Cereals in CHINA

Zhonghu He and Alain P.A. Bonjean, Editors

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The International Maize and Wheat Improvement Center, known by its Spanish acronym, CIMMYT® (www.cimmyt.org), is an international, not-for-profit research and training organization. With partners in over 100 countries, the center works to sustainably increase the productivity of maize and wheat systems to ensure global food security and reduce poverty. The center's outputs and services include improved maize and wheat varieties and cropping systems, the conservation of maize and wheat genetic resources, and capacity building. CIMMYT belongs to and is funded by the Consultative Group on International Agricultural Research (CGIAR) (www.cgiar.org) and also receives support from national governments, foundations, development banks, and other public and private agencies. CIMMYT is particularly grateful for the generous, unrestricted funding that has kept the center strong and effective over many years.

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Table of Contents

Zhonghu He and Alain P.A. Bonjean, who edited this book, with Thomas A. Lumpkin, CIMMYT Director General.

Preface

China, which has a very long history, abounds in agrarian testimonies from Neolithic times. As the sinologist Joseph Needham once wrote, "*the fundamental occupation, the root pen and the basis of the nation's wealth and well-being, was agriculture – as all philosophers and political economists from Confucius all agreed. The royal house of Chu claimed their descent from the agriculture deity Hou Chi, Prince Millet. Chinese emperors sacrificed at the altar of the spirit of the soil each spring and autumn, and in the spring it was also their duty to drive out to the royal fields near the capital and ceremonially plough a furrow, after which each of the chief ministers would in his turn put his hand to the plough.*"

Traditionally, the Chinese diet was largely vegetarian, with cereals its main "*fan*" or staple food. Most proteins came largely from legumes or protein-rich legume products such as bean-curd or soybean sauce.

The Chinese have farmed millet and rice in the basins of the Huang He (Yellow), Huai He (Huai), and Changjiang (Yangtze) rivers for several thousand years, and modern China is a major producer of a large range of cereals. Wheat, barley, maize, sorghum, oats, and even triticale are now cultivated in addition to rice and millet. Among these crops, maize and rice hybrids predominate, and several wheat hybridization systems are currently being evaluated.

Sustaining the enormous Chinese population in both historic and recent times would not have been possible without the cultivation of all these cereals. Today, steady production and genetic improvement of cereal crops are essential for food security and the stability of modern Chinese society. At present, Chinese cereal producers and researchers face huge challenges, and as population continues to grow and arable land to decline; they will also have to find ways to cope with ever-decreasing water resources and the predicted impacts of climate change. Despite its potential usefulness, very little information is available in English on the production and breeding of Chinese cereals, which have unique traits due to the varied dietary styles and multi-cropping systems that can be found across China's vast landscape. To fill this gap, the International Maize and Wheat Improvement Center (CIMMYT) which has worked closely with China for more than 30 years, the Chinese Academy of Agricultural Sciences (CAAS), China's leading agricultural research organization, and the Limagrain Group, a leading international cereal research company, have collaborated to produce this publication, *Cereals in China*. In addition to maize, wheat, and triticale, CIMMYT's mandated crops, the book also includes other important cereals such as rice, barley, millet, sorghum, and oats. In addition to Zhonghu He and Alain P.A. Bonjean, who edited this book on Chinese cereals, authors include experienced colleagues, breeders, and research professors from leading Chinese agricultural research institutes.

We feel confident that this publication will provide interesting and useful information on Chinese cereal production and breeding, not only to cereal crop professionals, but also to all who wish to learn more about food production and agriculture research in China. We also harbor the hope that it will contribute to inspire new vocations in plant breeding and related technologies among the new generation.

Thomas A. Lumpkin
Director General
CIMMYT

Aknowledgements and dedication

The editors are grateful to the chapter authors who toiled through several drafts of the manuscript. We also wish to thank Professors Xianmin Jiao and Jing Zhang of the Crop Research Institute, CAAS, who kindly reviewed the millet and barley chapters, respectively.

Our special thanks go to Professor Bob McIntosh of the University of Sydney, a well-known wheat scientist and our old friend, for his tireless efforts in reviewing and editing the entire book several times. He gave generously of his time and experience to correct errors and help authors and editors strike the right balance and eliminate gaps. We also thank Dr. Thierry Risacher, world renowned cereal biotechnologist, for reviewing several chapters. We are grateful as well to contract editor Alma McNab and CIMMYT science writer Mike Listman for editing the style and content, as well as to CIMMYT designers Miguel Mellado and Eliot Sanchez for the design, layout, and production.

This book is dedicated to our respective parents, Bao-ming He and Hua-lan Han, who passed away during the preparation of the book, and Paule and André Bonjean, who always understood the importance of farming and education. To them we owe our vocations in plant breeding and our commitment to international cooperation as a means of offering better food to all. It is also dedicated to our very supportive spouses, Li-hua Zhao and Yun-fang Zhao, and our children Yi-meng He and Thomas, Zhongzhong, Rémi, Baohua (Cécile), Luc, Alexandre (Yu-chun), and Zoe (Hua-chun) Bonjean, who allowed us to work evenings, weekends, and even holidays.

Zhonghu He and Alain P.A. Bonjean

Beijing, 21 February 2010

Map of the People's Republic of China.

A brief Chinese chronology

Dynasty	Period
Xia	2100–1600 BC
Shang	1600–1100 BC
Zhou	
Western Zhou Dynasty	1100–771 BC
Eastern Zhou Dynasty	770–256 BC
Spring and Autumn period	770–476 BC
Warring States	475–221 BC
Qin Dynasty	221–206 BC
Han	
Western Han	206 BC–24 AD
Eastern Han	25–220 AD
Three Kingdoms	
Wei	220–265
Shu	221–263
Wu	222–280
Western Jin	265–316
Eastern Jin	317–420
Northern and Southern	
Southern Dynasty	
Song	420–479
Qi	479–502
Liang	502–557
Chen	557–589
Northern Dynasty	
Northern Wei	386–534
Eastern Wei	534–550
Northern Qi	550–577
Western Wei	535–556
Northern Zhou	557–581
Sui	581–618
Tang	618–907
Five Dynasties	
Later Liang	907–923
Later Tang	923–936
Later Jin	936–946
Later Han	947–950
Later Zhou	951–960
Song	
Northern Song Dynasty	960–1127
Southern Song Dynasty	1127–1279
Liao	916–1125
Jin	1115–1234
Yuan	1271–1368
Ming	1368–1644
Qing	1644–1911
Republic of China	1912–1949
People’s Republic of China	1949–

Chapter 1.

Origins and historical diffusion in China of major native and alien cereals

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1. Introduction

China, one of the oldest civilizations in the world, has a long written history (Wadley and Martin, 1993) that includes records of numerous comments linked to cereals, beginning with the Shang dynasty, which flourished along the Yellow River between the 18th and 11th centuries BC. We have learned about the local emergence of agriculture before this period only through unwritten archaeological evidence.

Recent publications suggest, based on molecular evidence, that modern *Homo sapiens* in East Asia originated in Africa. They indicate two main settlements (Shi, 1998; Zhou, 2006). The first occurred around 60,000 years ago in mainland southeast Asia during the last Ice Age, and coincides with the absence of human fossils in eastern Asia 50,000-100,000 years ago. The second was the result of a later northward migration into northern China and Siberia. From there, other migrations towards Korea, Japan, and America followed (Su et al., 2000; Ke et al., 2001; Wells et al., 2001).

Agriculture in Asia began not in the eastern part, but in western Asia, where wheat, barley, other crops, and a few animals such as sheep and goats were domesticated well before 10,000 BC. In China, archaeological remains of the Neolithic period reveal agricultural sites dating from the 7th millennium BC (Figure 1), but agriculture may have started earlier, with pottery use about 14,000-10,000 BC confirmed (An, 1984).

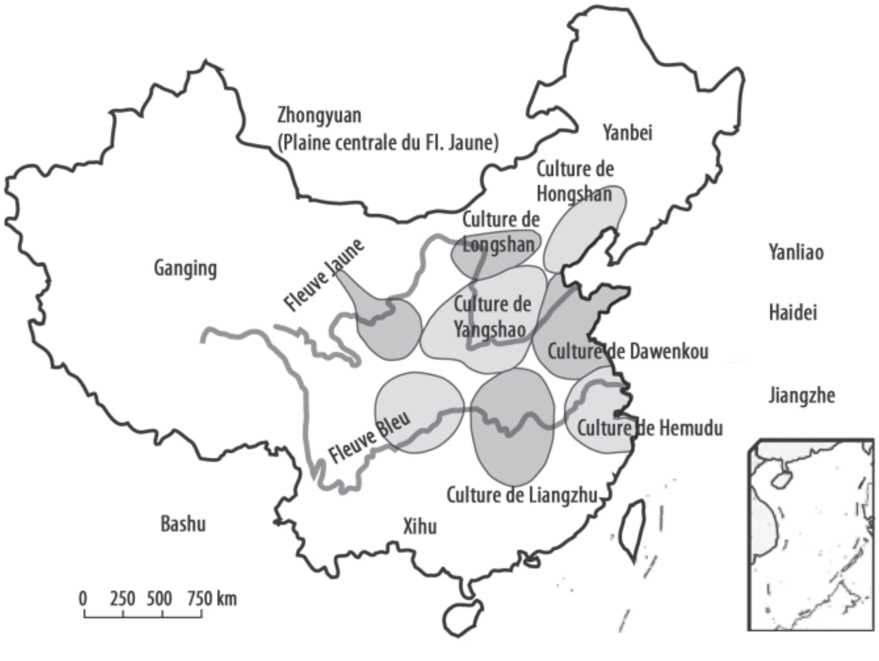

Figure 1. Regions where the main Chinese Neolithic cultures were located.
Source: Asia Art Museum - Chong Monn Lee Center for Asian Art and Culture

During the initial stages of Chinese agriculture between the 8th and early 6th millennia BC, at least two groups of human societies converted from their initial hunter-forager way of life to cereal production.

Based on evidence from several sites in northern China, proso millet (*Panicum milieaceum,* also called broomcorn millet) and foxtail millet (*Setaria italica*) were the main early crops of the famous Peilikang, Yangshao, and Seutong cultures and their succeeding groups (Wang, 1988; Weber and Fuller, 2006). These prosperous settlements, located in the fertile areas of the upper and middle

Yellow River Basin from 8,000 to 3,000 BC, were apparently the ancestors of modern Sino-Tibetan populations, indicating pre-historical migrations to the Himalayas (Figure 2). Millets were also a feature of the Longshan culture (4,400-4,000 BC) in the lower Yangtze Valley.

Rice (*Oryza sativa*) was the principal early cereal in the south, where both sub-species of the crop, *indica* and *japonica*, were present. These were identified at many locations, among them famous sites (Table 1) like Pengtoushan, Lixian County, Henan (8,200-6,200 BC); Bashidang, Lixian County, Henan (6,000-5 000 BC); Jiahu, Wuyang County, Henan (6,000-5,000 BC); and the Hemudu site (6,800-5,000 BC) in the lower Yangtze River Basin. Millets remained important in northern Chinese agriculture until the 20th century, when their production areas were taken over by other cereals, mainly maize and wheat. However, the development and expansion of rice never stopped.

Among the “five sacred cultivated plants” of ancient China that are thought to date from emperor Chin-nong in 2,700 BC, four were cereals (rice, barley,

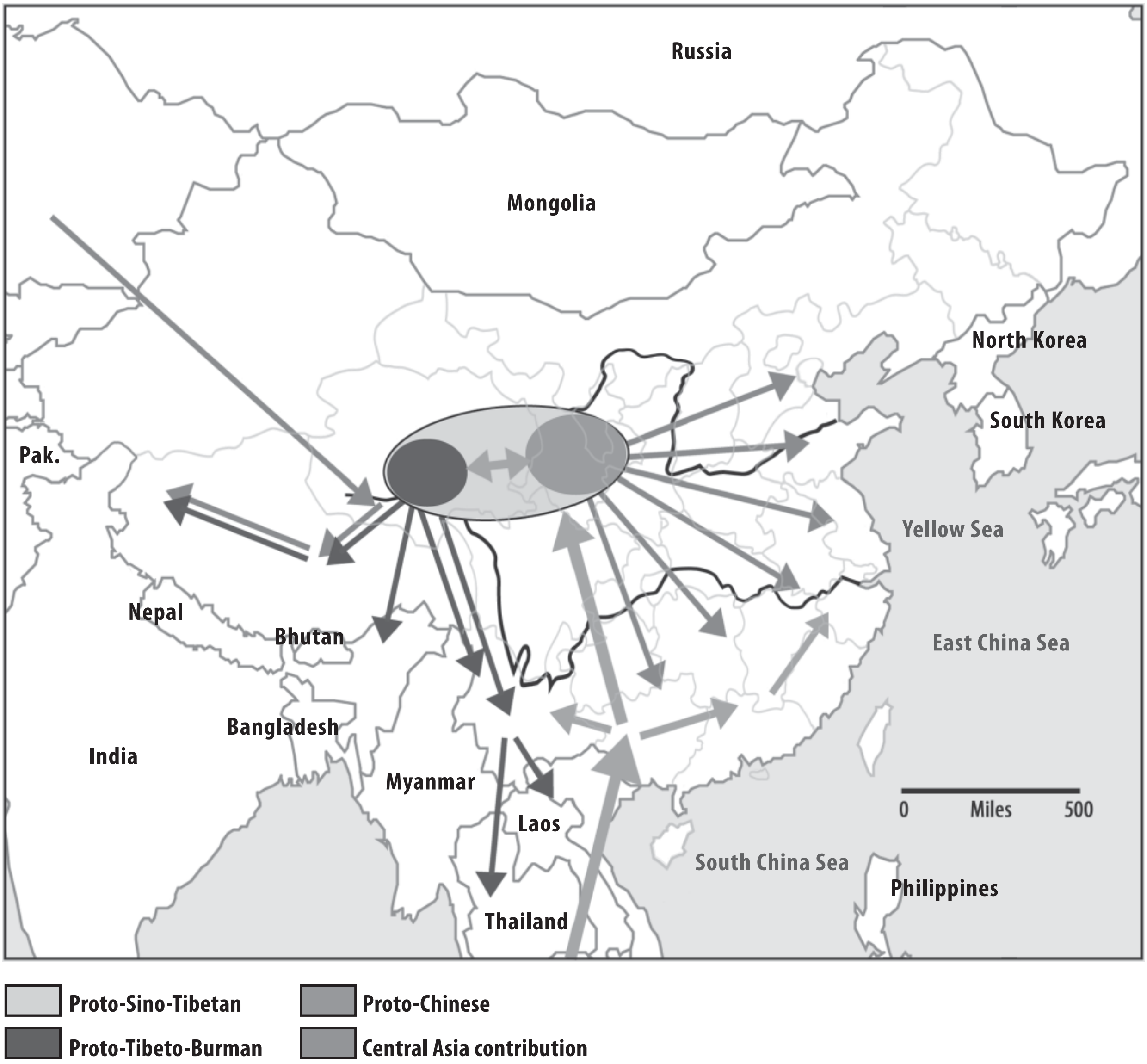

Figure 2. Putative migrations of Sino-Tibetan populations.
Source: Su et al. (1999, 2000).

wheat, and millet), and the fifth was soybean (Bray, 1984). Barley and wheat, originating from the Near East, were probably introduced into China by the end of the Neolithic period and have been authenticated by late Shang oracle-bones (1,766-206 BC). Barley may have been domesticated simultaneously in the central-western and western parts of China, where it flourished over a long period before significant wheat cultivation began. Wheat is clearly an introduction from western territories, following its domestication in the Near East, but it became a major crop in northern China only during the Han dynasty (206 BC-220 AD). Table 2 lists the main cereals in Chinese diets prior to the introduction of maize in China.

Sorghum is supposed to have been present in China by the 3rd century, but it may have been introduced earlier. Although it never became a major Chinese cereal, its impact on alcoholic beverage production was significant. Maize was introduced during the 16th century, but became popular only three or four centuries later. This was nevertheless an example of very rapid adoption by a human society.

Other secondary or minor cereals such as barnyard millet (*Echinochloa crus-galli*), finger millet (*Eleusine coracana*), kodo millet (*Paspalum scrobitulatum*), Job's tears (*Coix lacryma-jobi*), oat (*Avena sativa*), and rye (*Secale cereale*) were also cultivated in China during various historical periods, but will not be discussed here.

Table 1. Early Chinese cultures in major regions dated based on archaeological cereal remains.

Period (years BC)	Upper Yellow River Valley	Middle Yellow River Valley	Lower Yellow River Valley	Middle Yangtze River Valley	Lower Yangtze River Valley	Northeast and North	South and West
7,000 and older		Donghulin 9,220-8,750 Nanzhuangtou 8,500-7,700 Cishan 8,300-6,700 Peiligang 8,000-7,000 Laoguantai 8,000-7,000	Beixin 7,300-6,400	Pengtoushan 8,200-6,200	Luojiajiao # ,000	Xiaohexi 8,500-6,500 Xinle # 7,000 Zhuannian 7,800-7,200	Shangshan 7,000
6,000		Banpo 6,800-5,600	Early Dawenkou 6,300-5,500	Bashidang 6,000-5,000 Jiahu 6,500-5,000 Daxi 6,100-5,400	Majiabang 6,400-5 800 Hemudu 6,800-5,000 Houli 6,450-5,300	Xinkoiliu 6,100-5-000 Xinglongwa 6,200-5,400 Xinle 6,000-5,500 Xinlonggou 6,000	Dawidan 6,500-5,900
5,000	Majiayo # 5,100 Shilingxia # 5,800	Miaodigou I 5,900-5,000	Mid Dawenkou 5,500-4,800	Qujianling 5,300-4,500	Liangzhu 5100-4,200	Fuhe # 5,000 Hongshan # 5,000	Dadiwan-Laoguantai 5,850-5,400 Shixia 5,000-4,000
4,000	Machang 4,200-4,000 Banshan 4,600-4,000	Wangan 4,500-4,000 Miaodigou II # 4,800 Keshengzhuang 4,500-4,000 Xiwangcun 5,000-4,800	Longshan (Shandong) 4,400-4,000 Late Dawenkou 4,800-4,500	Qinghongquan III 4,400-4,000			Shankei # 4,800
3,000	Qija # 3,900		Yueshi 3,900-3,700				Tanshishan # 3,300

Table 2. Main cereals in Chinese diets during historical periods prior to the introduction of maize into China.

Period	Main cereals	Comments
Pre-historic period early Neolithic (8,000-5,500 BC)	Millets sown as crops in the Yellow River area and southern Inner Mongolia from 8,350 BC, with sickles, mortars, and pestles. First rice known in several sites of the Yangtze and Huai Basins, inside limited paddy rice fields, about 7,000-6,200 BC.	Stone sickles and knives, grindstones, and pestles. Storage pits among the houses, pottery. Other plants (oil cabbage, nuts, Chinese jujube) and animals (pigs, dogs, chickens). Also, roots and tubers in the south.
Pre-historic period middle Neolithic (5,500-3,000 BC)	Millets going north and south, east and west. First wheat introductions likely. Development of paddy rice agriculture in middle and lower Yangtze and Huai Basins.	Cereal cultivation widespread by about 4,000 BC. Several animal species domesticated during this period.
Pre-historic period late Neolithic (3,000-2,000 BC)	No major evolution in the north, except for agricultural tools and technical modifications. Wheat expansion in central-eastern provinces, with limited presence in the Hexi Corridor, Anhui and Henan Provinces. Development of four centers of rice cultivation, viz., Yunnan, upper reaches of Huai River, middle and lower reaches of Yangtze River in southern China.	3,000 BC: agriculture expanded to all easily cultivated parts of China. Invention of brewing of alcoholic beverages during the Xia dynasty. Millet noodles.
From the Shang dynasty (1,766-206 BC) to the Han dynasty (206 BC-220 AD)	Millets and recently introduced wheat and barley cultivated simultaneously in the north and west. Wheat area approaching that of millet by the end of the period, even though wheat productivity was low and its grain a kind of luxury compared to millet. Rice and various water foods (lotus arrowroot, water chestnut) in the south.	Development of the use of cereals for making alcoholic beverages. Beginning of double-cropping during the Shang dynasty with millets and wheat; the growth cycle of primitive rice was too long for double-cropping. Beginning of pest control, about 1,000 BC during the Zhou dynasty. Use of cast iron tools and beasts of burden to pull plows and beginning of irrigation during the Spring and Autumn periods (722-481 BC). Development of irrigation with the Han dynasty. Wheat noodles developed as a result of the introduction of improved flour technologies apparently from central Asia via the "Silk Road."
From the Three Kingdoms period (220-280 AD) to the Sui dynasty (581-618)	Millets, including non-glutinous and glutinous landraces, for both eating and brewing, and wheat in the north. Rice in the south. Barley everywhere, but secondary.	Acceleration of cereal based alcohol-making techniques after the 3rd century AD. Development of grain storage facilities along the rivers, used as food reserves, during the Sui dynasty.
Tang dynasty (618-907)	Millet and wheat are the dominant northern staple food; rice remains popular in the south, with new varieties appearing in rapidly expanding growing areas. Possible limited development of sorghum.	Appearance of new milling methods along the "Silk Road" to enhance the development of new wheat end-uses (e.g., dumplings, cakes, noodles).
Song dynasty (960-1279)	New developments in rice with the introduction of the short-season Champa varieties, which become the leading Chinese cereal in the empire. Explosion in numbers of rice varieties.	Double-cropping increases and gradually becomes established throughout southeast China. Agricultural loan program, land reclamation and water conservation measures. Re-birth of the granary system.
Yuan dynasty (1279-1368) and Ming dynasty (1368-1644)	Rice, wheat, and millet are the main Chinese cereals. Sorghum is developed during the Yuan dynasty. Maize is known by 1,505, if not earlier.	Presence of horizontal millstones for wheat. Reduction of millet area only during the 20th century.

Sources: Bray (1984), Anderson (1988), Soutif (1995), and Zishu (1998).

2. Millets

Proso or broomcorn millet (*Panicum milieaceum*) (or *shu* and *ch'i*) and foxtail or Italian millet (*Setaria italica* = *S. lutescens*) (or *su* and *liang*), along with rice, appear to be the oldest cereals cultivated in China (Sigault, 1994). It is interesting that the oldest known Chinese instruments for measuring cereal grain, including rice and wheat grains, have millet-related names.

