inducer lines (For review, see Kishii 2019), the maize-based wheat DH technology was more attractive at that time. This method is based on chromosome elimination phenomenon in which the maize chromosome is eliminated from the wheat cytoplasm, leaving only wheat chromosomes, in wheat x maize crosses (Fig. 3). Initially, wheat researchers used wild barley (*Hordeum bulbosum* L.) for wheat haploid induction, however wild barley is highly genotype independent and cannot be used for all wheat lines, especially for western wheat (Inagaki & Snape 1982). Since the 1980s, wheat researchers have discovered that a group of Panicoideae species including maize, sorghum and Perl millet could cross with wheat and induce wheat haploid more efficiently without the genotype dependency (Inagaki & Tahir 1990).

Dr. Inagaki was devoted to the improvement of several steps of the maize-based DH technology (Inagaki and Mujeeb-Kazi 1995; Inagaki 1997). The most important key step in wheat x maize crosses is that the crossed F_1 does not develop endosperm, so it is necessary to stimulate initial grain development, to conduct embryo rescue under a microscope two to three weeks after and to regenerate plants from the embryo on a solid culture medium.

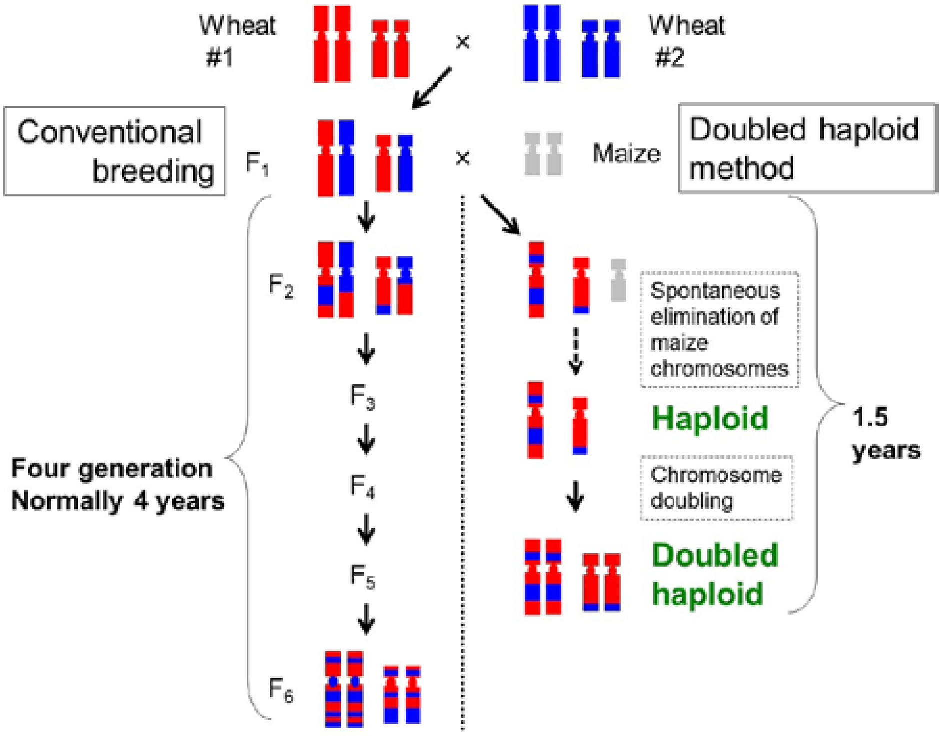

Fig. 2. A difference between conventional breeding and doubled haploid method in wheat
It takes five years to progress from F_1 to F_6 in the conventional wheat breeding, while maize-based DH technology can reduce to 1.5 years in doubled haploid method.