Although poorly documented until recently, the domestication of proso millet seems to have occurred in northern China or nearby territories of East Asia from *P. ruderale*, a wild species native to central China. The earliest significant use of common millet was established in the semi-arid regions along the margins of the loess plateau, sometimes called the "yellow heart" of China, and in the hilly flanks of the Inner Mongolian Plateau by 8,000 BC (Lu et al., 2009). It seems that the relatively dry conditions in the early Holocene may have been more favorable for the domestication of common millet than of foxtail millet. During the early Neolithic, proso millet appears to have been the first staple crop of populations of northern China, appearing significantly earlier than foxtail millet, at Cishan (8,300-6,700 BC), Niuyingzi and Beichengzi (before 6,500 BC), and Xinglonggou (6,200-5,200 BC). At Cishan it was stored in dry storage pits during the winter (Jiang et al., 2008). Then, between 6,500 and 4,500 BC, several waves of human migrations spread it to the more productive regions of the lower Yellow River and its tributaries.

Foxtail millet was domesticated from its wild progenitor, *Setaria viridis*, a species widely distributed in Eurasia and especially throughout continental East Asia. It was present at several Neolithic centers in China in the warmer postglacial period, as shown in Figure 3 (Pernes, 1983; Jiang et al., 2008). The very early presence of foxtail millet and of proso millet in central north China was confirmed by a few archaeological remains dating from 7,000-6,500 BC. Both crops were cultivated in Gansu, Shaanxi, Shanxi, Hebei, and Henan by the Peiligang, Cishan, and Dawidan cultures, followed in 5,000-3,000 BC by the Miaododigou, Majiayao, Banshan, Banpo, and Hougang cultures. These cultures were regrouped under the generic term of the Yangshao/Longshan transition, and soon afterwards in Shandong by the Dawenkou culture and in Liaoning by the Xinle culture (Lee et al., 2009). In these areas, foxtail millet was the principal crop for at least four millennia, whereas proso millet was significantly less important throughout the period (Toussaint-Samat, 1997; Yang, 1997).

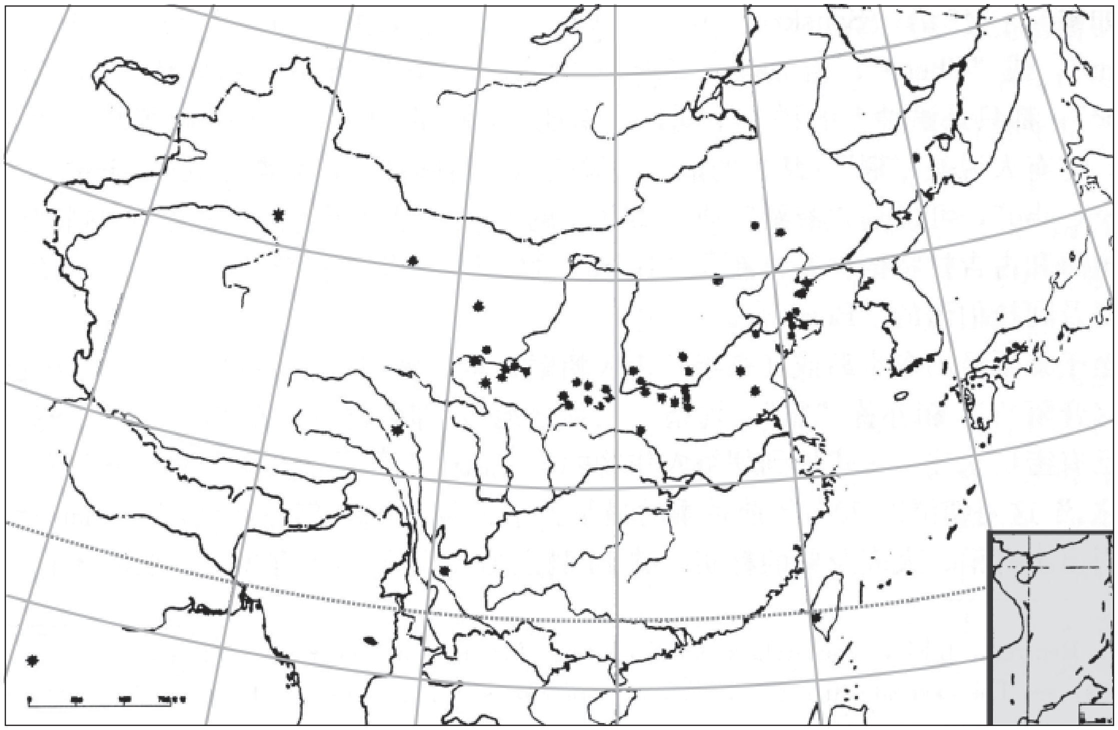

Figure 3. Distribution of the main Neolithic archeological sites where remains of *Panicum miliaceum* and *Setaria italica* have been found. Source: Jiang et al. (2008).

The early cultivation (between the fifth and third millennia BC) of millets in the dry areas of the loess-rich upper Yellow River Basin, and in semi-dry areas of the middle basin resulted in numerous cultivated types of millet with very good drought resistance and high tolerance to cold, combined with larger seeds and better lodging resistance than the wild types. They included varieties of various colors, and non-glutinous and glutinous types. Among them, a foxtail glutinous variety used to produce millet wine is known from Shang dynasty oracle bones. Proso millet was progressively cultivated in a smaller area than foxtail millet, which was preferred for its pleasant flavor (Pechenkina et al., 2002). In 2005, the oldest intact noodles yet discovered worldwide, estimated to be over 4,000 years old, were located on a terrace on the upper reaches of the Yellow River at Lajia, Qinghai Province. The noodles were made from both foxtail and proso millets (Lu et al., 2005).

From China, these crops spread to India, the Middle and Near East, Africa, Russia, Ukraine, and southern Europe. For example, archeological sites dating from 5,500 BC located west of the Black Sea show the presence of proso millet, suggesting to some authors that this species may have been domesticated from different ancestral stocks (i.e., that its domestication was possibly polyphyletic) (Jones and Liu, 2009). In Europe, these millets were grown for millennia, but began to compete with maize in the early 16th century and thereafter declined.

In China, foxtail and proso millets continued to be very important crops until the beginning of the 20th century (Kiple and Ornelas, 2000), when their areas significantly declined because they could not match the high yield potential and adaptation of modern rice, wheat, and maize varieties. However, today they are still produced for specialty foods or because of their adaptation to areas that are too dry or too cold for other crops.

3. Rice

The wild perennial species *Oryza rufipogon* and its annual variant *O. nivara* represent the complex ancestry of Asian cultivated rice (*O. sativa*) and of its two differentiated subspecies, *indica* and *japonica* (Smartt and Simmonds, 1995). This complex species is widely present in tropical and subtropical areas of Asia and Oceania, and in China it is distributed from Hainan in the south and Yunnan in the west to Taiwan in the east and Jiangxi in the north. This distribution was wider and more northern during the Mesolithic and Neolithic periods, and included the current territories of southern Sichuan, Chongqing, southern Hubei and Anhui, Jiangsu, and a large part of Shandong, as well as all of South China, including Taiwan and Hainan (Figure 4) (Jiang et al., 2008). *Oryza sativa* and *O. rupifogon/nivara* are genetically very close and produce fertile hybrids that segregate into progenies similar to domesticated rice or weedy progenies that are barely distinguishable from each other using molecular markers. *Oryza sativa* generally shows more phenotypic variation than *O. rufipogon/nivara*, but at the molecular level, genetic variation in *O. sativa* appears much less than in its wild progenitor. According to recent genomics data, differentiation between the two cultivated subspecies *indica* and *japonica* probably occurred partly within wild rice before domestication itself, but the two domestications are not totally independent, with both subspecies sharing ancestral populations and/or having recent gene flow between them (Gao and Innan, 2008).

From archaeological data analysis, the Yangtze River Valley and the region located to the south between the Yangtze and the Yellow River have been recognized as the area where rice was first domesticated (Figure 5).

In the 1970s, archeologists believed that rice was domesticated in the lower Yangtze River Valley, where several rice-producing Neolithic sites such as Hemudu (6,800-5,000 BC) and Luojiajiao (5,100-4,000 BC) in Zhejiang province, Caoxieshan (4,200-3,900 BC) in Jiangsu and Songze (circa 4,000 BC) in the vicinity of Shanghai had been studied (Wang, 1985; Bray, 1984; You, 1988).

In the 1990s, excavations of older rice remains at Yuchanyan (13,000-6,000 BC), Pengtoushan (6,200-5,800 BC) and Bashidang (7,000-6,000 BC) in Hunan presented the possibility of earlier rice domestication in the middle Yangtze region (Chen, 1997 a and b; Heyem, 1998; Pei, 1998; Ren et al., 1998; Zhang, 1998; Morishima, 2001). The recent discovery of further old rice remains at Xianrendong and Diatoghuan (12,000-9,000 BC) in Jiangxi, Shangshan (8,000 BC) in Zhejiang, and Zhengpiyan (8,300-5,000 BC) in Guangxi, has renewed speculation about the location of the earliest rice domestication. A broad area, including both the lower and middle Yangtze River regions, most probably constitute the area where Asian rice was domesticated in China, most likely

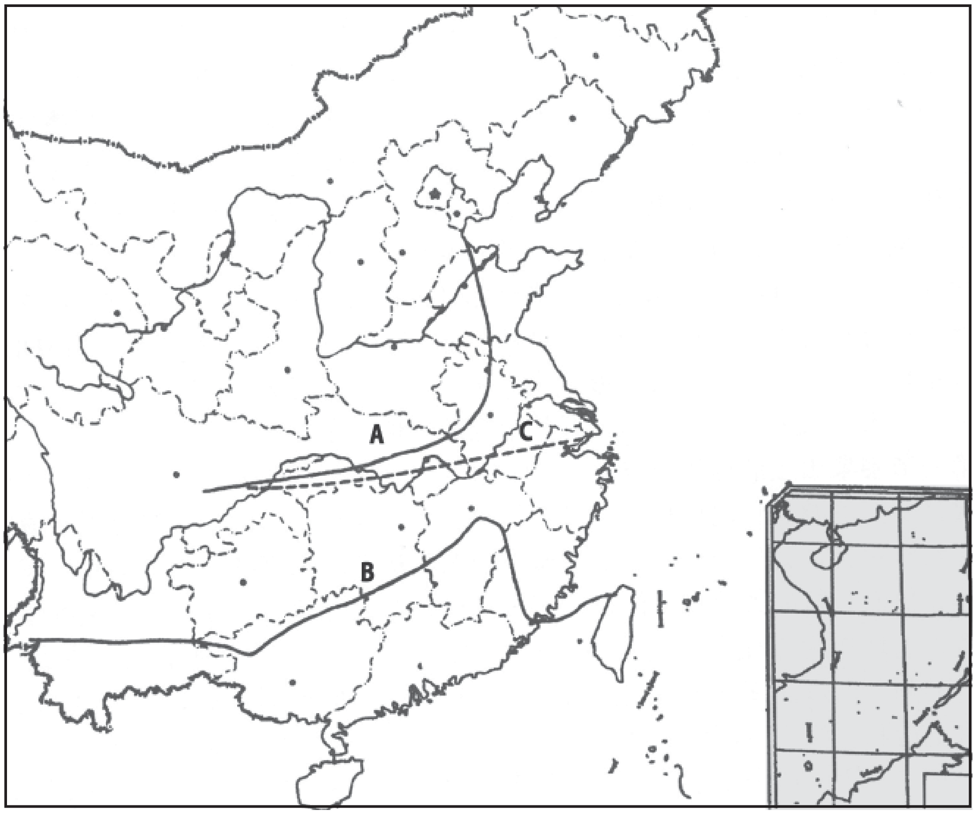

Figure 4. Northern distribution of *Oryza rufipogon* during the early Neolithic period (A) and at the present time (B). Source: Jiang et al. (2008).

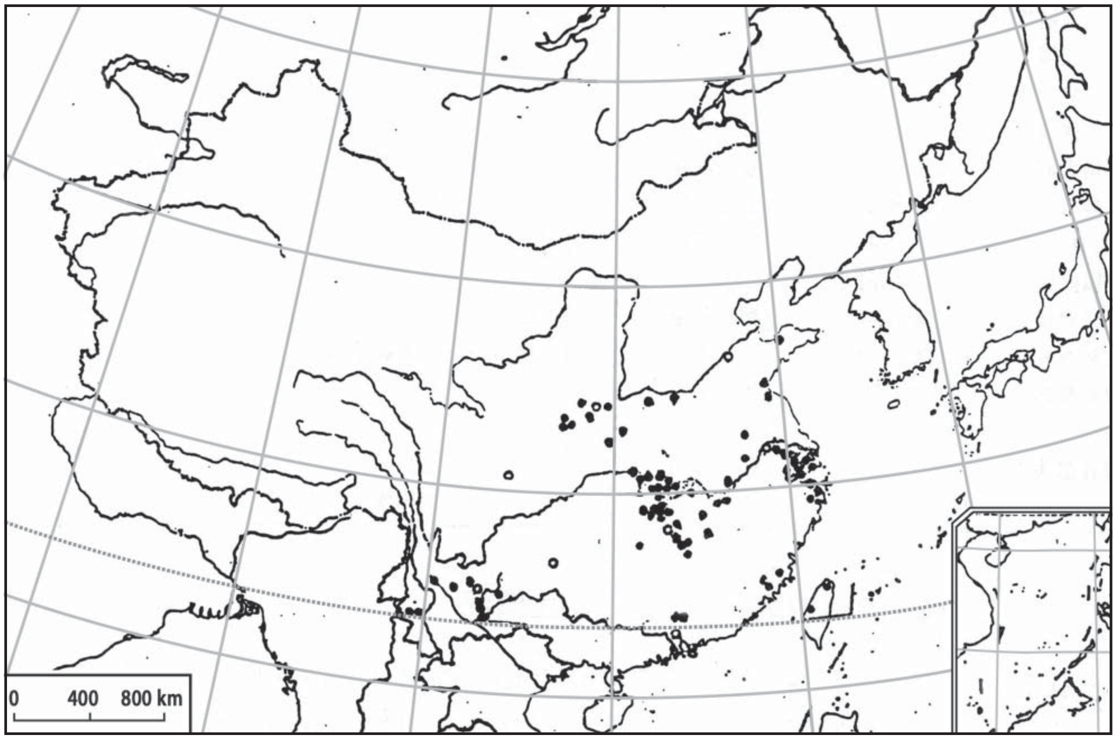

Figure 5. Distribution of Neolithic sites where rice artifacts have been found. Source: Jiang et al. (2008).

around 7,000 BC. The evidence comes mainly from the loss of seed shattering and color, changes in seed shape, reduction in seed dormancy, and changes in plant architecture (Sang and Ge, 2007; Jin et al., 2008; Fuller et al., 2009). The cultivated forms of *japonica* seem to be of Chinese origin, whereas *indica* more likely has a polyphyletic origin shared with other domestication sites in South Asia and possibly Southeast Asia as shown in Figure 6 (Kawakami et al., 2007; Londo et al., 2006; Sang and Ge, 2007; Jones and Liu, 2009).

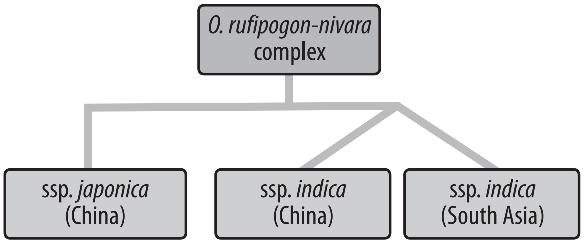

Figure 6. Most likely pathways of Asian rice domestication.

Before the domestication process started, wild rice populations were harvested by human populations for a long time, after which domestication was a gradual process. Archaeological evidence from Diaotonghuan and Tianlusoshan shows that the transition from the collection of wild rice to the cultivation of pre-domesticated rice, to the domesticated form with fixation of the non-shattering phenotype occurred over two to three millennia (Fuller et al., 2009). It also shows that the first farmers were creating rice paddy fields during this period, using fire to clear marshes of dense reeds, and also bones or wooden spades.

Thousands of rice landraces were created in China during the early stages of agriculture. They had numerous properties, e.g., short-to-long growth cycles, long and short grain, non-glutinous and glutinous endosperm, colored kernels, and a range of flavors (Jin et al., 2008; Izawa et al., 2009). It seems that during the Zhou period (1,027-221 BC) 'wet' rice types from southern mainland China, mainly the short-grained *japonica* types, which were more cold tolerant than *indica* types, diffused north-eastwards; from there, they spread to the Korean peninsula and Japan. Alternatively, rice could have spread by sea from Shandong to Korea and Japan (An, 1999). Other investigators have hypothesized the expansion of rice from Taiwan and the Ryukyu islands to Japan by sea; indeed, all possibilities could have occurred.

Between 300 and 400 AD, early varieties from the south spread to the Yangtze area, but they played a minor role. During the Five Dynasties and the beginning of the Song dynasty, the growing human population in the Yangtze Basin and in the southern provinces forced the Chinese Empire to utilize quick-ripening, drought-resistant rice varieties from Champa (a state located in southern Assam). This development was very fortunate, for it allowed multiple-cropping, and by the end of the 12th century, Champa types covered 80 to 90% of the paddy fields in the lower Yangtze Valley. The drought resistance of some Champa rice also facilitated the spread of rice cultivation into hilly areas where water availability was too low for traditional varieties (Zeng, 2001).

The development of rice in China has been ongoing, except in wartime, until the present time.

4. Wheat and barley

Historically, wheat and barley, native to West Asia (Bonjean and Picard, 1990), are known in China under the common name of *mai*, which means grain. Remains of wheat (*Triticum aestivum*), called *xiao mai* or small grain, and barley (*Hordeum vulgare*), called *da mai* or large grain, are very rarely found in Chinese Neolithic sites. In 1957, a wheat fossil was discovered in a Yangshao site at Dongguanmiao, Henan Province, dating back to approximately 5,000 BC, and in 1958, charred wheat grains were found in Neolithic sites at Diaoyutai, Anhui (Hu, 1957; Jin, 1962). It is unclear if wheat was cultivated in central eastern China during that period, but as both crops were well established in Afghanistan and other territories closer to China, they may have been introduced into northwestern China by traders (Zeven, 1979; Zhang, 1983).

Wheat and barley grains carbon-dated to 2,650 BC were recently found in the Xishanping archaeological site in northwestern China, which also suggests that wheat spread eastward into China. If so, the Gansu corridor would have been the key route. Currently, the oldest archaeological traces of wheat cultivation in China, likely to correspond with local cultivation, were excavated at Kongque He, Xinjiang, and at Diaoyutai in Anhui. Carbon-dating of these remains indicated 2,000 BC for the former, and 3,000-2,000 BC for the latter. Most early wheat remains have been dated to between 2,500 BC and 1,500 BC, suggesting that wheat was introduced into China sometime around 2,000 BC. A large part of these remains are concentrated in the middle to lower Yellow River area. This suggests that another pathway may have existed, or that there were several different pathways by which wheat entered and spread into China, for example, through the Mongolian grasslands, through Tibet, or along the coastal areas of South and Southeast Asia (Bray, 1984). These introductions of wheat (probably in successive waves from the Near East) were late relative to its use in Egypt and Europe, which may explain why almost all Chinese wheats are hexaploid. For example, it is also certain that wheat was cultivated in the 2,000 BC Haimenkou site of Jianchuan, a county in Yunnan, suggesting a southwestern introduction. Charred wheat spikes, together with bronze wares, ceramics, stoneware, horn artifacts, and animal remains, were recently excavated there.

Some authors hold that barley was probably introduced into China earlier than wheat, or that significant barley production started earlier (Badr et al., 2000), because its grain is softer than wheat grain and can be eaten as porridge or roasted, then pounded into flour and mixed with water, tea, honey, or butter, a preparation similar to the current Tibetan *tsampa* (Newman and Newman, 2006; Saisho and Purugganan, 2007). It is also possible that barley was domesticated in China separately from the Near East in the 3rd and 2nd millennia BC, given that in the 1970s, botanists discovered wild barley (*H. spontaneum*) in Tibet, Yunnan, and Sichuan, where both hulled and naked barley forms are known to occur. In any case, southwestern China, as well as a large part of the Himalayas, is a region where barley diversification and domestication occurred.

In the early stages of wheat and barley use, the Chinese population considered them inferior to millets. The cold winters and short summers of northwestern and northern China meant that initially only winter types were grown. Later, the expansion of wheat and barley into the more diverse eastern areas that had better moisture even in winter, plus advances in water management, provided opportunities to grow winter wheat and barley in rotation with summer millets, peas, and buckwheat (Peng, 1984). Inscriptions from the Shang dynasty prove that wheat was a main crop of northern Henan. *Shijing*, the Book of Songs, written during the Western Zhou period (1,066-771 BC) mentions wheat many times, indicating that it was widely cultivated along the middle and the lower parts of the Yellow River Valley before the 6th century BC. The *Fan Scheng-Chih Su* (current spelling: *Fan Sheng Zhi Shu*), a treatise on agriculture (1st century BC), suggests "putting wheat seeds for one night in a light decoction of pea and of silkworm dejections before putting them in soil" (Bray, 1984).

During the Han dynasty (206 BC-220), both spring and winter wheat were documented. Winter-planted wheat was moved to the middle Yangtze Valley, and spring wheat was cultivated in northern Hebei.

Wheat was introduced into China not only through the famous northern "Silk Road" from Turkmenistan, which passes through Xinjiang into Shaanxi. Different studies on a gametocidal inhibitor gene, on necrosis genes, and on beta-amylase isozymes indicate multiple routes through which wheat could have been introduced from the west, including a Myanmar route, a Tibetan route, and a sea route (Bonjean and Angus, 2001; Ghimire et al., 2005; Sun et al., 2009). The Myanmar route began in Afghanistan and reached Yunnan and Sichuan through Pakistan, India, and Myanmar. The Tibetan introduction route was probably linked to Buddhism or pre-Buddhism diffusion originating from India and reaching Tibet through Nepal or the Pamir Mountains, and then diffusing into Sichuan, Shaanxi, and Inner Mongolia. In the last route, wheat was brought by boat into southern China from the Indian or Pakistani coasts. It has also been demonstrated that wheat was later taken from China to Korea and then to Japan (Bonjean and Angus, 2001).

Prior to the Han dynasty, wheat was a delicacy reserved for the aristocracy. During the Han period, the development of animal- and water-powered flour mills, more powerful than hand-mills, enabled significant production of wheat and of wheat flour and the preparation of typical northern Chinese flour-based bread wheat products, such as steam bread, noodles, and dumplings.

It is estimated that, by the mid-17th century, wheat accounted for 50% of staple foods in northern China and 5% in the south. Since that time, wheat expansion in China has not stopped.

5. Sorghum

Cultivated sorghum (*Sorghum bicolor*) or *kaoliang*, which means "tall millet," is an African crop, domesticated in the savannahs of central-eastern Africa. It reached India about 3,000-2,000 BC, but the date of its introduction into China is uncertain. Some archaeologists claim it is present in Neolithic remains, but that seems unlikely (see more on this hypothesis in the chapter on sorghum breeding). However, in China there are two species of wild sorghum, *S. propinquun* and *S. nitidum*, that may have been harvested in the past, explaining recent archeological discoveries in Liaoning, Henan, and Shanxi. *Sorghum propinquun* has the same number of chromosomes as cultivated sorghum, perhaps because it hybridized with cultivated sorghum under the conditions of mainland China, later evolving into the typical *kaoliang*, a tall type of *S. bicolor*.

Most putative diffusion routes of cultivated sorghum are presented in Figure 7.

The book *Chih Min Yao Shu* (current spelling: *Qi Min Yao Shu*), in a section on exotic plants, quotes the late 3rd century manuscript *Kuang Chih* (current spelling: *Guang Ji*) which describes a cereal called *ta ho* (current spelling: *da he*) or great millet, very similar to sorghum and introduced probably from Sogdiana, an ancient kingdom located in the Zaravshan and Kashka Daryâ River Valleys and including the important oasis cities of Samarkand and Bukhara (present-day Uzbekistan). It compares this plant to *mu chi*, or tree millet, of central states such as Sichuan, suggesting other earlier introductions. In pre-modern times, the term *shu shu* or Sichuan millet also very likely referred to sorghum. For example, it is possible to read in *Po Wu Chih* (current spelling: *Bo Wu Zhi*) the following sentence: "If a field is planted with *shu shu* for three years, then for seven years after, there will be many snakes" (Bray, 1984). The text of another Northern Song, the *Pei Meng So Yen* seems to indicate that *shu shu* was already cultivated in northern China in the early 10th century. The first unmistakable botanical description of sorghum is found in the 1175 edition of the book *Hsi-An Chih* (current spelling: *Xin An Zhi*), which is a history of Hui-Chou prefecture in southern Anhui, written by the famous natural historian Lo Yuan.

The modern Mandarin name *kaoliang* for sorghum appears in 1313 in another book, the *Wang Chen Nung Shu* (current spelling: *Wang Zhen Nong Shu*), which describes in detail sorghum cultivars of the period: "ten-feet high plants with large panicles as a broom" and "grain as black as lacker and like frog's eyes" (Bray, 1984).

According to different sources, Sichuan would have been another, perhaps even earlier, point of entry for sorghum from India into China, or it might have come in through the southern coast of China, since it is known that sorghum was present much earlier in India. A maritime "Silk Road" (Ray, 2003; Li, 2006) via the Strait of Malacca was the regular route between India and China starting from the Tang dynasty (618-907) (Figure 8), but it probably had existed in a less regular way since more ancient times, and also reached Korea and Japan. The fact that Dravidian words related to rice cultivation appeared during the Yayoi period (500-300 BC) in Japan (Poudurai, 1999) supports much earlier contact. There are also very ancient routes into the interior of southern China via the Mekong River starting from its delta in Vietnam or via smaller eastern rivers and mountain passes (Barnes, 1999).

The Yuan and Ming populations were reasonably familiar with sorghum because it was used to produce a highly appreciated alcoholic beverage. It was also an edible staple and produced abundant straw, but it was never a major Chinese cereal (Gao et al., 1995). It was not until the Qing dynasty that it came to occupy a large area to address the demands of a growing population mainly in the poor and arid regions of the northeastern provinces. However, in the 1920s and 1930s, sorghum occupied only 4.7% of China's cultivated area, compared to 9.4% sown to both millets.

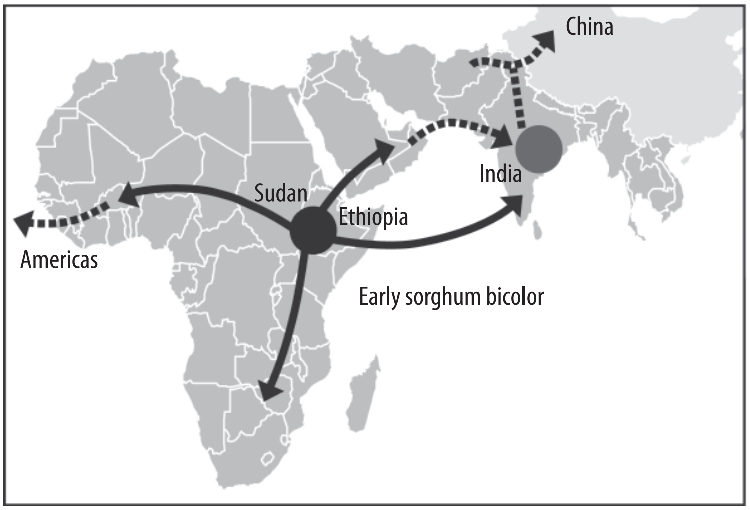

Figure 7. Most putative diffusion routes of sorghum.

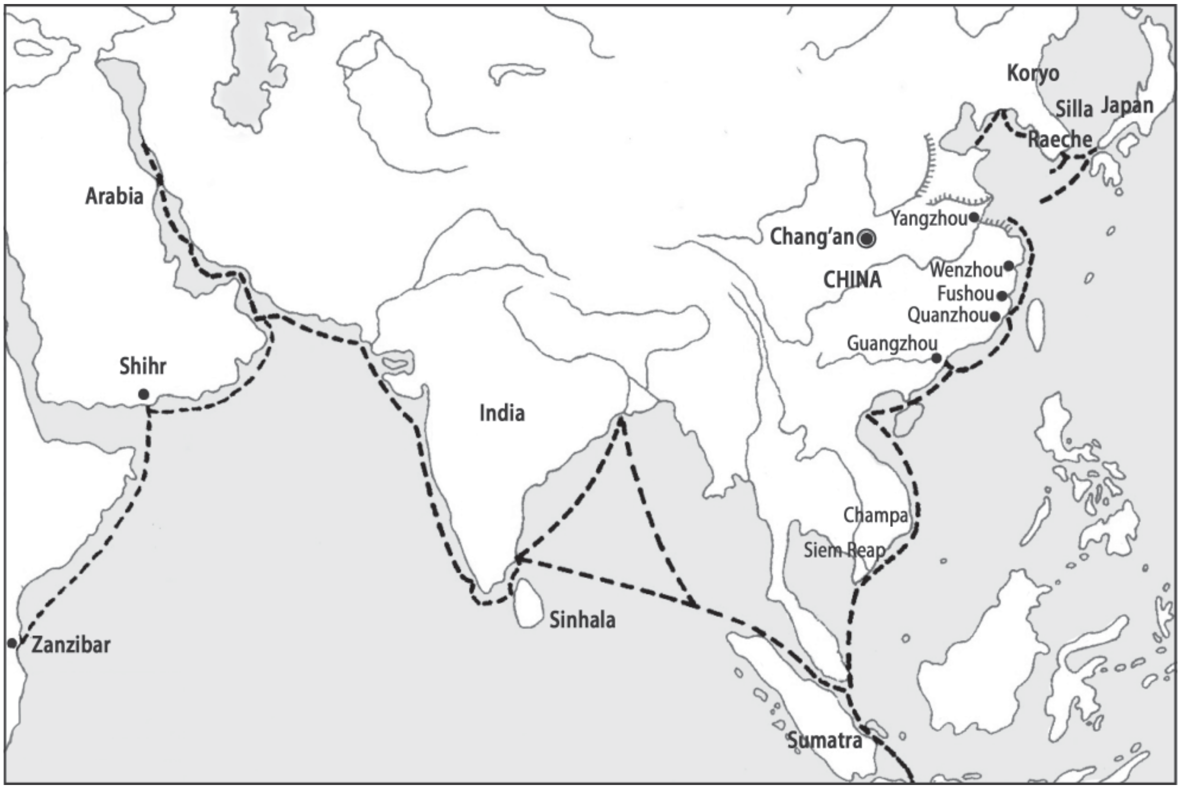

Figure 8. The maritime "Silk Road" used during the Tang dynasty.
Source: Li (2006).

6. Maize

A Chinese poem written around 1368 by Xie Jianfan, who lived in Nanjing (former Ming imperial capital), Jiangsu Province, surprisingly contains the word *yumi*, which indicates maize, and refers to "gold pearls;" nonetheless, a pre-Columbian introduction of maize into China is not confirmed by archaeological artifacts. Maize, which is of Meso-american origin, was probably introduced into China by European sailors before or during the period 1500 to 1510, soon after its introduction into Spain in 1496.

As presented in Figure 9, the presence of maize in China is clearly depicted in the book *Bencao Pinhui Jingyao*, presented in 1505 to Emperor Xiao Zong of the Ming dynasty as a new species, a kind of new *yi-yi ren*, or Job's tears. It is well described in *Annals of Yingzhou* published in 1511. Maize is also mentioned in 1551 in the *Annals of Xincheng County* in Henan Province, but according to gazetteer references and to publications like *Ben Cao Gang Mu*, it may have been introduced earlier, during 1525-1530, into other regions such as Henan, Anhui, Jiangzu, Zhejiang, and Fujian, either by sea routes or overland from India, Burma, Yunnan, and even Tibet. It is known under various 16th century Chinese names such as *yü mai* for tribute or jade wheat, *yü mi* for jade grain, *pao kufor* for wrapped grain, or *yü shu shu* for jade sorghum.

European sailors, particularly Portuguese navigators and colonists, appreciated this new high-yielding cereal that was easy to grow in hilly and poor soils. Due to its wide adaptation, some authors believe maize spread very quickly through China after its introduction, citing Spanish sources indicating that huge quantities of maize were collected as Ming taxes in the late 16th century. According to annual records of Yunnan Province, maize was widely planted there in 1574, covering 52,115 hectares by 1661, and becoming a major crop by 1766 (sown on 92,537 hectares). Given as a tribute to the Imperial government by several tribes in Yunnan, during this period maize also spread to northern and eastern provinces such as Sichuan, Gansu, Shaanxi, Guizhou, and Henan (Bray, 1984). The Portuguese priest Alvarez Semedo arrived in China in 1613 and reported in his travelogue that maize was grown in six provinces near Beijing and in Beijing itself for the emperor's court and the army. The use of maize silk for medicinal purposes was

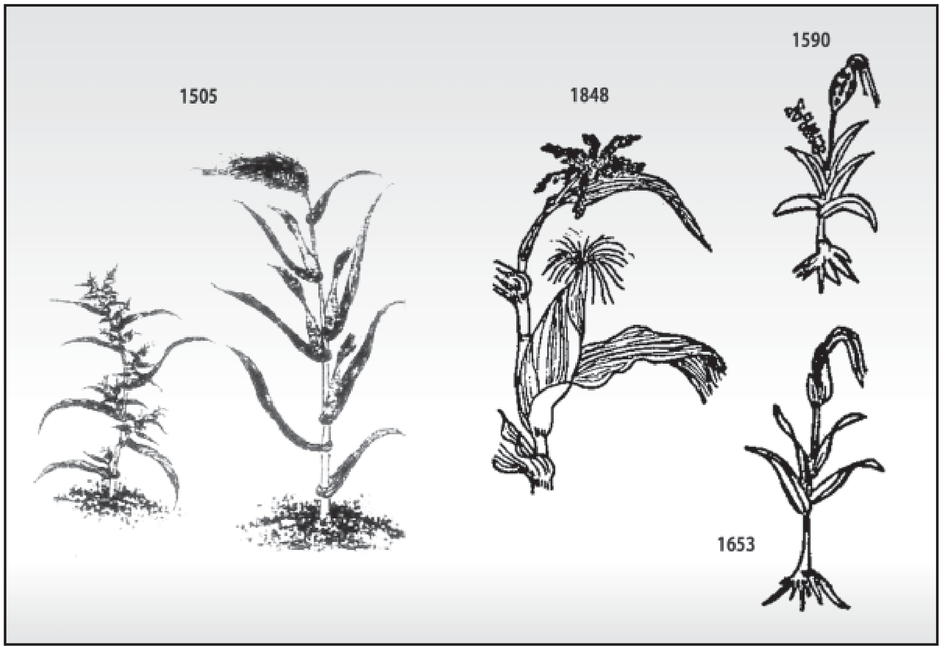

Figure 9. Maize as described in *Bencao Pinhui Jingyao* in 1505 (right) and other early Chinese representations of maize (left) that appeared in three editions (1590, 1653, and 1848) of *Pen Tshao Kang Mu*.
Source: Bray (1984).

recorded in the book *Dian Nan Ben Cao* written by Lan Mao (1397-1476).

However, Han populations disliked the taste of maize grain and preferred other cereals and tubers. It was mainly other populations, such as the Miao, Yi, and Yao peoples of the mountainous areas of southern China, who first cultivated it to complement their hunting diet. They developed a large range of colored landraces (red, yellow, black, dark green, and white), as well as non-glutinous and glutinous types, by growing maize as single plants, or very limited numbers of plants, in their paddy fields. These mountain tribes preferred and were accustomed to glutinous rice; they recognized the waxy character of some of the maize varieties bred through their farming practices, and used them for food and to produce new alcoholic beverages.

Waxy corn (*Zea mays* L. *sinensi*s Kulesh) is a special subspecies of cultivated maize (Huang and Rong, 1998.). Recent molecular studies performed in Sichuan revealed that the waxy character of Chinese maize is caused by *wx*, a single gene mutation on chromosome 9 of common maize, and suggested that Chinese waxy maize derived from flint maize originating from the tropical and subtropical areas of the Xishuangbannan region in Yunnan Province (Tian et al., 2009).

For three centuries following its introduction, maize was produced in the Empire predominantly by non-Han peoples in southern China. It was not until the 18th century that growth of the Han population in the over-crowded Yangtze Valley forced Chinese farmers to cultivate maize and sweet potato in the mountains of Sichuan, Yunnan, southern Shanxi, western Hubei, and southwestern Hunan. In the mid-to-late 19th century, a few British travellers who ventured into Xinjiang from India reported that maize was already established in oases located along the perimeter of the Taklamakan Desert.

Until the beginning of the 20th century, all maize types planted in China were local landraces. They were mainly yellow dent or flint grained, but waxy types originating from Yunnan and Guizhou were also common. These landraces were usually early-maturing, widely adapted to stress environments, low yielding (but competitive with other cereals of the period), and had relatively good grain quality.

Beginning in the 1920s, many maize types were introduced into China, mainly from the USA, by agricultural organizations, missionaries, and Chinese scholars returning from studying overseas. The most popular of these introductions were White Crane (1927), Golden Queen (1930), and Italian White (1931), mostly dent types with good yield potential, but later-maturing than the local landraces. During this period, maize productivity increased greatly, and the crop spread to northeastern China. Modern maize breeding in China started at Jinling University in Nanjing, Jiangsu Province, in 1926.

7. Conclusions

Proso millet (*Panicum miliaceum)* is the oldest Chinese cereal, for it existed before foxtail millet (*Setaria italica*). Both these millets and rice (*Oryza sativa*) are clearly indigenous to China and have been cultivated from the Neolithic Age in China's two major river basins, the Yellow River in the north and the Yangtze River to the south.

Millet and rice provided the essential food surpluses that allowed the development of the socially complex Chinese civilization, whereas wheat, sorghum, and maize were clearly introduced crops that in later historical periods contributed to feeding the growing Chinese population. Barley, also introduced from western and central Asia during Neolithic times, became established in a portion of southwestern China that is part of the Himalayan area, which evolved and became a secondary center of genetic diversity.

All these Chinese crops were determinants of the emergence of one of the oldest and most efficient farming systems in the world, characterized by the early development of multiple cropping systems and by the invention of row planting, which was critical for enhancing yields of field crops the world over. They remain, for the most part, key crops of China's agricultural economy. This book is dedicated to their study.

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References

An, Z. 1984. Early Neolithic culture in northern China. Archaeology 10: 934-936 (in Chinese).

An, Z. 1999. Origin of Chinese rice cultivation and its spread eastward. Beijing Cultural Relics 2: 63-70 (in Chinese).

Anderson, E.N. 1988. The Food of China.Yale University Press, New Haven. 314 pp.

Badr, A., Müller, K., Schäfer-Pregl, R., El Rabey, H., Effgen, S., Ibrahim, H.H., Pozzi, C., Rohde, W., and Salamini, F. 2000. On the origin and domestication history of barley (*Hordeum vulgare*). Mol Biol Evol 17: 499-510.

Barnes, G.L. 1999. The Rise of Civilization in East Asia: the Archeology of China, Korea and Japan. Thames & Hudson, London. 288 pp.

Bonjean, A.P., and Angus, W.J. 2001. The World Wheat Book, a History of Wheat Breeding. Lavoisier-Intercept, Paris. 1136 pp.

Bonjean, A.P., and Picard, E. 1990. Les Céréales à Paille: Origine, Histoire, Économie, Sélection. Ed. Softword, Paris. 208 pp.

Bray, F. 1984. Agriculture. In: Needham J. (ed.), Science and Civilization in China: Vol.6, Biology and Biological Technology, Part II: Agriculture. Caves Book Ltd., Taipei. 724pp.

Chen, C. 1997a. Developmental history of paddy rice and arid agriculture in ancient Chinese civilizations. Agricultural Archaeology 3: 51-53 (in Chinese).

Chen, C. 1997b. Rice cultivation, dry land agriculture and the developing locus of ancient Chinese civilization. Agricultural Archaeology 3: 51-57 (in Chinese).

Fuller, D.Q., Qin, L., Zheng, Y., Zhao, Z., Chen, X., Hosoya, L.A., and Sun, G.P. 2009. The domestication process and domestication rate in rice: spikelet bases from the lower Yangtze. Science 323: 1607-1610.

Gao, L.Z., and Innan, H. 2008. Non independent domestication of the two rice subspecies, *Oryza sativa* ssp. *indica* and ssp. *japonica*, demonstrated by multilocus microsatellites. Genetics 179: 965-976.

Gao, Y., Zhang, X., Gong, G., and Li, L. (eds.). 1995. Atlas of Main Crop Germplasm Resources in China. China, Agriculture Press, Beijing. 450 pp. (in Chinese).

Ghimire, S.K., Akashi, Y., Maitani, C., Nakanishi, M., and Kato, K. 2005. Genetic diversity and geographical differentiation in Asian common wheat (*Triticum aestivum* L.) revealed by the analysis of peroxidase and esterase isozymes. Breeding Science 55: 175-185.

Heyem, T. 1998. Rice cultures south of the Yangtze River and Japan: variations and background in harvest, drying and storage. Agricultural Archaeology 1: 335-343 (in Chinese).

Hu, Y.Q. 1957. Ancient wheat discovered in Anhui. Chinese Journal of Archaeology 1: 21-30 (in Chinese).

Huang, Y.B, and Rong, T.Z. 1998. Genetic diversity and origin of Chinese waxy maize. Crops l: 77-80 (in Chinese).

Izawa, T., Konishi, S., Shomura, A., and Yano, M. 2009. DNA changes tell us about rice domestication. Current Opinion in Plant Biology 12: 185-192.

Jin, S.B. 1962. Investigation on Anhui ancient wheat. Crop Science of China 1: 67-73 (in Chinese).

Jin, J., Huang, W., Gao, J.P., Yang, J., Shi, M., Zhu, M.Z., Luo, D., and Lin, H.X. 2008. Genetic control of rice plant architecture under domestication. Nature Genetics 40: 1365-1369.

Jiang, C., Du, Q., and Sun, Z. (eds.). 2008. China's Agricultural History. China Agriculture Press, Beijing. 469 pp. (in Chinese).

Jones, M.K., and Liu X. 2009. Origins of agriculture in East Asia. Science 324: 730-731.

Kawakami, S., Ebana, K., Nishikawa, T., Sato, Y., Vaughan, D.A., and Kadowaki, K. 2007. Genetic variation in the chloroplast genome suggests multiple domestication of cultivated Asian rice (*Oryza sativa* L.). Genome 50: 180-187.

Ke, Y., Su, B., Song, X., Lu, D., Chen, L., Li, H., Qi, C., Marzuki, S., Deka, R., Underhill, P., Xiao, C., Shriver, M., Lell, J., Wallace, D., Wells, R.S., Seielstad, M., Oefner, P., Zhu, D., Jin, J., Huang, W., Chakraborty, R., Chen, Z., and Jin, L. 2001. African origin of modern humans in East Asia: a tale of 12,000 Y chromosomes. Science 292: 1151-1153.

Kiple, K.F., and Ornelas, K.C. (eds.). 2000. The Cambridge World History of Food. Cambridge University Press, Vol. I & II.

Lee, G.A., Crawford, G.W., Liu, L., and Chen, X. 2009. Plants and people from the early Neolithic to Shang periods in North China. Proceedings of the National Academy of Sciences, USA 104: 1087-1092.

Li, Q., 2006. Maritime Silk Road. Wu Zhou Chuan Bo Press, Beijing. 200 pp. (in Chinese).

Londo, J.P., Chiang, Y.C., Hung, K.H., Chiang, T.Y., and Schaal, B.A. 2006. Phylogeography of Asian wild rice, *Oryza rufipogon*, reveals multiple independent domestications of cultivated rice, *Oryza sativa*. Proceedings of the National Academy of Sciences, USA 103: 9578-9583.

Lu, H., Yang, X., Ye, M., Liu, K.B., Xia, Z., Ren, X., Cai, L, Wu, N., and L., T.S. 2005. Millet noodles in late Neolithic China. Nature 437: 13-14.