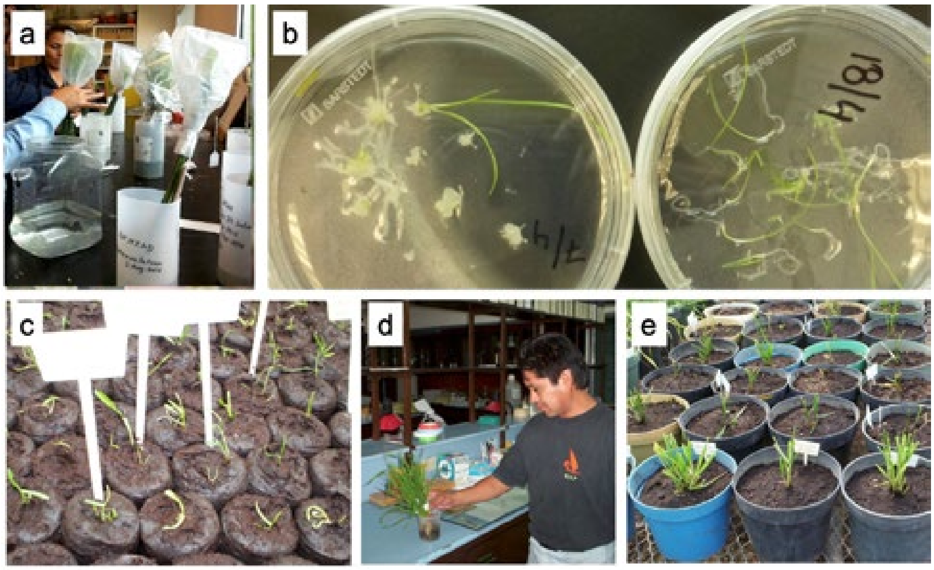

Fig. 3. Maize based doubled haploid production method in wheat

a) Cut spikes cultivated in sugar and 2,4-D solution after the pollination with maize pollen.
b) Cultivating embryos on mediums after embryo rescue. The right one is so-called ‘Inagaki’ medium, and the left one is older medium before Dr. Inagaki’s improvement.
c) Seedling plants after transplantation of b).
d) Larger plants treated with colchicine for chromosome doubling.
e) Plants in larger pot after colchicine treatment for growth.

Chromosome doubling was also a difficult key step. One of the important outcomes for CIMMYT was that Dr. Inagaki was able to raise the maize-based wheat DH technology to the practical level. In the late 1990-2000s, CIMMYT had the capacity to develop 5,000-10,000 wheat DH lines annually with a few technical staff, which was the largest production capacity in the world during that time. This is an important demonstration for other plant researchers and breeders to recognize that DH technology is applicable for breeding.

Wheat DH methods, including the maize-based wheat DH technology, have significantly advanced in the last two decades after the Dr. Inagaki's improvements, and DH wheat breeding and DH-derived varieties are already common in western countries. Twenty-one DH derived wheat varieties were released in China, Germany, Brazil, Canada, France, Hungary, Sweden, and the U.K. by 2003. In Romania, four of eight bread wheat varieties were maize based DH derived in 2002-2008. Canada released 27 wheat varieties using DH technology from 1997-2010, and these varieties cover more than 1/3 of Canada's wheat fields (DePauw et al. 2011). The U.S. also released three wheat varieties from 2015-2020 (Kishii & Singh 2020).

Durable disease resistance in wheat

Dr. Kazuhiro Suenaga has contributed to the development of a novel disease resistance strategy. There are two types of disease resistance genes: seedling resistance and adult plant (durable) resistance genes. Seedling resistance genes usually provide stronger resistance against disease, and only one or several genes are enough to exert complete resistance, while durable resistance genes have weaker effects and it is necessary to combine several genes to exert complete resistance (Singh et al. 2011b). In plant breeding history, researchers and plant breeders have had the tendency to utilize seedling resistance genes, as plants look cleaner without any disease symptoms. However, seedling resistance genes do not keep their effectiveness for a long time; pathogens mutate frequently and can overcome plant resistance, sometimes just in a few years. In the case of wheat production, the emergence of new disease races has threatened local and world wheat production several times throughout history. When the wheat stem rust race Ug99 appeared in Uganda in 1999, more than 80% of wheat varieties around the world did not have resistance against this new race, which put the world's wheat production at risk (Singh et al. 2011a). According to Olivera et al. (2015), another rust disease(yellow rust) arrived in Ethiopia about 10 years later and decreased about 30% of the country's wheat production. This crisis was solved by replacing existing varieties with new resistant wheat varieties. However, three years later, another stem rust disease race appeared, (which was not new but had existed in remote areas and reached Ethiopia for the first time) and reduced 30% of the country's wheat production again. The relationship between plant disease resistance and pathogens is best described as an arms race (Fig. 4). When one overcomes the other, the loser overcomes the winner and vice versa, and it is a never-ending story. The application of fungicide is a very effective way to control diseases, but it is costly for farmers in developing countries. One solution to end this arms race is to provide immunity to wheat varieties by combining several durable resistance genes.