Lu, H., Zhang, J., Liu, K., Wu, N., Li, Y., Zhou, K., Ye, M., Zhang, T., Zhang, H., Yang, X., Shen, L., Xu, D., and Li, Q. 2009. Earliest domestication of common millet (*Panicum miliaceum*) in East Asia extended to 10,000 years ago. Proceedings of the National Academy of Sciences, USA 106: 7367-7372.

Morishima, H. 2001. Evolution and domestication of rice. In: Khush, G.S, Brar, D.S., and Hardy, B. (eds.). Rice Genetics IV. Proceedings of the 4th International Rice Genetics Symposium, IRRI/SPI, pp. 63-77.

Newman, C.W., and Newman, R.K. 2006. A brief history of barley foods. Cereal Foods World 51: 4-7.

Pechenkina, E.A., Benfer, R.A., and Wang, Z. 2002. Diet and health changes at the end of the Chinese Neolithic: the Yangshao/Longshan transition in Shaanxi province. American Journal of Physical Anthropology 117: 15-36.

Pei, A. 1998. Pengtoushan culture crop remains in Chinese prehistoric agriculture. //www.carleton.ca/~bgordon/Rice/papers/pei88a.html.

Peng, S. 1984. Pest control methods in ancient Chinese agriculture. Agricultural Archaeology 2 : 266-268 (in Chinese).

Pernes, J. 1983. La Génétique de la Domestication des Céréales. La recherche 146: 910-919.

Poundurai, R. 1999. Early contacts of South India and China: an exploration of the phenomenon of Hindu diaspora. In: The Proceedings of Geoinformatics'99 Conference, Ann Arbor, 19-21 June, 1999, pp. 1-10.

Ray, H.P. 2003. The Archaeology of Seafaring in Ancient South Asia. Cambridge World Archeology. Cambridge University Press, 340 pp.

Ren, Z., Ma, S., and Ren, E. 1998. Re-exploring cultivated rice origin in Huai basin. Agricultural Archaeology 1: 183-187 (in Chinese).

Saisho, D., and Purugganan, M.D. 2007. Molecular phylogeography of domesticated barley traces expansion of agriculture in the old world. Genetics 177: 1765-1776.

Sang, T., and Ge, S. 2007. Genetics and phylogenetics of rice domestication. Current Opinion in Genetics and Development 17: 533-538.

Shi, X., 1998. From Xiachuan civilization to the origin of Chinese agricultural civilization. Agricultural Archaeology 354. (in Chinese).

Sigault, F. 1994. Les millets en Eurasie, d'une fête popualaire à des questions pour des chercheurs. Industrie des Céreales 10 : 23-32.

Smartt, J., and Simmonds, N.W. (eds.). 1995. Evolution of Crop Plants, 2nd edition. Longman Scientific & Technical, England, 531 pp.

Soutif, M. 1995. L'Asie, Source de Sciences et de Techniques. Presses Universitaires de Grenoble. 312 pp.

Su, B., Xiao, J., Underhill, P., Deka, R., Zhang, W., Akey, J., Huang, W., Shen, D., Lu, D., and Luo, J. 1999. Y-chromosome evidence for a northward migration of modern humans into eastern Asia during the last Ice Age. American Journal of Human Genetics 65: 1718-1724.

Su, B., Xiao, C., Deka, R., Seielstad, M.T., Kangwanpong, D., Xiao, J., Lu, D., Underhill, P., Cavalli-Sforza, L., Chakraborty, R., and Jin, L. 2000. Y-chromosome haplotypes reveal prehistorical migrations to the Himalayas. Human Genetics 107: 582-590.

Sun, Q.M., Zhou, R.H., Gao, L.F., Zhao, G.Y., and Jia, J.Z. 2009. The characterization and geographical distribution of the genes responsible for vernalization requirement in Chinese bread wheat. Journal of Integrative Plant Biology 51: 423-432.

Tian, M., Tan, G., Liu, Y., Rong, T., and Huang, Y. 2009. Origin and evolution of Chinese waxy maize: evidence from the Globulin-1 gene. Genetic Resoures and Crop Evolution 56 : 247-255.

Toussaint-Samat, M. 1997. Histoire Naturelle et Morale de la Nourriture. Larousse-in Extenso, Paris. 958 pp.

Wadley, G., and Martin, A. 1993. The origins of agriculture - a biological perspective and a new hypothesis. Australian Biologist 6: 96-105.

Wang, J., 1985. Earlier agriculture in Henan province and surroundings according to Peiligang site tools. Agricultural Archaeology 2: 81-85 (in Chinese).

Wang, J. 1988. Origin of 5000-year-old agriculture in the northern Huai area: data from Weichi Buddhist temple site. Agricultural Archaeology 1: 188-192 (in Chinese).

Weber, S.A., and Fuller, D.Q. 2006. Millets and their role in early agriculture. First Farmers in Global Perspective, Seminar of Uttar Pradesh State Department of Archaeology Lucknow, India, 18-20 January, 2006.

Wells, R.S.,Yuldasheva, N., Ruzibakiev, R., Underhill, P.A., Evseeva, I., Blue-Smith, J., Jin, L., Su, B., Pitchappan, R., Shanmugalakshmi, S., Balakrishnan, K., Read, M., Pearson, N.M., Zerjal, T., Webster, M.T., Zholoshvili, I., Jamarjashvili, E., Gambarov, S., Nikbin, B., Dostiev, A., Aknazarov, O., Zalloua, P., Tsoy, I., Kitaev, M., Mirrakhimov, M., Chariev, A., and Bodmer, W.F. 2001. The Eurasian heartland: a continental perspective on Y-chromosome diversity. Proceedings of the National Academy of Sciences, USA 98: 10244-10249.

Yang, Z. 1997. Food storage in pre-Qin days. Agricultural Archaeology 3: 2-8 (in Chinese).

You, X. 1988. Historical growth and values of rice agriculture. Agricultural Archaeology 4: 406-408 (in Chinese).

Zeven, A.C. 1979. The prehistoric spread of bread wheat to Asia. In: Ramanujam S (ed.). Proceedings of 5th International Wheat Genetics Symposium, Indian Society of Genetics and Plant Breeding, New Delhi, pp. 103-107.

Zeng, Y., Li, Z., Yang, Z., Wang, X., Shen, S., and Zhang, H. 2001. Ecological and genetic diversity of rice germplasm in Yunnan, China. Plant Genetic Resources Newsletter 125: 24-28.

Zhang, Y.Z. 1983. Brief summary of the ancient crops excavated in Xinjiang, China. Agricultural Archeology 122-126 (in Chinese).

Zhang, Z. 1998. Origin of rice agriculture on the middle and lower Yangtze River. Agricultural Archaeology 1: 206-211 (in Chinese).

Zhou, J. 2006. The rise of agricultural civilization in China: The disparity between archeological discovery and the documentary record and its explanation. Sino-Platonic Papers 175: 1-38.

Zishu, M. 1998. Artefacts of Ancient Chinese Science and Technology Shanghai/Beijing. National Museum of Chinese History, Beijing.

Chapter 2.

Rice production and genetic improvement in China

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1. Introduction

Rice, a leading staple crop globally, provides about 20% of the world's total caloric intake. More than 90% of all rice is cultivated in Asia. It is also widely grown throughout China, with the main production area being located in the central and southern regions. From 1986 to 2005, the area sown to rice in China was 30.7 million ha annually, with grain production of 182 million tonnes and an average yield of 5,940 kg/ha. During that period, rice accounted for 28.1% of the area under staple crops and 40.2% of all crops produced. In 2006-2008, the average rice area, yield, and production were 29.1 million ha, 6,409 kg/ha, and 187 million tonnes, respectively. In many Asian countries, including China, rice has been, and will continue to be, the principal food for more than one-half of the population. As such, it plays an essential role in food security and the overall economy.

There are two species of cultivated rice in the world: Asian cultivated rice (*Oryza sativa* L.) planted worldwide and African cultivated rice (*Oryza glaberrima* Steud.) grown mainly in western Africa. In China, all rice cultivars belong to *O. sativa*. Asian cultivated rice originated from common wild rice (*Oryza rufipogon* Griff.), which has the same chromosome number as cultivated rice ($2n = 18$) (Khush and Brar, 2001). It is likely that rice was domesticated concurrently and independently at many sites from the Assam-Meghalaya belt in India all the way to the mountain ranges of southeast Asia and southwest China (Chang, 1983). Currently, *O. rufipogon*, called common wild rice in China, is widely distributed in 113 counties of eight southern provinces. In Asia, *O. sativa* consists of two subspecies: *indica* and *japonica*. A tropical variant of the latter, called *javanica*, is sometimes considered a subspecies. Except for the *javanica* type, which was introduced from other countries, both *indica* and *japonica* are indigenous (Tang, 2007). Besides having different morphological traits, *indica* and *japonica* rices are assumed to be genetically differentiated due to reproductive barriers or incompatibility. In general, as indicated in Figure 1, *indica* rice is mainly planted in southern China, whereas *japonica* is grown mostly in the north (roughly above 29° N) and in higher mountain areas. Both *indica* and *japonica* cultivars are planted in central China.

Rice is the most ancient cereal crop, with a long history of cultivation in China. Based on current archaeological evidence, China has a history of rice cultivation that dates back about 10,000 years (Tang, 2007). The earliest record of rice can be traced to mythological writing in the book *Guan Zi* of the Shen-Nong era (21th century BC, Xia dynasty). Five food crops are mentioned in the book: *Shu* (broomcorn

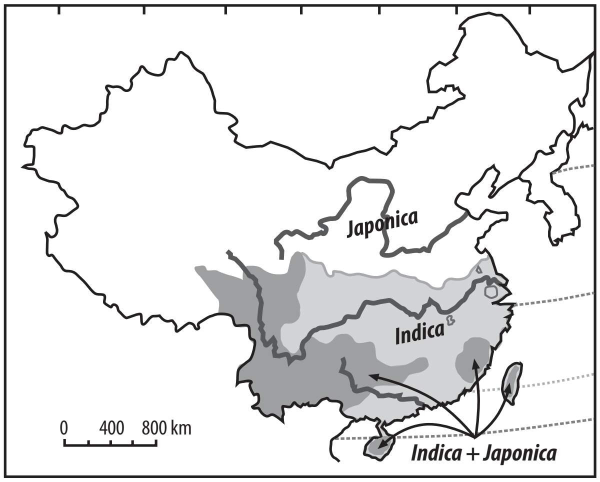


Figure 1. The traditional areas where *indica* and *japonica* varieties were grown in the mid-twentieth century, from Vaughan et al. (2008) rice 1:16-24.

millet, *Panicum miliaceum*), *Ji* (foxtail millet, *Setaria italica*), *Mai* (barley and wheat), *Dao* (rice), and *Shuu* (soybean). In ancient times, *japonica* rice was called *Keng* or *Jing*, *indica* rice *Hsien or Xian*, and glutinous (waxy) rice *Nuodao*.

2. Rice cultivation and production in China

Rice prefers moisture-prone environments and warm temperatures, requiring at least 10 °C for growth and no less than 22 °C for normal flowering. Due to its adaptation and short growing period, rice can be planted wherever temperatures and moisture conditions are favorable. In China, rice stretches from south to north, across five climatic zones: the tropics, subtropics, warm-temperate, medium-temperate, and cool-temperate. Mohe (53°27′N) in Heilongjiang Province may be the northern-most site of rice cultivation in the world, whereas Ninglang county in Yunnan Province is regarded as the highest site (altitude: 2,965 m) where rice is cultivated. Because of the effects of latitude, temperature, monsoon, precipitation, elevation, and topography, in general the intensity of rice production declines gradually from south to north and from southeast to northwest.

In China, *indica* rice is typically cultivated in the south and *japonica* rice in the north, but the two subspecies overlap in central China and some high-altitude regions in the south. According to 2007 statistical data, *indica* and *japonica* rice were planted on 21.63 and 7.31 million ha, respectively, representing 75% and 25% of the total rice area. There were also 0.29 million ha planted to glutinous rice.

Irrigated, upland, and rainfed lowland systems are the major rice cultivation patterns. Irrigated rice requires a large amount of water during the growth period and is usually planted in fields with ridges for containing the water. In contrast, upland and rainfed lowland rice depend completely on precipitation during the entire growing period. Upland rice is commonly planted in mountain and hilly areas, or on non-irrigated plains, whereas rainfed lowland rice is usually sown in fields bordered by ridges. In 2007, the areas cultivated with irrigated, upland, and rainfed lowland rice in China were 27.8, 0.6, and 0.9 million ha, respectively, representing 95%, 2%, and 3% of the total rice area.

On the basis of seed availability, commercially cultivated rice is classified as either hybrid or inbred (conventional). Hybrid F_1 seed must be produced for the former. In recent years, the area under hybrid rice has increased rapidly and now covers about half of the total rice production area. In 2007, the area sown to hybrid rice reached 15.6 million ha, whereas inbred rice was grown on 13.6 million ha.

2.1 Distribution of rice cultivation

Rice is distributed throughout China according to six ecological regions defined by topography and cropping system (Figure 2): region I comprises a narrow belt in southern mainland China; region II is located in the general area of central China; region III comprises the entire territory of southwestern China; region IV is located in the north; region V is in the northeast; region VI is in the northwest (Min et al., 1988).

Region I: Southern China: rice double cropping
Region II: Central China: rice single and double cropping
Region III: Southwestern plateau: rice single and double cropping
Region IV: Northern China: rice single cropping
Region V: Northeastern China: short-season rice single cropping
Region VI: Northwestern China: dry rice single cropping

Figure 2. Regions of China where rice is grown.
Source: Chinese Academy of Agricultural Sciences.

Of all six regions, region II is the most important rice growing area, because it has the largest percentages of cultivated area and production. Regions I and III rank second and third, and region VI has the smallest area and production (Table 1).

Region I: Southern China: rice double cropping. This region comprises a narrow belt of the southern mainland (covering the southern parts of Guangdong, Guangxi, Fujian, and Guizhou) plus Taiwan and Hainan. In 2005, 5.75 million ha were sown to rice in this region, accounting for 20.0% of

Table 1. Area sown to rice (mha) and grain production (mt) in six rice eco-regions of China.

Year	Region I		Region II		Region III		Region IV		Region V		Region VI		Total
	Amount	%	Amount	%	Amount	%	Amount	%	Amount	%	Amount	%	
Cultivated area													
1986	7.6	23.6	17.3	53.8	4.9	15.2	0.7	2.3	1.3	4.2	0.3	0.9	32.2
1990	7.7	23.1	17.7	53.5	4.8	14.8	0.8	2.7	1.6	5.0	0.3	0.9	33.0
1995	6.9	22.5	16.2	52.9	4.6	15.3	0.8	2.8	1.7	5.6	0.3	0.9	30.7
2000	6.4	21.4	14.9	50.4	4.4	15.0	0.9	3.2	2.6	9.0	0.3	1.0	29.6
2005	5.8	20.0	14.5	50.3	4.6	16.0	0.8	2.8	2.8	9.9	0.3	1.0	28.8
Production													
1986	31.9	18.5	99.6	57.8	27.8	16.2	4.0	2.8	7.1	4.2	1.7	1.0	172.2
1990	37.5	19.8	103.9	54.9	30.7	16.2	5.3	3.1	9.7	5.1	2.0	1.0	189.3
1995	36.1	19.5	101.0	54.5	30.3	16.4	5.7	3.1	10.2	5.6	1.6	0.9	185.2
2000	34.3	18.3	95.3	50.8	31.7	16.9	5.9	3.2	17.9	9.6	2.2	1.2	187.5
2005	29.2	16.2	91.8	50.9	31.4	17.4	5.8	3.2	20.1	11.1	2.1	1.2	180.5

the total rice area. Water resources and sunlight in the region are sufficient for a 260-365 day rice growing period, 5,800-9,300 °C of cumulative temperature (≥ 10 °C), 1,000-1,800 h of sunshine, and 700-2,000 mm of precipitation during the rice growing season. Red and yellow soils are the principal types of soil found in the rice fields. The dominant crop is *indica* rice, usually rotated in one- or two-year cycles with upland crops such as sugarcane, peanut, potato, and beans.

Region II: Central China: rice single and double cropping. The largest rice producing region in China, region II spans a vast area from the coast in the east to the Chengdu Plains in the west, and from the Nanling Mountains in the south to the Huai River in the north. It includes all or most parts of Jiangsu, Zhejiang, Anhui, Jiangxi, Hunan, Hubei, and Sichuan, as well as the suburbs of Shanghai and Chongqing (all along the Yangtze River). In 2005, the total rice area in region II was 14.5 million ha, accounting for 50.3% of the national rice area. The climate is typically subtropical, with warm and humid monsoons. The rice growth period lasts 210-260 days, with 4,500-6,500 °C of cumulative temperature, 700-1,500 h of sunshine, and 700-1,600 mm of precipitation. Rice soils are mostly alluvial and sedimentary in the plains, and red, yellow, and brown on hilly slopes. In this region, *indica*, *japonica*, and glutinous rice are both double and single cropped. Hybrid *indica* rice plays an important role, accounting for 55% of the regional rice area. From the 1960s to 1980s, double-cropped rice occupied a leading position in this region, covering more than 45% of the regional rice area, especially in Zhejiang, Jiangxi, and Hunan, where that figure reached as high as 80-90%. Since the 1990s, reforms in the agricultural structure and changes in cropping systems caused the double-cropped rice area to decline sharply, especially the area sown to early-maturing rice with poor grain quality. The Taihu, Lixiahe, Wanzhong, Boyanghu, Dongtinghu, Jianghai, and Chengdu Plains in this region are historically famous for their rice production and will continue to play a pivotal role in grain production and food security in China, despite the decline in rice area, which has gone from 68% of the national rice area in the 1970s to 50% in recent years.

Region III: Southwestern plateau: rice single and double cropping. Region III comprises all or parts of Hunan, Guizhou, Guangxi, Qinghai, Yunnan, Sichuan, and Tibet, including the Yungui and Qingzang Plateaus. Because of the sharp variations in altitude, day and night temperatures vary greatly across the region. The largely subtropical climate is characterized by seasonal warmth and moisture. *Indica* and *japonica* rice cover 4.4-4.9 million ha, with a growth period of 180-260 d, 2,900-8,000 °C of cumulative temperature, 800-1,500 h of sunshine, and 500-1,400 mm of precipitation during the rice growing period. Rice fields mostly have red, red-brown, yellow, and yellow-brown soils. Single cropped rice is the dominant cultivation pattern, with rice double cropping restricted to warm, humid lowland areas. On the Yungui Plateau, *indica* rice is grown mostly in the low-altitude zone (< 1,400 m), *japonica* rice in the high-altitude zone (> 1,800 m), with overlapping in the intermediate zone (1,400-1,800 m). Upland rice and rainfed lowland rice are sown in mountain areas or hilly slopes without irrigation.

Region IV: Northern China: rice single cropping. This region is delimited by the Qinling Mountains and the Yellow River in the south and the Great Wall in the north, with the western boundary being the central Shaanxi Plains. All of Beijing, Tianjin, and Shandong, as well as parts of Henan, Hebei, Shanxi, Shaanxi, Jiangsu, and Anhui, are included in region IV. In 2005, rice area in this region was 0.8 million ha, accounting for 2.9% of the total rice area. The temperate monsoon produces high temperatures and high relative humidity in summer and low temperatures in spring and autumn. Consequently, the rice cycle in this region is shorter than in regions I and II. There are 4,000-5,000 °C of cumulative temperature (≥ 10°C), 2,000-3,000 h of annual sunshine, and 580-1,000 mm of precipitation. Rice soils are mainly yellow damp, saline-alkaline, brown soils, and black clays. Water shortages and widespread saline-alkaline soils constrain rice production. The leading cultivation pattern is single cropped *japonica* rice irrigated with river and underground water. Upland rice is also cultivated in some areas that have no irrigation or sufficient precipitation.

Region V: Northeastern China: short-season rice single cropping. This is the northern-most region where rice is produced, with average temperatures of only 2 to 10 °C and the shortest rice growing period. Region V comprises all of Heilongjiang and Jilin and parts of Liaoning and Inner Mongolia, with a rice area of 2.8 million ha. Annual cumulative temperatures are 2,000-3,700 °C, and there are 2,200-3,100 h of sunshine and 350-1,100 mm of precipitation. Despite the abundant sunlight, daytime and nighttime temperatures vary widely in spring and autumn, shortening the rice growing season. Cold damage is common during the vegetative stage of the rice crop in spring. Soils in rice fields are fertile and include black clod, meadow, brown, and saline-alkaline types. Single cropped *japonica* rice is the predominant system. Heilongjiang Province is famous for producing *japonica* rice of excellent quality. Due to the remarkable improvement in irrigation systems over the last 25 years, the rice area in Heilongjiang has expanded from 0.2 million ha in 1981 to 2.4 million ha in 2005. As a result, Heilongjiang is now one of the main *japonica* rice-producing provinces in China.

Region VI: Northwestern China: dry rice single cropping. Region VI in northwestern China comprises Xinjiang and Ningxia, most of Gansu and Inner Mongolia, the northern parts of Qinghai, Shaanxi, and Hebei, as well as the northwestern portion of Liaoning. This is the driest region in China. Due to water shortages and extremely low precipitation (150-200 mm annually), the rice area is only 0.3 million ha, located near rivers or in relatively small portions of irrigated farmland. Rice soils are usually poor in fertility, and only single cropped *japonica* is cultivated in region VI.

2.2 Diseases, insect pests, and abiotic stresses

Rice can be affected by a large number of diseases and insect pests. The main fungal diseases in China include blast (caused by *Magnaporthe oryzae*), sheath blight (*Thanatephorus cucumeris*), brown spot (*Cochliobolus miyabeanus*), false smut (*Ustilaginoidea virens*), kernel smut (*Tilletia barclayana*), foolish seedling (*Gibberella fujikuroi*), and stem rot (*Magnaporthe salvinii*). Two bacterial diseases, bacterial blight (*Xanthomonas campestris* pv. *oryzae*) and bacterial leaf streak (*X. campestris* pv. *oryzicola*), are prevalent in some areas. The major virus diseases are rice transitory yellowing (RTYV) and rice dwarf (RYV). The most important nematode disease is rice white tip caused by *Aphelenchoide besseyi*. According to the areas of occurrence and yield losses, blast, bacterial leaf blight, and sheath blight are the three most important diseases. Foolish seedling usually occurs in southern China, whereas rice dwarf and stem rot occasionally cause significant damage in central China. In recent years, bacterial leaf streak has tended to be more damaging in the southern rice areas.