Dr. Kazuhiro Suenaga from JIRCAS came to CIMMYT as visiting scientist from 1998-2002 and contributed durable resistance research in wheat leaf rust (by *Puccinia triticina*) by providing his expertise in molecular science. Progress in durable disease resistance was slow before the 1990s, because it was difficult to detect small effects of durable resistance genes. It was essential to utilize molecular marker technology to overcome this problem, and so Dr. Suenaga conducted molecular research together with CIMMYT molecular scientists. By the early 2000s, two adult resistance genes for leaf rust had been discovered: *Lr34* and *Lr46* (Table 1). Dr. Suenaga developed molecular markers for these two genes at CIMMYT (William et al. 2006; Suenaga et

Fig. 4. Resistant and susceptible wheat lines to yellow rust disease

The left front wheat line shows some degree of resistance. But if the resistance relays on one or two seedling resistance genes, it may become susceptible in emergence of a new disease race like the right front plant line. The maintain of disease resistance is important and difficult, because disease races will not stop mutating.

Table 1. List of durable/multiple resistance genes identified in wheat

Leaf rust	Yellow rust	Stem rust	Powdery mildew	Spot blotch	Barley yellow dwarf virus	References
Lr34	*Yr18*	*Sr57*	*Pm38*	*Sb1*	*Bdv1*	Singh et al. (2012)
Lr46	*Yr29*	*Sr58*	*Pm39*			Singh et al. (2013)
Lr67	*Yr46*	*Sr55*	*Pm46*			Herrera-Foessel et al. (2014)
Lr68						Herrera-Foessel et al. (2012)
		Sr56				Bansal et al. (2014)
	Yr30	*Sr2*				Singh et al. (2005); Singh et al. (2008); Mago et al. (2011)

Leaf rust resistance gene, *Lr34* turns to be identical to at least five disease resistance gene and is described as *Lr34* = *Yr18* = *Sr57* = *Pm38* = *Sb1* = *Bdv1*. For other case, *Lr46* = *Yr29* = *Sr58* = *Pm39*, *Lr67* = *Yr46* and *Yr30* = *Sr2*. *Lr68* and *Sr56* are durable resistance genes, but effects on multiple disease have not been confirmed.

al. 2007). This effort eventually led to the isolation of the *Lr34* gene (Krattinger et al., 2009). In contrast to the majority of cloned cereal disease resistance genes which belong to the race-specific nucleotide-binding site-leucine-rich repeat (NBS-LRR) gene family (Steuernagel et al. 2016), *Lr34* encodes a totally different class of gene: a cytoplasm membrane ABC transporter gene (Krattinger et al., 2009). A very interesting fact that appeared later is that *Lr34* is identical to other disease resistance genes which have been known for other wheat diseases, namely *Yr18* (yellow rust by *P. striiformis* f. sp. *tritici*), *Sr57* (stem rust by *P. graminis* f. sp. *tritici*) and *Pm38* (powdery mildew by *Blumeria graminis*), *Sb1* (spot blotch by *Bipolaris sorokiniana*), (*Bdv1* by barley yellow dwarf virus) (Ravi et al. 2015). One disease resistance gene is effective for multiple diseases. By 2021, a total of six durable resistance genes have been identified (Table 1). The number of genes to become immune or nearly immune is different among diseases, but it is thought to be 4-5 genes for leaf rust (CIMMYT, Singh RR, personal communication). Even though these adult plant resistance genes are known to have a negative effect on grain yield, this problem can be easily overcome by combining positive genes for yield and selecting plants in the field.

It is no longer a dream to achieve wheat plants which are immune to many diseases. We have reached this position in less than 20 years after finding linked markers for *Lr34* and *Lr46* which was achieved by a Japanese visiting scientist.

Wheat wild relatives for heat and drought tolerance

The CIMMYT genebank has many lines of wheat wild relatives which usually have higher levels of disease resistance and abiotic stress tolerance, as many wild plants have adapted to harsh environments and disease hot spots. These are difficult to utilize in breeding due to the presence of many so-called ‘wild characters’ which reduce grain yield and quality, so that specific works for wild relatives are necessary to utilize them in breeding.