Major insect pests in China include rice leafhopper (*Nephotettix cincticeps*), brown planthopper (*Nilaparvata lugens*), white-backed planthopper (*Sogatella furcifera*), rice thrips (*Stenochaetothrips biformis*), yellow rice borer (*Tryporyza incertulas*), striped rice borer (*Chilo suppressalis*), leaffolder (*Chaphalocrocis medinalis*), and rice gall midge (*Orseolia oryzae*). Of these, yellow rice borer, striped rice borer, brown planthopper, white-backed planthopper, and leaffolder often cause severe damage. In the south, gall midge occasionally results in yield losses, and rice thrip may injure plants from the seedling to early tillering stages.

Abiotic stress is caused by unfavorable environmental factors, such as cold, drought, and soil salinity. Cold damage frequently occurs at the seedling stage of early-season rice and at the booting to flowering stages of late-season rice in central China. From March to April, when rice seedlings are growing in nurseries, low temperature or unseasonable cold in spring may cause severe rotting of germinating seeds, buds, roots, and young seedlings, leading to seedling shortages and weak plants. In mid to late September, cold winds often delay panicle differentiation and heading in late rice, leading to poor flowering, low seed-setting rates, and high yield losses. In northern and northeastern China, cold stress can be severe in some years, causing yield reductions due to late and weak development, low tiller numbers, small panicles, and poor seed set.

Both low precipitation and uneven rainfall distribution during the rice growing season can cause drought damage, which is frequent in northwestern and northern China. This results in very weak plant growth, blighted leaves, poor pollination, and greatly reduced yields. Similar damage also occurs in the hills, mountains, and poorly irrigated areas of central, southern, and southwestern China, when high temperatures (>40 °C) and extreme drought occur at booting and heading in summer.

On the southeastern coast, high soil-salt levels are an obvious problem for rice production. In northwestern and northern China, soil salt content has accumulated and reached 0.2-0.6% in some farmlands, resulting in poor rice growth and low yields. If in addition drought occurs, salinity damage is aggravated by the high soil evaporation rates. Drought and salinity are significant constraints to the expansion of rice cultivation in the northern and northwestern rice regions.

By all accounts, the biotic and abiotic stresses mentioned above are serious constraints to rice production in China. Breeding for resistance or tolerance to these stresses is an imperative objective for rice breeding and improvement programs, but breeding objectives vary across the six regions due to the large differences in ecological conditions.

2.3 Cultivation systems

In general, there are four major cultivation systems roughly consistent with the six major production regions. In northeastern China (region V), a cultivation system combining irrigated single-cropped rice and winter fallow is common because of the low winter temperatures and short growing season. However, a three-year rotation (such as rice–rice–green manure, and rice–rice–beans) is also practiced in some fields to improve soil structure and fertility.

In northern and northwestern China (regions IV and VI), there are three crop cultivation systems, namely single cropping, three harvests in two years, and two harvests annually. Rice is planted continuously with winter fallow or rotated with upland crops (corn, beans, or vegetables) in the single-cropping system; rotated as spring rice–wheat–summer rice–winter fallow in the two-year-three-harvest system; and rotated as wheat–rice in the one-year-two-harvest system.

In the single-cropped rice area in central and southwestern China (parts of regions II and III), cultivation systems are diverse, depending on temperature, precipitation, topography, and local customs. Although continuous cropping of single rice with winter fallow is widely practiced, there are several other cropping systems, such as rice rotated with wheat, barley, broad bean, corn, vegetables, or peanut in a one-year cycle, and rotations of rice–rice–wheat or barley, rice–rice–forage crops, and rice–rice–potato in two-year cycles.

In the double-cropped rice area in southern China (region I and parts of regions II and III), early rice–late rice–winter fallow is a traditional and popular cropping system. In addition, the temperature and light resources allow three harvests annually in this area, using a rotation pattern of rice–rice–wheat, barley, rapeseed, broad bean, or green manure. In recent years, the area of early *indica* rice has declined largely due to its poor quality. Consequently, double-cropped rice in the three-harvest system is being partially replaced by single-cropped rice, and other rotation patterns, such as (1) wheat or barley–beans or vegetables–rice and (2) green manure–soybean–rice, are expanding.

Rice is traditionally sown in seedling nurseries and transplanted into paddy fields at the young seedling stage. This requires labor-intensive operations. Over the last 30 years, the migration flow of rural labor to urban areas has resulted in fewer farmers engaged in agriculture. Labor- and time-saving techniques are imperative to make up for labor shortages. Since the mid-1980s, new techniques such as dry seedling nurseries, direct seeding in dry and wet rice land, and seedling broadcasting by hand or by machine have been initiated and widely expanded. In 2001, the rice areas using direct seeding and seedling broadcasting reached 0.9 million ha and 7.6 million ha, accounting for 3.3% and 26.5% of the total rice area, respectively (Tang, 2002).

Another significant advance was the development of rice–fish or shrimp production in southern China beginning in the 1980s (Figure 3). The combination of a staple food plus proteins has improved the diets of millions of farmers.

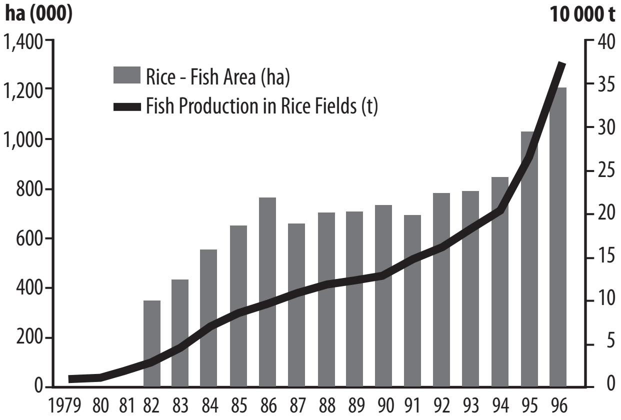


Figure 3. Development of rice–fish production in China.
Source: FAO.

2.4 Current area and production

At the beginning of the 20th century, the rice area in China was about 14 million ha. By the end of the 1940s, the total single-cropped rice area reached 25 million ha. However, the average grain yield was only 1.00-1.75 t/ha. Since the establishment of the People's Republic in 1949, sustainable progress has been achieved in rice scientific research and production. From 1949 to 2007, the total area, average yield, and total production of rice increased from 25.7 to 29.2 million ha, 1.89 to 6.38 t/ha, and 48.6 to 186.5 million tonnes, or 13.7%, 237.6%, and 283.4%, respectively (Figure 4). Expansion of the production area and yield increases were estimated to have contributed 5.8% and 94.2%, respectively, to these advances in productivity. Improvements in breeding technologies and agronomic practices have played crucial roles in the significantly enhanced rice yields.

Although rice is produced in almost all provinces, nine provinces (Hunan, Jiangxi, Jiangsu, Heilongjiang, Hubei, Sichuan, Anhui, Guangdong, and Guangxi) account for 74% of national production. Rice production by province in 2008 is shown in Table 2. Hunan has the largest rice area and also ranks first in production.

After 1949, rice production increased in four steps (Cai and Chen, 1999; Cheng, 2005a). In the first step (in the 1950s), the rice area expanded rapidly, leading to a large increase in production, but average yields remained unchanged. For instance, production rose from 48.6 million tonnes in 1949 to 80.8 million tonnes in 1958 due mainly to 6.2 million ha of additional rice land (from 25.7 million ha to 31.9 million ha) compared with a small increment (0.6 t/ha) in yield (from 1.9 to 2.5 t/ha). The other three steps were all characterized by distinct contributions from increased yields, resulting from revolutionary use of rice genetic resources in breeding. In the second step (early 1960s to mid-1970s), many semidwarf cultivars were released, resulting in average yields of more than 3.5 t/ha and national production of approximately 126 million tonnes in 1975. The first hybrid rice cultivar was released for commercial use in the same year, and the upsurge of hybrid rice thereafter pushed Chinese rice production into the third step (mid-1970s to mid-1990s). By 1990, hybrid cultivars were planted on 55% of the rice area, and average yield

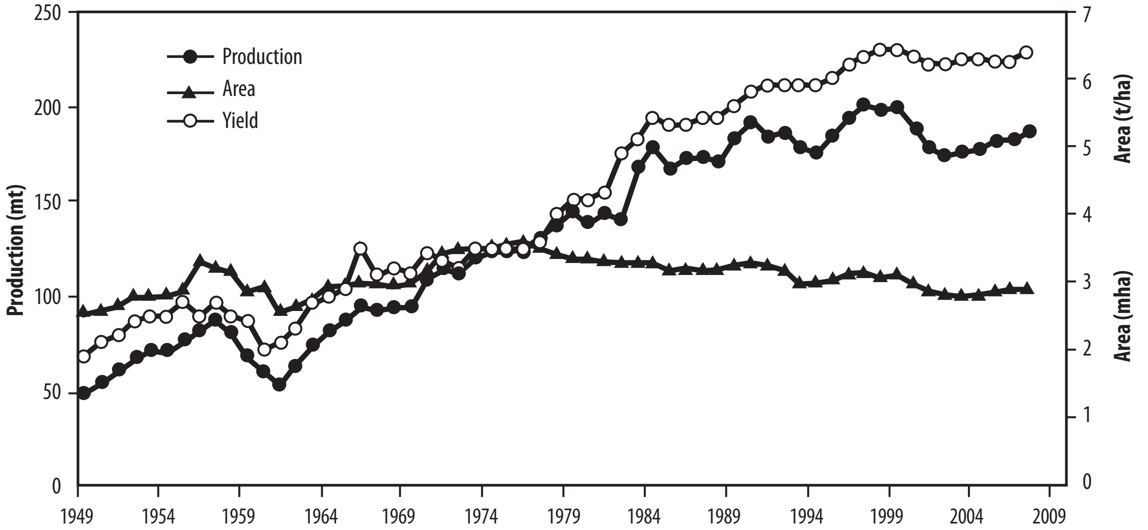


Figure 4. Area, yield, and production of rice in China from 1949 to 2007.

and production exceeded 5 t/ha and 170 million tonnes, respectively. The fourth step began in the mid-1990s with the development and release of super rice. Super rice includes both inbred cultivars and hybrids with such traits as high yield potential, good quality, and multiple resistance/tolerance to biotic and abiotic stresses. By 2007, the average yield and production reached 6.38 t/ha and 186.5 million tonnes, respectively. A number of inbred and hybrid cultivars with the potential to yield more than 15 t/ha have been developed (Table 3), among which II-you 084 produced 18.47 t/ha, the highest yield on record, in a field trial at Yongsheng, Yunnan Province, in 2003 (Cheng, 2005b).

Table 2. Chinese rice area, production, and average yield by province, 2008.

Province	Area (1000 ha)	Production (1000 t)	Average yield (kg/ha)
Hebei	81.5	55.6	6815
Inner Mongolia	97.9	70.5	7204
Liaoning	658.7	505.6	7676
Jilin	658.7	579.0	8790
Heilongjiang	2390.7	1518.0	6350
Shanghai	108.6	89.3	8223
Jiangsu	2232.6	1771.9	7937
Zhejiang	937.5	660.4	7045
Anhui	2218.9	1383.5	6235
Fujian	861.2	508.8	5908
Jiangxi	3255.5	1862.1	5720
Shandong	130.7	110.4	8499
Henan	604.7	443.1	7328
Hubei	1978.9	1533.7	7750
Hunan	3932.0	2528.0	6429
Guangdong	1946.9	1003.3	5153
Guangxi	2119.2	1107.6	5227
Hainan	310.0	143.8	4641
Chongqing	673.5	529.4	7860
Sichuan	2035.9	1497.6	7356
Guizhou	691.1	461.1	6672
Yunnan	1017.5	621.0	6103
Shaanxi	124.6	83.1	6668
Ningxia	80.3	66.4	8268
Xinjiang	70.8	41.0	5793
Total	**29241.6**	**19189.6**	**6563**

Source: Chinese Agricultural Statistical Data Collection 2008, Ministry of Agriculture of China.

2.5 End-uses

Rice is the staple food with the longest history, widest distribution, and most diversity in China. People from different cultures and areas within the country have different ways of preparing and consuming rice products, which vary in style, taste, and method of preparation, according to regional, ethnic, and seasonal features. Nonetheless, there are some common and traditional rice products that are used across the whole nation.

Cooked rice refers to milled rice simply cooked with water; steamed, braised, and boiled rice are the main types of cooked rice. Distinctively flavored rice dishes can be prepared by adding other ingredients such as meat, fish, vegetables, and legumes. Medicinal ingredients may also be added during the preparation and cooking procedures.

Rice porridge of a liquid or semi-liquid consistency is milled rice cooked with water. Porridge is believed to be easily digested and is favored for people with health problems and children. As with cooked rice, meat, fish, and vegetables can be added to rice porridge to give it a special flavor, and pharmaceuticals are sometimes added.

After grinding, milled rice can be processed into many products having different shapes and tastes. The best-known types include rice noodles, *Niangao* (glutinous rice cake), *Tangyuan* (stuffed dumpling, a traditional food of southern China), *Yuanxiao* (shape

Table 3. Highest rice yields on record in China.

Cultivar	Type	Yield (t/ha)	Area (ha)	Site	Year
Shennong 6014	*japonica* inbred	12.15	na*	Shenyang, Liaoning	2005
Peiyouteqing	*indica* hybrid	12.97	na	Qianyang, Hunan	1994
Zhongzheyou 1	*indica* hybrid	12.51	na	Chengzhou, Zhejiang	2004
Guangchao 6	*indica* inbred	11.06	7.460	Jiedong, Guangdong	2001
Shanyouming 86	*indica* hybrid	12.77	6.759	Youxi, Fujian	2001
II-youhang 1	*indica* hybrid	13.92	6.740	Youxi, Fujian	2004
II-youming 86	*indica* hybrid	17.94	0.748	Yongsheng, Yunnan	2001
Teyou 175	*indica* hybrid	17.78	0.747	Yongsheng, Yunnan	2001
II-you 084	*indica* hybrid	18.47	0.068	Yongsheng, Yunnan	2003
II-you 6	*indica* hybrid	18.30	0.714	Yongsheng, Yunnan	2004
II-you 28	*indica* hybrid	18.45	0.078	Yongsheng, Yunnan	2005

* na = Data not available.
Source: Cheng (2005b).

similar to *Tangyuan*, but has a sweet center and is rolled in rice flour, more traditional in northern China), *Maqiu* (ball shaped, rolled in sesame seeds and fried in oil), puddings, breads, crackers, and fermented foods. Ground rice products are colorful when made of brown, red, or purple rice genotypes.

Zongzi, a glutinous rice dumpling, is prepared in several steps. First, glutinous rice is soaked in water for several hours; then it is wrapped in special bamboo leaves, and finally it is cooked in boiling water. As it is wrapped, stuffing (e.g., jujube, red bean, or meat) is put in the rice preparation.

Rice is a good substrate for making alcoholic beverages and beer. Shaoxing City in Zhejiang Province is world famous for its red rice wine. *Jiafan* and *Nüerhong*, two types of rice wine that are well known throughout the country, are both made from high-grade *japonica* glutinous rice. Sweet rice wine, red or white, is a traditional homemade drink made from *indica* or *japonica* glutinous rice.

Rice bran, the by-product of rice-milling, is generally composed of the embryo, the aleuronic layer, and the pericarp. Because of its high oil, vitamin, and protein contents, rice bran can be eaten directly or used to produce forage or cooking oil.

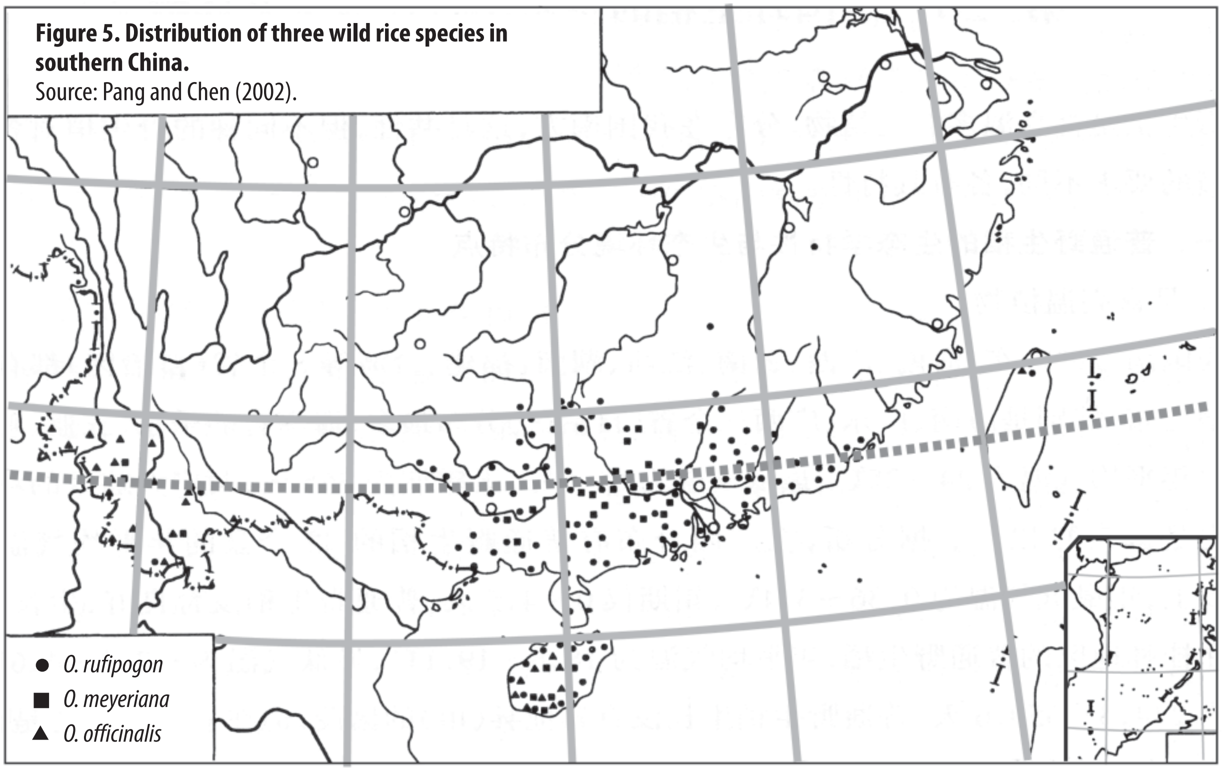
3. History of rice cultivation

3.1 Wild rice distribution

Of the three species of wild rice (*O. rufipogon*, *O. officinalis*, and *O. meyeriana)* in China, *O. rufipogon* (common wild rice having the AA genome) is widely distributed, extending from Taoyuan County (121°15′E), Taiwan, in the east to Jinghong County (100°47′E), Yunnan, in the west, and from the Sanya area (18°09′N), Hainan, in the south to Dongxiang County (28°14′N), Jiangxi, in the north. Wild rice grows in marshlands near river banks, grassy lowlands, and hilly slopes (300-600 m above sea level) in 113 counties of Yunnan, Guangdong, Guangxi, Hainan, Hunan, Fujian, Jiangxi, and Taiwan (Pang and Chen, 2002). Dongxiang in Jiangxi is the northern-most location for common wild rice in China and perhaps in the world.

Oryza officinalis, with the CC genome, is distributed across 38 counties in Guangdong, Hainan, Guangxi, and Yunnan. *Oryza meyeriana*, with the GG genome, has been reported in 27 counties of Hainan and Yunnan. Distribution of the three wild rice species in southern China is shown in Figure 5.

Figure 5. Distribution of three wild rice species in southern China.
Source: Pang and Chen (2002).



According to old writings and archaeological findings, common wild rice was grown in southern and central China (the middle and lower basins of the Yangtze River) in ancient times. As direct evidence of this, four grains of common wild rice with long awns and other wild rice characteristics were discovered among 146 rice grains excavated in the Hemudu site (6,950 ± 130 BC), Zhejiang, in eastern China (Sato et al., 1991). They were considered to be wild rice grains after being examined under a scanning electron microscope and found to have the following characteristics: (1) much denser bristles on the long awn than other rice grains excavated from Hemudu and than current cultivars; (2) traces of natural shedding at maturity, as evidenced by a brittle spikelet at the base point of the rachis; and (3) narrow grain. The finding revealed that *O. rufipogon* had been grown on the lower reaches of the Yangtze River in eastern China (about 31°N) at least 7,000 years ago, although today it is not found in the same area of Zhejiang and Jiangsu. In the Jiahu archaeological site (8,285-7,450 BC, 33°37′N), ancient rice grains were excavated that possess characteristics of both primitive cultivated rice and *O. rufipogon*.

In historical records, common wild rice (*O. rufipogon* and its *spontanea* form) had many names, such as *Ni*, *Li*, and *Lu*. As recently as 1950, the *spontanea* form of the *Keng* type was found in Donghai County, Jiangsu, at about 34.5°N.

Due to human activities such as construction of houses, factories, roads, irrigation systems, reservoirs, and eco-environmental pollution control systems, approximately 70% of the habitats of *O. rufipogon* found in China from the 1950s to the 1980s have disappeared.

3.2 Excavated rice remains

More than 192 excavated rice remains (grains, hulls, stems, and leaves) estimated to be more than 1,500 years old have been found in central, southern, and southwestern China. Of these, 144 date back to the Neolithic age and are more than 3,500 years old (Figure 6). Sixteen rice remains dating back to 12,300-7,000 BC and located in the middle and lower basins of the Yangtze River are considered the most ancient (Table 4).

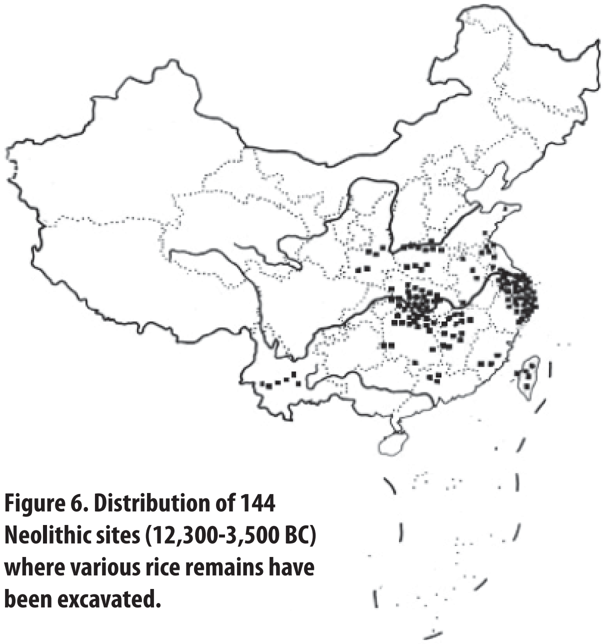


Figure 6. Distribution of 144 Neolithic sites (12,300-3,500 BC) where various rice remains have been excavated.

Table 4. Sixteen Chinese sites where charred rice remains from 12,300-7,000 years ago were found.

Excavation site	Location	Era	Charred remains
Hemudu, Yuyao county, Zhejiang	Lower reaches of Yangtze River	6,950 ± 130 BC	Thousands of grains, including a few *O. rufipogon*
Luojiajiao, Tongxiang county, Zhejiang	Lower reaches of Yangtze River	7,040 ± 150 BC	Hundreds of grains, mainly primitive *japonica*
Tongjiaao, Cixi county, Zhejiang	Lower reaches of Yangtze River	Ca. 7,000BC	A few hulls
Shangshan, Pujiang county, Zhejiang	Lower reaches of Yangtze River	11,400–8,600 BC	A great number of hulls in pottery
Kuahuqiao, Xiaoshan county, Zhejiang	Lower reaches of Yangtze River	8,220–7,660 BC	Thousands of grains and hulls
Tianluoshan, Yuyao county, Zhejiang	Lower reaches of Yangtze River	7,000–5,600 BC	Hundreds of grains
Erjian village, Lianyungang city, Jiangsu	Middle reaches of Huai River	7,885 ± 480 BC	A few grains
Lijia village, Xixiang county, Shaanxi	Middle reaches of Yangtze River	Ca.7,600 BC	Vestiges of grain hulls on burned soil
Pengtoushan, Li county, Hunan	Middle reaches of Yangtze River	8,200–7,450 BC	Vestiges of grains and hull on roughcast of earthenware
Jiahu village, Wuyang county, Henan	Upper reaches of Huai River	8,285–7,450 BC	Hundreds of grains of primitive *japonica* and *indica*
Longqiu village, Gaoyou county, Jiangsu	Lower reaches of Yangtze River	6,300–7,000 BC	Hundreds of grains
Bashidang, Li county, Hunan	Middle reaches of Yangtze River	8,000–9,000 BC	Hundreds of grains
Yuchanyan, Dao county, Hunan	Middle reaches of Yangtze River	12,300 ± 1,200 BC	A few grains and hulls with mixed *indica*, *japonical*, and *O. rufipogon* characteristics
Dulinau, Chalin county, Hunan	Middle reaches of Yangtze River	Ca. 7,000 BC	A few grains
Chengbeixi, Zhicheng county, Hubei	Middle reaches of Yangtze River	8,000–7,000 BC	A few hulls in pottery
Zhichengbei, Zhicheng county, Hubei	Middle reaches of Yangtze River	Ca. 7,000 BC	A few hulls in pottery

In the 1970s, a large quantity of rice remains were excavated from the Hemudu site (29°58′N, 121°22′E) located in the Yangtze River delta in Zhejiang, together with numerous bones and stone tools used for primary land preparation and harvesting, as well as subtropical plants and animals. Thousands of carbonized rice grains dated 6950 ± 130 BC were found at the site, together with rice leaves and straw (Figure 7). The dimensions of the carbonized grains varied considerably in length and width, and the material was judged to be a mixed population of primitive *japonica* rice, primitive *indica* rice, and a few grains of common wild rice based on grain length, width, shape, and size, as well as the characteristics of the bi-peak-tubercle on the lemma and opal. From the Neolithic remnants in Jiahu village (33.4°N, 113°E) in Henan, located near the southern region of the Huai River, hundreds of carbonized rice caryopses dated 8,942–7,868 BC were excavated in the early 1990s. Morphological studies revealed that most of these ancient rice grains belonged to, or approached, the *Keng* (*japonica*) type in appearance, and a few resembled *Hsien* (*indica*).

In the 1980s, many carbonized rice hulls in earthenware dated 8,200–7,450 BC from Pengtoushan near the southern basin of the middle Yangtze River in Hunan were discovered in the same layer with many bones and roughly-made stone tools. In the mid 1990s, rice hulls and rice opals dated 12,000–10,000 BC from Yuchanyan (25°30′N, 110°30′E), Dao County, Hunan, were excavated from the same soil layer, together with plants, animals, stones, and bone tools. The Yuchanyan rice is considered the most ancient and primitive cultivated form, dating back to 10,000 BC (Yuan, 1996). In 1996, hundreds of Bashidong rice grains dated 9,000–8,000 BC were excavated from Li County, Hunan. They were identified as small grains of ancient cultivated rice, similar to *Keng* (*japonica*) in length and to *Hsien* (*indica*) in width. In recent years, charred remnants of rice grain hulls in pottery dated about 11,400–8,600 BC were found in Shangshan village, Pujiang County, Zhejiang. In 2002, thousands of carbonized rice grains and hulls with many primitive farming stone and bone tools, dated 8,220–7,660 BC, were excavated from Kuahuqiao remains, Xiaoshan County, Zhejiang, also located on the lower reaches of the Yangtze River.

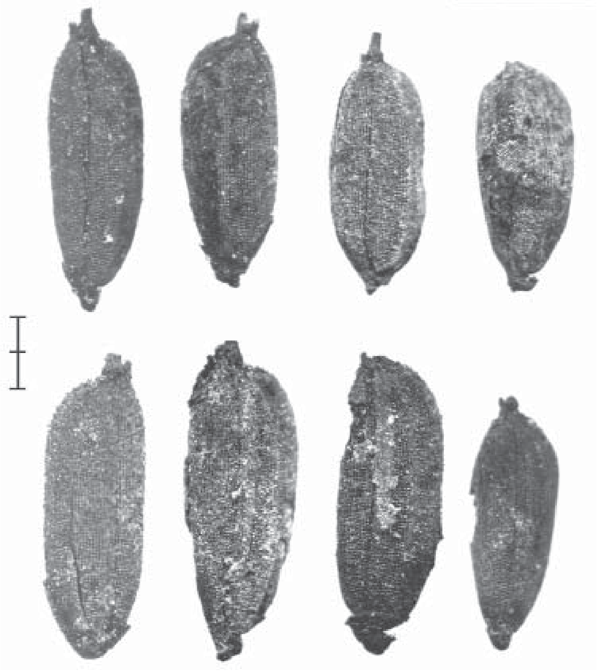


Figure 7. Ancient rice grains (6,950 ± 130 BC) excavated from the Hemudu site in Zhejiang.

3.3 Origin of Chinese cultivated rice

Most investigators tend to agree that Chinese cultivated rice originated in the middle to lower reaches of the Yangtze River and upper reaches of the Huai River (Tang et al., 1993; Wang et al., 1996). From this center of origin, primitive rice was disseminated in multiple directions, under diverse environmental (i.e., latitude, elevation, temperature, precipitation, sunshine) and cropping (planting date, soil type, farming method) conditions. In the long term, primitive cultivated rice evolved and was domesticated under natural and artificial selection pressures, and ultimately differentiated into the *indica* and *japonica* subspecies, plus a variety of types including early and late maturing, paddy and upland, and waxy and nonwaxy endosperm types. These cultivated rices have a large range of distinct agronomic traits and physiological characteristics, revealing their great genetic diversity.

3.4 Genetic resources

Chinese rice germplasm is collected and conserved in the China National Crop Genebank in Beijing, with a duplicate collection maintained at a site in Qinghai Province under natural cold conditions at a high altitude. In 2005, the collection held 69,660 accessions (Table 5), including 49,352 traditional landraces, 4,749 modern cultivars, 1,113 hybrid rice (hybrids, male-sterile lines, maintainer lines, and restorer lines), and 5,699 wild rice accessions (Han and Gao, 2005).

Table 5. Numbers and percentages of rice germplasm accessions conserved in the China National Crop GeneBank, Beijing.

Type	1981–1990	1991–1995	1996–2000	2001–2005	2006	Total	%
Traditional cultivar	41,355	5,586	1,813	594	4	49,352	70.9
Modern cultivar	1,656	1,609	1,056	199	229	4,749	6.8
Foreign material	5,046	2,515	361	511	120	8,543	12.3
Hybrid material	534	508	na*	20	51	1,113	1.6
Wild species	3,474	1,769	356	na	100	5,699	8.2
Genetic stock	na	198	na	6	na	204	0.3
Total	**52,065**	**12,185**	**3,586**	**1,330**	**504**	**69,660**	**na**
%	74.7	17.5	5.1	1.9	0.7	na	100

* na = Data not available.
Source: Han and Gao (2005).

4. Rice genetic improvement

4.1 Genetic improvement before the 1950s

Throughout the long history of rice cultivation, a large number of cultivated landraces were created through natural mutation and artificial selection. According to ancient records, elite selections began to be conceptualized during the Xi-Zhou dynasty (11th to 8th century BC). Until the Han dynasty (2nd century BC to 2nd century AD), panicle selection was widely practiced to improve landraces or produce new ones. During the Song dynasty (960–1,127), Zhancheng Dao, an early-maturing *indica* rice, was introduced from Vietnam to Fujian Province and then gradually spread to Jiangxi, Zhejiang, Guangdong, Anhui, and Hunan Provinces in southern China. From the 10th to the 14th century, this introduced landrace played an important role in the development of many early *indica* landraces in the middle and lower reaches of the Yangtze River. In the Ming and Qing dynasties (13th–19th century), many elite mutants were selected from rice fields using single seed or/and pure line selection. These mutants had characteristics such as early maturity, large grains, and large panicles. Some early-maturing landraces with good drought tolerance—for example, Jiugongji and Houxiaji—were developed using the above methods and recommended to farmers for planting. The book *Shoushitongkao* (1742) recorded 3,429 farmer cultivars/landraces, and summarized rice improvement results over a long period.

Agricultural organizations initiated the scientific improvement of rice landraces in 1919. In 1924, two improved cultivars were released by the Dashengguan Agricultural Experimental Farm in Jiangsu. These were bred from the tall landraces Jianghuyangxian and Dongguanbai by panicle selection. In 1929, cultivar Zhongdamaozitou with high yield potential was bred from the landrace Maozitou in Guangdong through pure line selection. In 1930, large-scale pure line selection began to be applied at the Zhejiang Rice–Wheat Farm. Early-maturing *indica* cultivars Zhechang 504 and Zhechang 505, the late-maturing *indica* cultivar Zhechang 3, the late *japonica* cultivar Zhechang 129, and the late glutinous cultivar Zhechang 204 were subsequently released. In 1934, the early-maturing *indica* rice Nantehao was developed from the landrace Boyangzao through pure line selection at the Jiangxi Agricultural Experiment Farm, Jiangxi. Nantehao was outstanding, for it could be planted twice a year in double-cropping rice regions during the 1940s and 1950s. It was grown over a large area and was a leading parent for developing many early *indica* cultivars. A total of 258 cultivars were developed from Nantehao during the 1960s to 1970s, including the important cultivars Nante 16, Aijiaonante, Guangchang 13, Liantangzao, and Lucaihao. From the 1920s to the 1940s, pure line selection was the leading rice breeding method in China.

Professor Ding Ying, a pioneer of rice cross-breeding, first screened elite plants descended from natural crosses between cultivated *indica* and common wild rice *O. rufipogon*, and subsequently released the cultivar Zhongshan 1. Thereafter, hybridization among rice cultivars became a popular rice breeding method, and important cultivars such as Baotaihong, Zhongshanbai, Baoxuan 2, Baotai'ai, and Zhuyin 2 were developed. In the 1950s, most cultivars in China remained as tall as landraces, and some improved cultivars showed a yield potential of 2 to 3 t/ha.

4.2 Improvement since the 1950s

Following the establishment of the People's Republic of China in 1949, rice breeding became an important activity of the national food crop extension system.

Over the years, various breeding methods were gradually adopted, from pure line selection, hybridization, mutation, hybrid rice, anther culture, inter-species crossing to biotechnology. The breeding of dwarf rice in the late 1950s and 1960s, and of hybrid rice from the 1970s to the 1980s were major achievements of rice breeding in China (Min, 1992). The super rice breeding program, including both inbreds and hybrids, started in the mid-1990s and continues to this day (Cheng et al., 2007). During the past 60 years, more than 4,500 modern inbred and hybrid cultivars have been registered and released, generating large economic and social benefits. As a result, national average rice yield increased from 1.9 t/ha in 1949 to 6.38 t/ha in 2007.

Dwarf rice. The commercialization of dwarf rice started in the late 1950s and marked the beginning of a period of unprecedented progress. The objectives of breeding dwarf rice were to enhance fertilizer utilization, improve tillering capacity, reduce lodging, and increase grain productivity by shortening plant height. In 1956, a dwarf variant, subsequently named Aijiaonante, was selected from its tall parent Nante 16 in Chaoyang County, Guangdong. That same year, a short heavy-tillering cultivar Dee-Geo-Woo-Gen was crossed with the well-adapted tall landrace Tsai-Yuan-Chung to produce the modern cultivar Taichung Native 1 (TN 1), released by the Taichung Agricultural Experiment Farm in Taiwan. With its dwarf stature and high yield potential, TN 1 showed excellent performance. Similarly, short-statured cultivar Aizizhan 4 was crossed with tall cultivar Guangchang 13 to produce the famous dwarf cultivar Guangchang'ai at the former South China Agricultural Research Institute in Guangdong in 1959. In 1966, the International Rice Research Institute (IRRI) at Los Baños, the Philippines, released the modern cultivar IR8, a semidwarf *indica* cultivar with high yield potential. Derived from a cross between Dee-Geo-Woo-Gen and Indonesian tall cultivar Peta, IR8 was widely distributed in Asian countries. The four cultivars, Aijiaonante, Guangchang'ai, TN 1, and IR8, carried a common semidwarfing gene *sd1.* The release and widespread use of these cultivars initiated a new era of dwarf rice breeding and the so-called "Rice Green Revolution" in Asia.

In the 1960s and 1970s, the wide use of semidwarf materials as parents resulted in the development of numerous short, strong-tillering, and high-yielding cultivars for all ecological regions and cropping systems. The most famous short *indica* cultivars were Zhenzhuai (*ai* means short in Chinese), Zhenzhuai 11, Guangluai 4, Ainanzao 1, Qingxiaojinzao, Erjiuqing, Guiluai 3, Yuanfengzao, Guangjie 9, Xiangaizao 7, Xianfeng 1, Zhenshan 97, Lunanzao 1, Guichao 2, Xiangzhongxian 1, Guangxuan 3, Nanjing 1, and Guangerai 5. The most important short *japonica* cultivars included Nongken 58 introduced from Japan, Guihuahuang from Italy, as well as Nonghu 6, Tongqingwan, Ewan 5, Xiushui 48, Nanjing 35, Huxuan 19, Songliao 2, Jingyu 1, Hejiang 12, and Changbai 1.

From the 1950s to the 1980s, China introduced many exotic rice cultivars/lines with the *sd1* gene to be used directly and indirectly in rice genetic improvement, including Nongken 57 and Nongken 58 from Japan; IR26, IR30, and IR661 from IRRI; Milyang 23 and Milyang 46 from Korea; and BG902 from Sri Lanka. The *japonica* cultivar Nongken 58, introduced in late 1950s from Japan, was planted on 11 million ha in China from the 1960s to 1980s (Tang et al., 2004).

Mutagenesis. As was done in other parts of the world, China explored the use of mutagenesis in rice improvement, and new useful genetic stocks and cultivars were developed. An outstanding example was the cultivar Zhefu 802, bred in 1982 from cultivar Simei 2 following radiation with ^{60}Co-γ. Zhefu 802 was planted on 9.73 million ha during 1983-2002. Recently, new mutagenic approaches such as tilling and ecotilling have appeared and produced interesting results in gene discovery and crop improvement. Space breeding may be considered the newest technology in this field (Jin et al., 2004; Wan, 2009).

Hybrid rice breeding. From the 1970s to 1980s, hybrid rice breeding was launched in China by Professor Longping Yuan and others. Hybrid rice benefits from the heterosis between different cultivars or between subspecies (Yuan, 1987). Hybrid breeding aimed not only to further increase yield potential, but also to improve adaptation. In 1970, a common wild rice plant (*O. rufipogen*) with cytoplasmic male sterility (*cms*) was found in Hainan. Through wide cooperation and a national outlook to tackling key problems, the three lines (a cms line, a maintainer line, and a restorer line) necessary for breeding hybrid rice were developed in 1973. Many exotic cultivars/lines, such as IR24, IR26, IR30, IR661, and Milyang 46, were evaluated as elite restorer lines or genetic resources for the development of three-line hybrid rice (Ding et al., 2007). Several elite hybrids, such as Nanyou 2, Nanyou 6, Shanyou

2 and Shanyou 6, were tested and later released. Large-scale (0.13 million ha) experimental sowing of hybrid rice began in 1976. By 1980, the area planted to hybrid rice had reached 4.7 million ha, and more than 16 million ha by 1990. From the 1980s to the 1990s, a large number of hybrids were developed and released. An excellent *indica* hybrid, Shanyou 63, from parents Zhenshan 97A and Minghui 63 (Gui630/IR30), was widely planted in southern and central China, reaching a maximum area of 6.8 million ha in 1990 and a cumulative area of 62.8 million ha from 1983 to 2007. Table 6 lists the most important rice hybrids over the past 30 years.

In the mid-1980s, following observations by Professor Mingsong Shi, a two-line hybrid rice system was developed based on the cultivar Nongken 58S, which showed photosensitive genetic male sterility (PGMS) in the field (Yuan, 1987). Compared to the three-line hybrid system, the two-line system had distinct advantages: (1) there was no need for a maintainer line, which simplified the propagation procedure; (2) it was possible to utilize *indica–japonica* heterosis if the wide compatibility gene (*wc*) was used for high seed-setting rate; (3) two-line hybrids had higher yield potential than three-line hybrids. However, two-line hybrid rice can only be developed in countries such as China, which allows cultivation in a wide range of latitudes. In recent years, many excellent two-line hybrids, such as Liangyoupeijiu, Peiliangyou 288, Peizashuangqi, and Xiangliangyou 68, have been released. By 2005, 140 two-line hybrids had been officially released. Cultivar Liangyoupeijiu is widely planted in central China, with a cumulative area of 5.4 million ha in 1999–2007. Three-line and two-line hybrids currently account for approximately 54.5% of the total rice area in China, and up to 60% of the rice production.

Breeding super rice. Breeding of super rice was started by IRRI in the mid-1990s (Peng et al., 1994). In 1996, the Chinese Ministry of Agriculture (MOA) officially sponsored the Super Rice Breeding Program aimed at developing both inbred and hybrid rice. The key concepts underlying "super rice" can be summarized as new plant types, use of elite germplasm, and subspecies heterosis (Yuan, 2001; Cheng, 2005b). The primary objectives in breeding super rice are to develop high yield potential, good grain quality, and multiple disease and pest resistances. In addition, the resulting cultivars should have high water-use efficiency, high fertilizer-use efficiency, and wide adaptation. The major targets of super rice are: (1) yields of more than 6.7 t/ha (100 mu) in experimental rice fields, stable yield potential of 9.0–10.5 t/ha by 2000, 12.0 t/ha by 2005, and 13.5 t/ha by 2015; (2) in high-yield experiments (0.1–0.2 ha), yields must be 12.0 t/ha by 2000, 13.5 t/ha by 2005, and 15 t/ha by 2015; (3) in farmers' fields, yields should be about 10% higher than those of the leading commercial inbred or hybrid cultivars; in general, the national average rice yield is expected to reach 7.5 t/ha by 2030 due to the release of super rice cultivars; (4) grain quality of super rice should reach grades I to III on the MOA's National Superior Rice Quality scale, namely,

Table 6. The 15 most important Chinese 3-line hybrids with annual plantings exceeding 0.4 million ha and accumulated areas of over 4 million ha.

Hybrid		Largest area		Cumulative area	
	Cross	Amount (mha)	Year	Amount (mha)	Period
Nanyou 2	Erjiunan 1A/IR24	2.98	1978	>6.7	1976–1986
Shanyou 2	Zhenshan 97A/IR24	2.78	1984	11.3	1981–1988
Shanyou 6	Zhenshan 97A/IR26	1.74	1984	9.3	1981–1994
Shanyou 46	Zhenshan 97/Milyang 46	0.45	1996	5.8	1991–2007
Shanyou 63	Zhenshan 97A/Minghui 63	6.81	1990	62.8	1983–2007
Shanyou 64	Zhenshan 97A/Ce 64-7	1.90	1990	12.7	1984–2002
Shanyougui 33	Zhenshan 97A/Gui 33	0.76	1990	4.7	1984–1999
Weiyou 6	V20A/IR26	1.55	1986	8.2	1981–1992
Weiyou 64	V20A/Ce 64-7	1.35	1990	11.7	1984–2003
Gangyou 22	Gang 46A/CDR22	1.43	1998	9.1	1994–2007
D-you 63	D-Shan A/Minghui 63	1.11	1990	5.7	1986–2001
Teyou 63	Longtepu A/Minghui 63	0.43	1997	4.3	1984–2007
II-you 838	II-32A/Fuhui 838	0.79	2000	5.9	1995–2007
Jinyou 207	Jin 23A/Xianhui 207	0.71	2004	4.1	2000–2007
Liangyoupeijiu	Peiai 64S/Yangdao 6	0.82	2002	5.4	1999–2007

northern *japonica* rice, grade I, southern *japonica* rice, grade II, and southern *indica* rice, grade III; and (5) super rice should have excellent resistance to diseases and insects. In the northern *japonica* rice regions, blast resistance is essential, whereas in the southern *indica* and *japonica* rice regions, multiple resistance to blast, bacterial blight, brown planthopper, and leafhopper is required.