Bread wheat (*Triticum aestivum*; 2n = 6x = 42, AABBDD) formed about 8,000 years ago as a hybrid between tetraploid *T. turgidum* L. (2n = 4x = 28, AABB) and the wild goat grass diploid *Aegilops tauschii* Coss (2n = 2x = 14, DD), followed by spontaneous chromosome doubling (Kihara 1944; McFadden & Sears 1946). This natural event of hybrid formation and spontaneous chromosome doubling happened only 1-2 times in about 10,000 years (Matsuoka 2011). Synthetic wheat is artificially re-created new bread wheat from crosses between wheat and wild goat grass (Kihara 1944; McFadden & Sears 1946). CIMMYT has produced synthetic wheat lines since the 1980’s (Mujeeb-Kazi 1995), and the author and his colleagues have about 800 new synthetic wheat lines since 2004 which is about a half of total synthetic wheat developed at CIMMYT. These have been utilized in new wheat variety development, and by 2019, at least 85 wheat varieties derived from synthetic hexaploidy wheat had been released in 21 different countries, covering 25% of wheat fields in Southwest China and 8% of wheat fields in India (Aberkane et al. 2020). Synthetic wheat has the advantage of disease resistance (Fig. 5) and heat and drought tolerance (Reynolds et al. 2007; Trethowan & Mujeeb-Kazi 2008; Pradhan et al. 2012; Jafarzadeh et al. 2016; Elbashir et al. 2017; Bhatta et al. 2018).

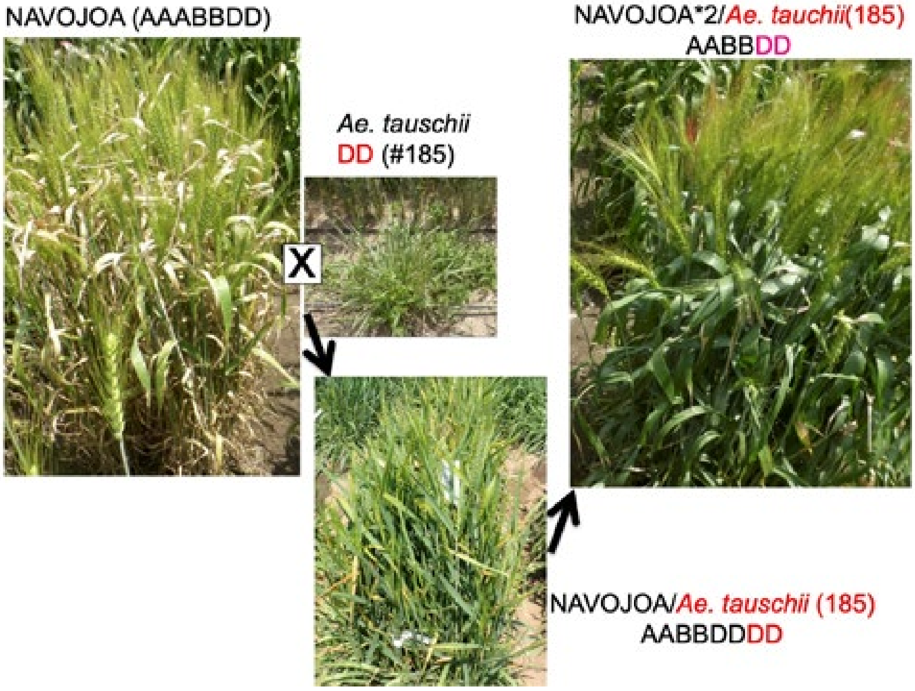

Fig. 5. Transfer of a yellow rust resistance gene from wheat ancestor of *Aegilops tauschii* to bread wheat
Firstly, bread wheat line 'NAVOJOA' (yellow rust susceptible) was crossed with *Ae. tauchii* (185) to produce synthetic wheat 'NAVOJOA/*Ae. tauchii* (185)'. Then this synthetic wheat was backcrossed with 'NAVOJOA', and resistance plants for yellow rust were selected in field.

Wheat wild relatives for a new trait of BNI

Wheat wild relatives can also provide a completely new trait of BNI. Semi-dwarf wheat varieties are highly productive when nitrogen fertilizer is applied, but this has negative effects on the environment -- a common criticism of the Green Revolution. Plants can take either nitrate (NO_3^-) and ammonium (NH_4^+) from the soil as an inorganic nitrogen source, but NO_3^- will leach from the soil very quickly due to the repellency of negative charges of clays and soil organic matter and cause water pollution. It also converts to the potent greenhouse gas nitrous oxide (N_2O). BNI will be one of the mitigation strategies for nitrogen fertilizer-related environmental pollution by preventing the conversion of NH_4^+ to NO_3^- in the soil system. Some plant species release chemical compounds that inhibit soil nitrification by preventing nitrification enzyme activities of soil bacteria. A tropical pasture species, *Brachiaria humidicola* (Rendle) Schweick, and sorghum are known to have high BNI activity, and a responsible compound for *B. humidicola* has been identified as bachialactone (Subbarao et al, 2009) and for sorghum as sorgoleone (Tesfamariam et al. 2014). An interesting finding is that within 3 years of establishment, *B. humidicola* plots indicated a 90% decline in soil ammonium oxidation rates (Subbarao et al, 2013).

Since about 20% of the world's nitrogen fertilizers are applied to world wheat production (Galloway et al. 2008), BNI-wheat may be able to significantly reduce the pollution from nitrogen fertilizer. The author and JIRCAS started a collaborative wheat BNI project in 2013. Preliminary studies before 2013 suggested that wheat lines did not have a high BNI activity, but one of the perennial wild wheat relatives, *Leymus racemosus* (Lam.) Tzvelev showed about 8 times higher BNI in hydroponic experiments (Subbarao et al. 2007). A strong BNI activity of *L. racemosus* was identified on the *L. racemosus* $3Ns^b$ (= Lr#n) chromosome in an analysis of *L. racemosus* chromosome addition wheat lines in which one of the *L. racemosus* chromosomes was added to wheat (Subbarao et al. 2007; Edet et al. 2018). Some *L. racemosus* chromosome translocation lines were developed in which the short or long chromosome arm of $3Ns^b$ was transferred on to the wheat 3B chromosome. Only the short arm translocation showed a high BNI, indicating that the responsible gene(s) are on the $3Ns^b$ short arm (In preparation). The wheat-*L. racemosus* $T3BL.3Ns^bS$ (= translocation of wheat 3B long arm +$3Ns^b$ short arm) chromosome was successfully transferred to several CIMMYT elite wheat lines by sequential backcrossing and selection for $T3BL.3Ns^bS$

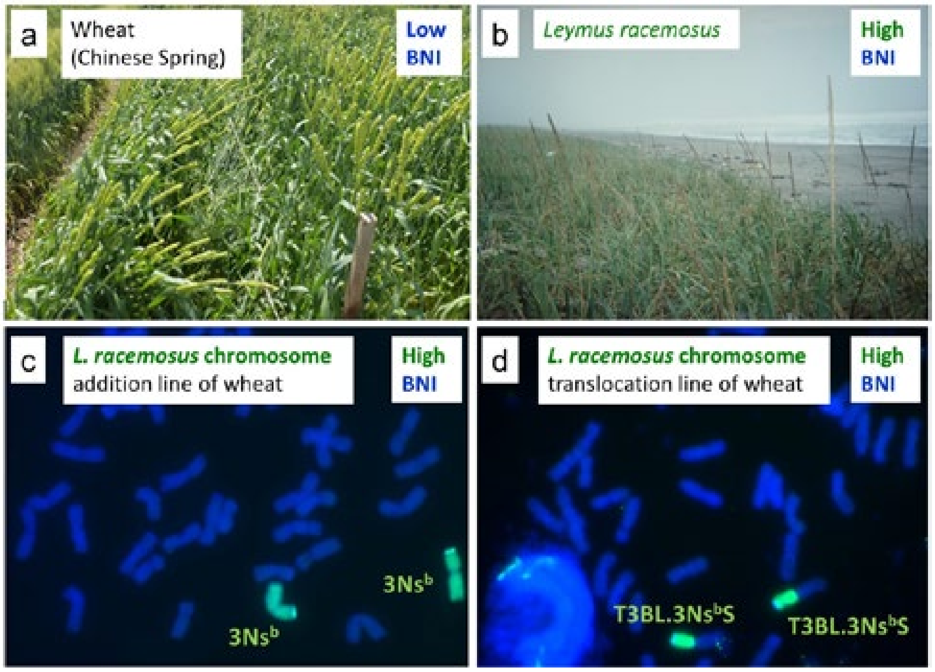

Fig. 6. Wheat and *Leymus* plants and chromosomal images of the addition (3Ns^b) and translocation lines (T3BL.3Ns^{b}S)
Wheat has low BNI, while *Leymus* has high BNI. The high BNI character of *Leymus* was transferred into wheat in forms of *Leymus* chromosome addition line (left bottom) and translocation line (left right). The arrows indicate *L. racemosus* chromosomes (3Ns^b) or the short arm part of *L. racemosus* chromosomes (3Ns^b).