By 2007, about 70 super rice cultivars had been released and were widely planted. They show excellent performance in the field, e.g., they yield nearly 10.5 t/ha in many larger farmers' fields (7–70 ha), and 12 t/ha in smaller fields (1–2 ha). In 2006–2007, the MOA listed 33 new super rice cultivars that could be grown in the main rice regions (Table 7).

Application of new techniques in rice breeding. New technological methods applied in plant breeding include tissue culture, cell engineering (anther, pollen, and somatic cell culture), inter-species hybridization, embryo rescue, molecular marker-assisted selection (MAS), functional gene cloning, transgenics, recombinant DNA, space breeding, and molecular breeding. Methods that have been successfully applied in rice breeding include anther culture, MAS, transgenics, and space breeding.

Use of anther culture started in the 1970s and later became a basic rice breeding technique. Many *indica* and *japonica* cultivars were developed using this approach and subsequently released, including *japonica* inbreds Zhonghua 8, Zhonghua 9 and Zhejing 66; *indica* inbreds Shanhua 369, Xianghua 1 and Ganzaoxian 31; and *indica* hybrids Nanhua 1 and Shanhua 62. During 1977–2000, cultivars developed using anther culture covered about 2.1 million ha. In addition, other cultivars, such as the early *indica* cultivars Hezhenmi, Zhongzu 1, and Zupei 2, were developed from somaclonal variants generated from tissue culture.

Table 7. Thirty-three super rice cultivars widely used in China.

Cultivar	Type	Subspecies	Year released	Extension area
Jijing 102	Inbred	*japonica*	2006	Northeastern China
Songjing 9	Inbred	*japonica*	2006	Northeastern China
Longdao 5	Inbred	*japonica*	2006	Northeastern China
Longjing 14	Inbred	*japonica*	2006	Northeastern China
Kendao 11	Inbred	*japonica*	2006	Northeastern China
Tiejing 7	Inbred	*japonica*	2006	Northeastern China
Wujing 15	Inbred	*japonica*	2006	Lower Yangtze River Basin
Zhongzao 22	Inbred	*indica*	2006	Lower Yangtze River Basin
Guinongzhan	Inbred	*indica*	2006	Southern China
Tianyou 122	3-line hybrid	*indica*	2006	Southern China
Yifeng 8	3-line hybrid	*indica*	2006	Middle area of Yangtze River
Jinyou 527	3-line hybrid	*indica*	2006	Middle area of Yangtze River
D-you 202	3-line hybrid	*indica*	2006	Middle area of Yangtze River
Q-you 6	3-line hybrid	*indica*	2006	Middle area of Yangtze River
Yongyou 6	3-line hybrid	*indica*	2006	Lower Yangtze River Basin
Qiannanyou 2058	2-line hybrid	*indica*	2006	Southwestern China
Y-liangyou 1	2-line hybrid	*indica*	2006	Middle area of Yangtze River
Zhuliangyou 819	2-line hybrid	*indica*	2006	Middle area of Yangtze River
Liangyou 287	2-line hybrid	*indica*	2006	Middle area of Yangtze River
Peizataifeng	2-line hybrid	*indica*	2006	Southern China
Xinliangyou 6	2-line hybrid	*indica*	2006	Lower Yangtze River Basin
Longjing 18	Inbred	*japonica*	2007	Northeastern China
Qianchonglang	Inbred	*japonica*	2007	Northeastern China
Liaoxing 1	Inbred	*japonica*	2007	Northeastern and North China
Ningjing 1	Inbred	*japonica*	2007	Lower Yangtze River Basin
Huaidao 9	Inbred	*japonica*	2007	Lower Yangtze River Basin
Chujing 27	Inbred	*japonica*	2007	Southwestern China
Yuxiangyouzha	Inbred	*indica*	2007	Southern China
Ganxin 688	3-line hybrid	*indica*	2007	Middle area of Yangtze River
Neiliangyou 6	3-line hybrid	*indica*	2007	Central China
II-youhang 2	3-line hybrid	*indica*	2007	Southern China
Fengliangyou 4	2-line hybrid	*indica*	2007	Lower Yangtze River Basin
Xinliangyou 6380	2-line hybrid	*indica*	2007	Central China

Molecular marker-assisted selection (MAS) has been widely adopted by rice breeders since the mid-1990s. Using IRRI lines IRBB21 and IRBB60 carrying the bacterial leaf blight (BLB) resistance gene *Xa21*, the China National Rice Research Institute (CNRRI) in Hangzhou developed several hybrid cultivars with *Xa21* by crossing and MAS methods (Cao et al., 2003; Cheng et al., 2004) (Table 8). These hybrids are high yielding and have stable BLB resistance and wide adaptation. *Xa21* was originally found in *O. longistaminata*, a wild rice from Africa. Using MAS, the resistant genes *Xa4* and *Xa21* were transferred into the restorer line Shuhui 527 at Sichuan Agricultural University to develop elite hybrid cultivars, such as D-you 527, Gangyou 527, and Xieyou 527. Two high-yielding genes, *yld1* and *yld2*, were introgressed from wild rice *O. rufipogon* to restorer line Q611 (Ce 64-7/9311) by the China National Hybrid Rice Research and Development Center (CNHRRDC) in Changsha, Hunan Province, using MAS to produce the high yielding hybrid Y-you 7 (Yuan, 2008).

Since 1987, China has carried out eight space experiments in artificial satellites using more than 70 plant species (Wan, 2009). From these experiments, new cultivars with excellent traits were developed, including several elite rice cultivars (Table 9). Boyou 721, an *indica–japonica* hybrid bred via space breeding, has a yield potential of 10.5 t/ha in large areas, or about 15% higher than that of local commercial hybrids.

Transgenic rice. Transgenic rice breeding developed rapidly in several institutes in the 1990s (Tu et al., 1998; Shu, 2001). Generally, functional genes, such as genes for pest and herbicide resistance, are considered for transfer into rice cultivars. *Bt*-transgenic rice has been the most widely studied and some cultivars are undergoing environmental tests prior to release (Jiang et al., 2003). Nutrient genes, such as the β-carotene gene, have been transferred into commercial rice cultivars to improve grain quality through internationally cooperative projects. In some institutions, transgenic rice lines with favorable traits such as high photosynthetic capacity and tolerance to abiotic stresses are being studied in the laboratory. Inbred lines Kemingdao 1, Kemingdao 2, and Kemingdao 3 carrying the *Bt* gene have shown good resistance to stem borer (Shu et al., 1998). The *Xa21* and *Bt* genes were transferred simultaneously into CMS, maintainer, and restorer lines at several institutions and universities (Zhou et al., 2002; Wang et al., 2002). In late November 2009, the MOA provided food safety certificates for transgenic rice cultivars Shanyou 63 and Huahui 1, both carrying the *Bt* gene (http://www.ftchinese.com/story/001030082).

Table 9. Details on *indica* rice cultivars bred through space breeding, 2000–2005.

Cultivar	Type	Yield in cultivar trial (t/ha)	Recommended area
Ganzaoxian 47	Inbred	5.11	Central China
Huahang 1	Inbred	7.22	Southern China
Zhongzao 21	Inbred	6.14	Central China
Ganwanxian 33	Inbred	6.00	Central China
Shengbasimiao	Inbred	5.42	Southern China
Zhongjia 3	Inbred	6.92	Central China
Yuehang 1	Inbred	5.88	Southern China
Zhe 101	Inbred	7.17	Central China
Teyouhang 1	3-line hybrid	8.60	Central China
II-youhang 1	3-line hybrid	11.13	Southern China
II-youhang 148	3-line hybrid	7.68	Southern China
Peizataifeng	2-line hybrid	7.64	Southern China
Peizahang 7	2-line hybrid	6.38	Southern China

Source: Wan (2009).

Table 8. Hybrid rice cultivars with the *Xa21* gene bred using molecular marker-assisted selection (MAS).

Hybrid	Cross	Restorer parentage	BLB* resistance gene	Province and year released
Guodao 1	Zhong 9A/Zhonghui 8006	(Duxi1/Minghui 63) BC$_4$F$_1$//(Duoxi 1/Minghui 63)/IRBB60	*Xa4, xa5, xa13, Xa21*	Zhejiang, 2002; MOA**, 2004
Guodao 3	Zhong 9A/Zhonghui 8006	(Duxi 1/Minghui 63) BC$_4$F$_1$//(Duoxi 1/Minghui 63)/IRBB60	*Xa4, xa5, xa13, Xa21*	Zhejiang, 2004; Jiangxi, 2004
Guodao 6	Neixiang 2A/Zhonghui 8006	(Duxi 1/Minghui 63) BC$_4$F$_1$//(Duoxi 1/Minghui 63)/IRBB60	*Xa4, xa5, xa13, Xa21*	Zhejiang, 2004; MOA**, 2006
Zhonguou 218	Zhong 9A/Zhonghui 8006	(Fuhui 838)^3//(Fuhui 838/IRBB21)	*Xa21*	Zhejiang, 2002, Jiangxi , 2003, MOA**, 2004
Xieyou 218	Xieqingzao/Zhonghui 218	(Fuhui 838)^3//(Fuhui 838/IRBB21)	*Xa21*	Jiangxi, 2002
II-you 8006	II-32A/Zhonghui 8006	(Duxi 1/Minghui 63) BC$_4$F$_1$//(Duoxi 1/Minghui 63)/IRBB60	*Xa4, xa5, xa13, Xa21*	Zhejiang, 2005
II-you 218	II-32A/Zhonghui 8006	(Fuhui 838)^3//(Fuhui 838/IRBB21)	*Xa21*	Zhejiang, 2005

* BLB = Bacterial leaf blight.

** MOA = Ministry of Agriculture.

5. Future prospects

Given the rapid economic development and expansion of urban areas in China, the greatest challenge to rice production is to produce more grains with less land and water. Food security and environmental protection are major themes in modern times. According to the General Targets of the Food and Nutrition Development Program for 2010, a national annual food production of 570 million tonnes will be needed to feed nearly 1.4 billion people. Rice will account for 228 million tonnes of that sum, which means that annual rice production will have to increase 28% over the amount produced in 2001. It is estimated that by 2030 the population in China may reach 1.6 billion, and that the total food demand will be 640 million tonnes, including an estimated 256 million tonnes of rice (Ren, 2004; Cheng, 2005a). According to these estimates, rice production in 2030 will need to be 44% greater than in 2001. Because there are few opportunities to increase the cultivated area in the future, increased production will inevitably depend on raising yields while maintaining high-grain quality, which gives rice breeding high priority for the future. To develop new cultivars that fit the requirements, the major challenge will be to discover and use elite genetic resources present in cultivated rice, wild rice, and rice relatives, as well as to create novel germplasm or genetic materials. Biotechnology will be a powerful tool in novel gene detection, gene pyramiding, and hastening the breeding cycle. In addition, rice cultivation systems also need to be improved with the purpose of increasing water and fertilizer use efficiencies, and reducing chemical input application.

5.1 Exploration and utilization of elite germplasm with genetic diversity

The semidwarf allele *sd1* and the cytoplasmic male sterility gene *cms* can be regarded as major achievements in rice improvement, along with the wide compatibility materials carrying the *WC* gene that allowed the utilization of heterosis between rice subspecies. Currently, *indica–japonica* heterosis is the major strategy in super rice breeding. However, other elite genes need to be combined with the hybridity. Cooperation at the national level is an essential component of the super rice breeding program. The current priorities of research on genetic resources focus on exploring, evaluating, and utilizing *P(T)GMS* (photo- or thermo-sensitive genetic male sterility), the *WC* gene, QTLs for high yield, high nitrogen and phosphorus use efficiencies, drought tolerance, salinity tolerance, and high quality. Progress in these fields will be highly beneficial to future rice breeding and production.

Germplasm exchange between and within countries has been extremely important. Exotic germplasm has contributed greatly to Chinese rice cultivar development in the past. Restorer lines IR24, IR26, and IR30 introduced from IRRI became the most important donors of the restorer gene for the three-line hybrid rice system (Tang et al., 2004). Active international cooperation will continue to facilitate multilateral exchange of genetic resources. China has introduced numerous rice genetic resources through the International Network of Genetic Evaluation for Rice (INGER), which involves more than 62 countries coordinated by IRRI. Through INGER, China has not only obtained a large number of genetic materials and multi-site and multi-trait evaluation data, but also introduced new ideas and technologies for better genetic resource conservation and maintenance.

5.2 Super rice breeding

IRRI initiated the super rice breeding program in 1989, with the key ideas of creating a new plant ideo-type (NPT) and using *javanica* germplasm. Many rice NPT lines with high yield potential, disease resistance, and good grain quality were developed and distributed for evaluation in many rice-producing countries of South and Southeast Asia.

Super rice breeding in China focuses on utilizing elite gene(s), building plant ideo-types, creating strong subspecies heterosis by intercrossing *japonica*, *indica*, and *javanica* genotypes, and combining conventional breeding methods and biotechnological tools. The super rice breeding program has been operating for 15 years and will continue with support from the government. The cumulative area sown to super rice cultivars from 1999 to 2005 reached 13 million ha, with an average yield 750 kg/ha higher than that of common cultivars. In 2005, the Chinese MOA initiated the Super Rice Research and Extension in China Project. According to this plan, at least 20 leading super rice inbred cultivars and hybrids would be released to farmers by 2010; the area planted to super rice would cover about 30% of the total rice area; and the average yields of leading super rice cultivars would be 60 kg/ha higher than those of commercial cultivars being used in 2005. Cheng et al. (2007) summarized the project's breeding strategies as increasing the genetic diversity of parents, raising total biomass yield, improving leaf posture, and invigorating the root system by increasing its absorption capacity. The project aimed to reach a national yield level of 6.5 t/ha by 2010 and 8.1 t/ha by 2030.

Three constraints to breeding of super hybrid rice were noted: scarcity of super rice germplasm, especially early maturing genotypes; unstable yields caused by reduced seed-setting rates; and lack of understanding of the formation of yield potential (Chen et al., 2007). Rice scientists are attempting to break through these barriers, and hope to achieve substantial progress in the near future.

It is necessary to accelerate the development of high quality inbred cultivars and hybrids, especially early-maturing *indica* cultivars for southern and central China. Breeding cultivars with high nutritional quality (high levels of iron, zinc, and vitamin A) and specialty rice (e.g., low glutelin, high Lys, resistant starch, and aromatic rice) will also become breeding priorities.

5.3 Applications of biotechnology

Over the last 20 years, China has achieved notable progress in rice biotechological research. Anther culture has become a basic method in crop breeding. Embryo rescue enabled scientists to widen the scope of breeding possibilities by introducing genes from wild rice species or from non *Oryza* species. For example, somatic hybridization has been attempted with a rice weed, barnyard grass (*Echinochloa oryzicola*), to broaden the *O. sativa* genepool.

In both *japonica* and *indica* rices, transgenic lines and plants with good resistance to diseases and insects have been created using mainly electroporation, biolistic and *Agrobacterium*-mediated methods, for example, the *Bt* transgenic line Kemingdao, which carries *Xa21* and *Xa23* and is resistant to bacterial leaf blight, and transgenic plants that are tolerant to herbicide PPT and carry the *bar* gene. In December 2009, China released its first genetically modified (GM) rice carrying a *Bt* gene for insect control. Given the huge investment in long-term GMO projects, it is expected that GMOs will play a crucial role in future rice production.

Molecular marker techniques are being increasingly used in many ways, e.g., for hybrid seed identification and intellectual property protection (Wang et al., 2005). Molecular markers have been used to map genes or QTLs associated with important traits, such as fertility, wide compatibility, resistance/tolerance to biotic and abiotic stresses, grain traits, plant type, and plant growth and development (Table 10). Given the recent progress in whole-genome fine-mapping, high sequencing coverage of both the *indica* and *japonica* genomes, and bioformatics, it is expected that marker-assisted selection (MAS) will play an increasing role in enhancing breeding efficiency for numerous traits and accelerating the release of new improved hybrid varieties and inbred lines.

To decipher rice genetics at the nucleotide level, a genomics plan was sponsored by the Chinese Ministry of Science and Technology Committee in 1992. A BAC physical map of the rice genome was released in 1996. In 2001, Chinese scientists finished sequencing the *indica* rice genome and made it publicly available. Other studies focused on rice functional genomics to assist breeding programs (Han et al., 2007). The availability of the rice genomic sequence also permitted a change from forward genetics to reverse genetics. A major challenge is

Table 10. Examples of tagged rice genes being used in molecular marker-assisted selection (MAS).

Trait	Genes with linked markers
Disease resistance	
Blast	*Pi1, Pi2, Pi4 , Pi5, Pi7, Pi10, Pi11, Pi12, Pi18, Pi20, Pi21, Pi44, Pib, Pita2, Pita, Pikm, Pb1*
Bacterial blight	*Xa1, Xa3, Xa4, Xia5, Xa10, Xa13, Xa21, Xa22(t)*
Yellow mosaic virus	*RYMV*
Tungro virus	*RTSV*
Rice stripe	*Stv-b(i)*
Insect resistance	
Gall midge	*Gm2, Gm4(t)*
Brown plantopper	*Bph1, Bph10, Bph(t)*
Green leafhopper	*GLH, Grip3, Grip11, Grh1*
Whitebacked planthopper	*WBPH*
Abiotic stresses	
Waterlogging tolerance	*Sub1*
Salt tolerance	*Salt, OSA3*
Heterosis and wide compatibility	
Heterosis	*tgms1.2, tms2, tms3, tgms, tms4, pms1, pms2, pms3, ms-h(t), Rf1, RF, Rf-2, Rf3, Rf5, Rfu, Rf*
Hybrid breakdown	*Hwd1, Hwd2*
Wide compatibility	*S5*
Grain quality	
Grain aroma	*Fgr*
Cooked-kernel elongation	*KNE*
Amylose	*Wx*
Other traits	
Photoperiod sensitivity	*Se1*
Semidwarfing	*sd1, sd2*
Shattering resistance	*Sh2, Sh4, Sht*
Cleistogamy	*Superwoman1-cleistogamy*
Root number	*EXP15*

to determine the functions of previously unknown genes that are revealed by sequencing and/or bioinformatics. Another challenge is to understand the functions of apparently redundant genes that may play different roles in different kinds of tissues or have various effects in response to different agro-climatic environments or field practices.

Simultaneously, new high-throughput technologies were developed for use in expression analysis. Biochips and genome-wide SNP discovery platforms, such as Illumina (HaplOryza) and Affymetrix (OryzaSNP), can be used in genetic analysis. RNA hybridization is used to reveal gene expression difference and identify pathways by association (Xue et al., 2003).

The development of molecular maps has been important for understanding the orthologous relationships between the rice genome and those of other cereals, or even other crops. The syntenous relationships among cereals have, for example, resulted in the discovery of common genes, such as those for dwarf stature (*D8*) in maize and wheat (*Rht1*) based on genomic information derived from rice. In the future, these types of approaches will become increasingly important for all cereal genetic improvement.

A few biotechnological methods are currently being applied in rice research and breeding; others need to be perfected before they can be applied. It was reported recently that more than 200 high yielding cultivars widely grown in China (http://www.dnong.com/info/keji/2009/193411) carry *DEP1*, a key mutant gene that confers high yield potential and probably increases rice yields by 15-20%. The *DEP1* gene should continue to play an important role in super rice breeding and possibly in the genetic improvement of other food crops.

In terms of rice physiology, photosynthetic efficiency is one of the most interesting topics. In recent years, Chinese researchers have been attempting to transfer the highly efficient photosynthesis gene from C_4 crops (e.g., maize) to rice (C_3). This would enable CO_2 and water use efficiencies in the C_4 pathway to be utilized in transgenic rice, and to eventually allow higher grain production (Yuan, 2008). Studies on the synergistic action of photosynthesis and the accumulation of assimilation products in grains not only explain the fundamental reasons for yield increases, but also demonstrate their theoretical value to rice breeding and improvement.

5.4 Development of an integrated rice cultivation system

It is well known that any significant breakthrough in rice production will foster changes and innovations in breeding and crop management. Terms such as: (1) strong seedlings, sufficient fertilizer application, and large numbers of plants and panicles that came with semidwarf cultivars of the 1960s and 1970s; (2) scanty, strong seedlings, few plants with large panicles or scanty, short, and flat based on hybrid rice in the 1980s; and (3) dry nursery, direct seeding, seedling broadcasting, and fertilizer formulation in the 1990s, attempted to describe and promote attributes of leading cultivars in each phase of agronomic development. Optimal cropping systems and cultivation techniques are essential for achieving the yield and quality potentials of cultivars and increase economic returns from rice. Labor-saving cropping practices, including minimum or zero tillage, direct seeding, seedling broadcasting, fewer irrigations, fertilizations, or spray applications during rice growth, and mechanized harvesting, are welcomed by farmers because they save inputs and increase profits. Furthermore, a suitable cropping system for a given cultivar will not only improve yield and quality, but will also meet the demands of intensification, mechanization, and simplification. Integrated rice cropping systems targeted to producing high yields and good quality grain based on optimal growth conditions, environmental protection, reduced use of natural resources, labor, and time need to be developed over the next ten years.

With the rapid development of computer and information technologies, China has initiated a precision agriculture system for rice production with the aid of agricultural expert systems and databases on field management, fertilization, irrigation, disease and pest prediction and management, and remote sensing models for yield estimation.

5.5 Water-saving cultivation

High water use efficiency is a worldwide priority. Compared with other countries, water usage in China is relatively low, i.e., only 80% of the world average use per hectare and 26% of the average use per capita. However, as the gap between the water that is required for agriculture and the water available is becoming greater due to the increasing demands of urbanization and industry, even greater shortages are inevitable (Ye et al., 2002).

Rice is a water-thirsty crop. It is estimated that a paddy rice crop needs 8,000 to 15,000 m^3 of water/ha, the wide variation being related to differences in temperature, evaporation rate, and soil leakage during the growing period. Upland rice consumes only 3,000 to 3,500 m^3 of water/ha, equivalent to 60-75% of the water needed for paddy rice. A current challenge is to develop aerobic rice, a paddy rice genotype with tolerance to water stress that grows well with reduced irrigations. Aerobic rice, a type of upland rice, has great potential because it could save huge amounts of irrigation water, and would be especially suitable for fields with limited irrigation, such as those in the central and northern rice regions.