using florescence in situ hybridization (Fig. 6). Field tests were conducted in both Mexico and Japan in 2020. One of elite wheat line 'MUNAL' with 3BL.3NsbS (+ BNI) showed a 5-10% increase in grain yield over 'MUNAL' parents (-BNI) in Obregon field, Mexico. Interestingly, the results indicated that 'MUNAL' with 3BL.3Ns^{b}S (+ BNI) showed a much higher yield increase, with 10-50% higher yields in all three nitrogen conditions tested (0N, 120N (a half) and 250N kg/ha (the maximum nitrogen) in Tsukuba, Japan (Subbarao et al. 2021).

Other Japanese contributions

Many mid to long-term staff (four out of six) were JIRCAS visiting staff, and they achieved excellent results in science and agriculture. While it is beyond the scope of this paper to discuss in detail, another JIRCAS visiting researcher, Dr. Tomohiro Ban worked on the wheat fusarium head blight (FHB) disease which is a serious problem in humid areas and is expanding to other regions due to climate change (Timmusk et al. 2020). Dr. Jiro Murakami also initially joined CIMMYT as an FHB project member. Even though it is difficult to describe, interns and visiting students have contributed very much to CIMMYT research and food production by bringing their scientific expertise to the center and achieving impressive scientific outputs.

Dr. Masaru Iwanaga (former CIMMYT Director General)

Dr. Masaru Iwanaga served as CIMMYT general director from 2002-2008. When Dr. Iwanaga was appointed as Director General, CIMMYT faced numerous financial threats. He conducted massive reform not only in finance but also organizational management, governance system and research strategy, which strengthened the institution and made it possible to expand the institute later on. His time was also a period when the possibility of world food crisis had become a reality. The crisis of Ug99 stem rust became apparent in the early 2000's as mentioned above (Singh et al. 2011a), soon after he took the position. Fortunately, the food crisis was avoided, as CIMMYT could quickly develop and distribute new Ug99 resistant wheat lines to the world. In 2008, some countries began producing seeds for new stem rust resistance wheat varieties (CIMMYT 2012). Then in 2007, severe drought also hit Australia in 2007, reducing about 50% of Australia's wheat production, spiking world wheat prices and significantly affecting developing countries (Perez 2013), which led social instability and uprising in the Middle East (Kelley et al. 2015).

The drought in Australia reminded many people about the importance of stable food supply and price as well as potential threat of drought for world food security, but Dr. Iwanaga's foreseeing in CIMMYT research strategy understood well this threat before the incident. One of important CIMMYT research focus during his time was drought tolerant maize for Africa (DTMA). This has been a long-time CIMMYT effort since 1990's, and some drought tolerance maize varieties have demonstrated more than 30% higher yields than conventional varieties in drought-prone environments (Banziger et al. 2006) which were cultivated in 13 countries of eastern, southern and western Africa in 2014 (La Rovere, R. et al. 2014). These amazing achievements have been recognized as an example on breeding for climate change adaptation (De Pinto et al. 2019).

Supports from Japanese government

It is notable that Japanese government has provided so many funds for infrastructure and research funds to CIMMYT in the form of Official Development Assistance (ODA) from the Ministry of Foreign Affair. CIMMYT genebank and the first bioscience building were built using these funds. Without these excellent infrastructures, the level of CIMMYT research activities/capacity would be much less than the current level. The research funds are the blood of CIMMYT to sustain research staffs and activities for a long run which is the most important factor to create big impacts/benefits in society and humanity. Special research funds from the Ministry of Agriculture have provided since 2014. These funds are utilized for BNI research and wheat blast disease, the latter which is another emerging-disease threat for wheat production (Ceresini et al. 2018).

Final remark

Even though the number of Japanese researchers who have worked at CIMMYT is limited compared to other countries, they have contributed greatly to CIMMYT research and to world food production. One Japanese researcher played a crucial role for CIMMYT direction and reform as CIMMYT Director General. Japanese government has supported CIMMYT for infrastructure and research funds which are important to achieve higher research level and for long-term research activity to create big impacts/benefits in society and humanity. The outlook for global wheat and maize supply has not been optimistic and will become worse in the future due to an increasing world population, the impacts of heat and drought as well as the spread of new diseases caused by climate change. The scientific achievements left by Japanese scientists at CIMMYT, in addition to supports from Japanese government will play an important role in mitigating these problems.

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