Water-saving cultivation is supported by two key approaches, namely drought tolerant cultivars and water-saving cropping systems. It is imperative to develop upland drought tolerant paddy rice cultivars (aerobic rice) with high yield potential and good grain quality. At the same time, cropping systems with reduced irrigation frequency and volume must be developed to enable such cultivars to meet their potential. Moreover, there are also opportunities for farming communities to better utilize precipitation, ground water, and irrigation water in the future.

References

Cai, H.F., and Chen, Q.G. 1999. China's rice industry in the 21st century. In: Prospects of Rice Genetics and Breeding for the 21st Century. China Agricultural Science & Technology Press, Beijing. pp 18-25 (in Chinese).

Cao, L.Y., Zhuang, J.Y., Zhan, X.D., Zheng, K.L., and Cheng, S.H. 2003. Hybrid rice resistance to bacterial blight developed by marker-assisted selection. Chinese Journal of Rice Science 17: 184-186 (in Chinese with English abstract).

Chang, T.T. 1983. The origins and early cultures of the cereal grains and food legumes. In: David, N.K. (ed.). The Origins of Chinese Civilization. University of California Press, USA, pp. 65-94.

Chen, L.Y., Xiao, Y.H., Tang, W.B., and Lei, D.Y. 2007. Prospect and practice of three-procedure breeding on super hybrid rice. Chinese Journal of Rice Science 21: 90-94 (in Chinese with English abstract).

Cheng, S.H., 2005a. Food security and super rice breeding. China Rice 4: 1-3.

Cheng, S.H. 2005b. Super rice breeding. In: Cheng, S.H., and Li, J. (eds.). Modern Rice in China. Jindun Press, Beijing, China. pp. 238-282 (in Chinese).

Cheng, S.H., Zhuang, J.Y., Fan, Y.Y., Du, J.H., and Cao, L.Y. 2007. Progress in research and development on hybrid rice. Annals of Botany 100: 959-966.

Cheng, S.H., Zhuang, J.Y., and Zhao, L.Y. 2004. Molecular breeding of super hybrid rice. Chinese Journal of Rice Science 185: 377-383 (in Chinese with English abstract).

Ding, L., Qi, Y.W., Zhang, H.L., Zhang, D.L., Li, Z.C., and Tang, S.X. 2007. Genetic diversity of restorers of three-line hybrid rice in China. Acta Agronomica Sinica 33: 1587-1594 (in Chinese with English abstract).

Han, B., Xue, Y.B., Li, J.Y., Deng, X.W., and Zhang, Q.F. 2007. Rice functional genomics research in China. Philosophical Transactions of the Royal Society B: Biological Sciences 362: 1009-1021.

Han, L.Z., and Gao, G.L. 2005. Status of collection, conservation and propagation of rice germplasm in China. Journal of Plant Genetic Resources 6: 359-364 (in Chinese with English abstract).

Jiang, J.H., Guo, Y.M., Yang, Y.G., and Zheng, J.G. 2003. Research and application of transgenic rice. Chinese Bulletin of Botany 20: 736-744.

Jin, J., Zhu, C., Zhang, H.X., and Sun, Z.X. 2004. Preliminary study on a gravity-insensitive rice mutant. Journal of Zhejiang University: Science 5: 144-148 (in Chinese with English abstract).

Khush, G.S., and Brar, D.S. 2001. Rice genetics from Mendel to functional genomics. In: Khush, G.S., Brar, D.S., and Hardy, B. (eds.). Rice Genetics IV. IRRI, Los Baños, Philippines. pp. 3-6.

Min, S.K. 1992. An overview of rice breeding in China. In: Xiong, Z.M., and Cai, H.F. (eds.). Rice Breeding. China Agricultural Science and Technology Press, Beijing, China. pp. 58-68 (in Chinese).

Min, S.K., Wu, X.Z., Yao, C.X., and Li, L.P. 1988. Regionalization of Rice Cropping in China. Zhejiang Science & Technology Press, Hangzhou, China. p. 167 (in Chinese).

Pang, H.H., and Chen, C.B. 2002. Geographical distribution of wild rice species in China. In: Pang, H.H., and Chen, C.B. (eds.). Germplasm Resources of Wild Rice. Guangxi Science and Technology Press, Nanning, China. pp. 3-7 (in Chinese).

Peng, S.P., Khush, G.S., and Cassman, K.G. 1994. Evolution of the new plant ideotype for increased yield potential. In: Cassman, K.G. (ed.). Breaking the Yield Barrier. IRRI, Los Baños, Philippines. pp. 5-20.

Ren, B.Q. 2004. Analysis of food security. Economist 2: 47-50.

Sato, Y.I., Tang, S.X., Yang, L.J., and Tang, L.H. 1991. Wild rice seeds found in an oldest rice remain. Rice Genetics Newsletter (8):76-78.

Shu, Q.Y. 2001.Transgenic rice breeding. In: Li, M.F. and Zhou, K.D. (eds.). Rice Biotechnological Breeding. China Agricultural Science and Technology Press, Beijing, China. 167-238 (in Chinese).

Shu, Q.Y., Ye, G.Y., and Cui, H.L. 1998. Breeding for transgenic rice "Kemingdao". Journal of Zhejiang Agricultural University 24: 579-580 (in Chinese with English abstract).

Tang, S.X. 2002. Seedling broadcasting in China: an overview. In: Pandey S. (ed.). Direct Seeding: Research Strategies and Opportunities. IRRI, Los Baños, Philippines. pp. 177-184.

Tang, S.X. 2007. Origin and domestication of cultivated rice (*O. sativa* L). In: Cheng, S.H. and Li, J. (eds.). Modern Rice in China. Jindun Press, Beijing, China. pp. 9-30 (in Chinese).

Tang, S.X., Min, S.K., and Sato, Y.I. 1993. Exploration of the origin of Keng rice (*japonica*) in China. Chinese Journal of Rice Science 7: 129-136 (in Chinese with English abstract).

Tang, S.X., Wei, X.H., and Javier, E. 2004. Introduction and utilization of INGER rice germplasm in China. Agricultural Science in China. 3: 561-567.

Tu, J.M., One, I., and Zhang, Q.F. 1998. Transgenic rice variety IRF-2 with *Xa21* is resistant to bacterial blight. Theoretical and Applied Genetics 97: 31-36.

Wan, J.M. 2009. New technologies for rice genetic breeding. In: Wan, J.M. (ed.). China Rice Genetic Breeding and Variety Genealogy. China Agriculture Press, Beijing, China. pp. 188-217 (in Chinese).

Wang, A.J., Yao, F.Y., and Wen, F.J. 2002. Obtaining transgenic rice plants resistant to both stem borer and bacterial blight disease from *Bt* and *Xa21* gene transferral. Acta Agronomica Sinica 28: 857-860 (in Chinese with English abstract).

Wang, X.K., Zhang, J.Z., Chen, B.Z., and Zhou, H.Y. 1996. A new discovery about the origin of rice cultivation in China. In: Wang, X.K. and Sun, C.Q. (eds.). Origin and Differentiation of Chinese Cultivated Rice. China Agricultural University Press, Beijing,. pp. 8-13 (in Chinese).

Wang, Y.H., Xue, Y.B., and Li, J.Y. 2005. Towards molecular breeding and improvement of rice in China. Trends in Plant Science 10: 610-614.

Xue, Y.B., Li, J.Y., and Xu, Z.H. 2003. Recent highlights of the China rice functional genomics program. Trends in Genetics 19: 390-394.

Ye, Y.L., Mei, D.L., Li, K., and Liao, G.Q. 2002. The water crisis and the utilization of water saving bio-techniques in rice production. China Rice 6: 20-22 (in Chinese).

Yuan, J.R. 1996. New and important evidence of rice origin obtained from Yuchanyan. Chinese Historical Relic News, March 3 (in Chinese).

Yuan, L.P. 1987. The assumption of breeding strategy of hybrid rice. Hybrid Rice 1: 1-3 (in Chinese).

Yuan, L.P. 2001. Breeding super hybrid rice. In: Peng, S.B., and Hardy, B. (eds.). Rice Research for Food Security and Poverty Alleviation. IRRI, Los Baños, Philippines. pp. 143-150.

Yuan, L.P. 2008. The progress of super hybrid rice breeding. China Rice 1: 1-3 (in Chinese).

Zhou, Y.L., Zhang, Q., Wang, C.L., Xing, Q.D., Zhai, W.X., Pan, X.B., and Zhu, L.H. 2002. Resistance of *Xa21* transgenic hybrid rice Shanyou 3 and Shanyou 559. Chinese Journal of Rice Science 16: 93-95 (in Chinese with English abstract).

Chapter 3.

Maize breeding and production in China

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1. Introduction

China is the second largest maize producer in the world after the USA, and maize is the second leading crop in China after rice. Since its introduction into China in the early 16th century, maize has become one of the country's major cereal crops. From 1949 to 2008, the maize area, average yield, and production have increased from 11.3 to 29.9 million ha, from 935 to 5,555 kg/ha, and from 10.5 to 165.9 million tonnes, respectively (Table 1). The significant increase in maize production is largely due to the adoption of hybrids, improved cropping systems, and better crop management technologies, including mulching, seedling transplantation, irrigation system development, increased use of chemical fertilizers, improved technologies for disease and insect control, and increased economic benefits of maize compared with other crops (Li, 1988; Meng et al., 2006).

Maize is cultivated in all seasons and in almost every province of China, but the main maize growing areas extend from 50 to 22°N, covering a vast territory along the eastern seacoast and reaching the highlands of Xinjiang to the west. China's "Maize Belt," the leading maize producing area, covers a broad diagonal swath from northeastern China to the southwestern provinces, passing through a large corridor in northern China to the southwest, including the provinces of Jilin, Heilongjiang, Liaoning, Inner Mongolia, Hebei, Shanxi, Shaanxi, Shandong, Henan, Sichuan, Guizhou, Yunnan, and Guangxi (Figure 1) (Meng et al., 2006). In 2008 (Table 2), five provinces, including Inner Mongolia, Jilin, Heilongjiang, Shandong, and Henan, shared 49.0% of the area and 53.5% of the production, respectively.

Maize trading in China started in the early 1960s. During 1961-1983, China imported a total of 12.5 million tonnes of maize grain. The country became a net exporter during 1984-1994, marketing a total of 63 million tonnes (annual average: 5.7 million tonnes). Sharp competition in the mid-1990s resulted in China briefly becoming a net maize importer again, purchasing 5.0 million tonnes in 1995. From 2000 to 2007, China exported an average 8.0 million tonnes annually.

Table 1. Maize area, yield, and production in China, 1949-2008.

Year	Output (mt)	Area (m ha)	Yield (kg/ha)	Year	Output (mt)	Area (m ha)	Yield (kg/ha)
1949	10.5	11.3	935	1979	60.0	20.1	2985
1950	13.0	11.7	1117	1980	62.6	20.3	3075
1951	13.7	12.0	1139	1981	59.2	19.4	3045
1952	16.9	12.6	1350	1982	60.6	18.5	3270
1953	16.9	13.1	1275	1983	68.2	18.8	3630
1954	17.1	13.2	1305	1984	73.4	18.5	3960
1955	20.3	14.6	1395	1985	63.8	17.7	3615
1956	23.1	17.7	1305	1986	70.9	19.1	3705
1957	21.4	14.9	1440	1987	79.8	20.2	3945
1958	23.1	16.3	1418	1988	79.9	19.7	4065
1959	16.6	13.0	1279	1989	80.4	20.3	3945
1960	15.0	14.1	1137	1990	98.8	21.4	4620
1961	15.5	13.6	1139	1991	100.8	21.6	4680
1962	16.3	12.8	1275	1992	98.1	21.0	4665
1963	20.6	15.4	1335	1993	102.7	20.7	4962
1964	22.7	15.4	1485	1994	99.3	21.1	4693
1965	23.7	15.7	1515	1995	111.9	22.7	4917
1966	28.4	16.0	1776	1996	127.5	24.5	5203
1967	27.4	15.1	1815	1997	104.3	23.7	4387
1968	25.0	14.6	1718	1998	132.9	25.2	5267
1969	24.9	14.6	1710	1999	128.1	25.9	4945
1970	33.0	15.8	2086	2000	106.0	23.1	4598
1971	35.9	16.7	2143	2001	114.1	24.3	4699
1972	32.1	16.7	1922	2002	121.5	24.7	4927
1973	38.6	16.6	2340	2003	116.0	24.1	4815
1974	42.9	17.4	2475	2004	131.9	25.6	5154
1975	47.2	18.6	2550	2005	139.4	26.4	5287
1976	48.2	19.2	2505	2006	145.5	26.9	5394
1977	49.4	19.7	2520	2007	151.9	29.2	5190
1978	55.9	19.9	2805	2008	165.9	29.9	5555

Source: Statistics of China Agriculture, 1949-2008.

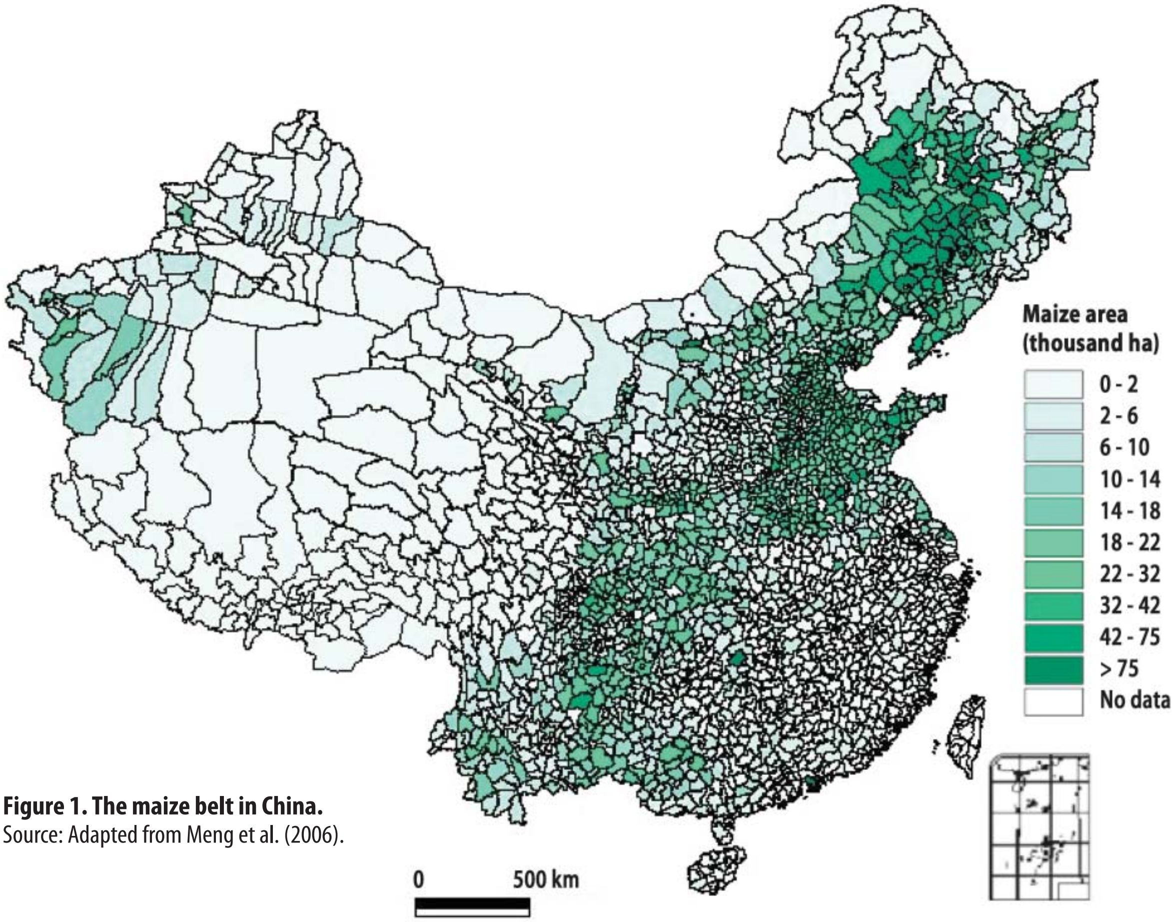

Figure 1. The maize belt in China.
Source: Adapted from Meng et al. (2006).

Chinese maize is used in four ways. At present, around 10% is used for food (compared with 70% in the 1950s). The feed processing industry was initiated very late in China; by 1998, more than 80% of maize was used for animal feed, and 40% was processed as formula feed. Maize feed use will continue to increase in the future. About 9% of maize is for industrial use, and less than 1% is used as seed. Based on estimates from the Center for Chinese Agricultural Policy (CCAP) at the Chinese Academy of Sciences (CAS), the percentage of processed maize increased from 3.0% in 1985 to 8.0% in 2008. However, other estimates suggest that more than 25% of the maize was used by the processing industry in 2008.

Maize originated in Mesoamerica about 6,000 to 7,000 years ago. There are several theories on how maize made its way to China. The Portuguese may have transported it to India, from where it may have traveled to China by sea in the early 16th century. Another presumed pathway is from Europe through Turkey and then on to Arabia, Persia, India, Tibet, and finally to China (Tong and Zhao, 1988). The Silk Road route may have also been a pathway for maize into northwestern China.

The presence of maize in China is described in the book *Bencao Pinhui Jingyao*, presented in 1505 (Ushibayashi, 2005) to Emperor Xiao Zong of the Ming dynasty, as a new kind of *yi-yi ren* or Job's tears. It was also described as a new species in *Annals of Yingzhou, Anhui Province*, published in 1511. Other early mentions of maize appear in the county records of Anhui, Guangxi, Henan, Jiangsu, Gansu, Yunnan, Zhejiang, Fujian, Guangdong, Shandong, Shaanxi, Hebei, Hubei, Shanxi, Jiangxi, Liaoning, and Hunan Provinces successively from the early to mid-16th century. By the mid-18th century, maize was widely grown in the southern provinces. At that time, maize was grown in hilly and mountainous areas where conditions were not suitable for paddy rice. After making its way to northern China and becoming a staple crop there, maize was exported to Korea and, later, to Japan (Tong and Zhao, 1988).

Table 2. Chinese maize area, production, and average yield by province, 2008.

Province	Area (000 ha)	Production (000 t)	Average yield (kg/ha)
Beijing	146.2	88.0	6018
Tianjin	159.8	84.3	5275
Hebei	2841.1	1442.2	5076
Shanxi	1378.6	682.8	4953
Inner Mongolia	2340.0	1410.7	6029
Liaoning	1884.9	1189.0	6308
Jilin	2992.5	2083.0	7127
Heilongjiang	3593.9	1822.0	5070
Shanghai	3.6	2.1	5882
Jiangsu	398.5	203.0	5093
Zhejiang	25.9	11.1	4290
Anhui	705.1	286.6	4065
Fujian	37.0	13.6	3678
Jiangxi	15.6	6.6	4207
Shandong	2874.2	1887.4	6567
Henan	2820.0	1615.0	5727
Hubei	470.4	226.4	4814
Hunan	241.3	128.0	5305
Guangdong	143.4	63.5	4425
Hainan	17.4	7.0	4007
Chongqing	455.6	246.0	5401
Sichuan	1323.8	637.0	4812
Yunnan	1325.8	529.6	3994
Guizhou	734.6	391.2	5325
Tibet	4.0	2.2	5572
Shaanxi	1157.6	483.6	4178
Gansu	557.2	265.4	4763
Qinghai	2.1	1.8	8378
Ningxia	208.5	149.9	7191
Xinjiang	585.5	425.3	7624
Total	**29863.7**	**16591.4**	**5556**

Source: Chinese Agricultural Statistical Data Collection 2008, Ministry of Agriculture.

2. Maize producing regions of China

Maize growing areas in China extend from cool-temperate and warmer-temperate areas to subtropical and tropical ecological zones. Based on the history of cultivation, temperature, photoperiod response, rainfall, frost-free period, and crop rotation system, five major maize growing regions are recognized: the northern spring maize region, the summer maize region in the Yellow, Huai, and Hai River Valleys, the southwestern hilly summer maize region, the southern China fall and winter maize region, and the northwestern irrigated spring maize region.

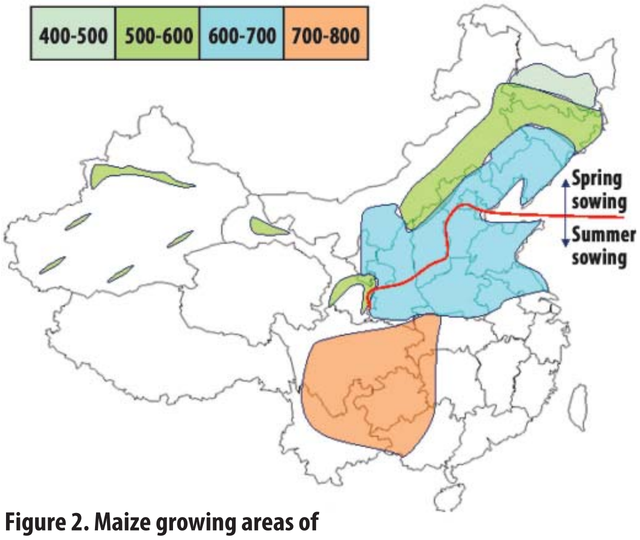

Figure 2. Maize growing areas of China in the FAO index.

Numbers indicate international FAO index of maize earliness.
Source: Limagrain China.

2.1 The northern spring maize region

This region includes Heilongjiang, Jilin, Liaoning, Ningxia and Inner Mongolia, and parts of Shanxi, Hebei, Shaanxi, and Gansu. It is the most important commercial maize producing area in China, comprising around 40% of the national maize area and 44% of the production (Wu, 1997).

The northern spring maize region has a cold, dry winter, with a frost-free period of 130-170 days. The precipitation range is normally 400-800 mm annually, with 60% of that coming in July through September. The northeastern provinces, characterized by level upland plains, fertile soils, suitable weather, and ample sunshine, are suitable for maize growing. Most of the region's crop is dryland, and only one fifth is irrigated.

Maize is sown only once a year in this region due to lower temperatures and shorter frost-free period. There are three major cropping systems: (1) maize alone is planted on more than half of the maize area; (2) maize interplanted with soybean, the predominant system in the northeastern provinces, covers about 40% of the maize area; and (3) maize intercropped with spring wheat emerged and developed in the northern parts of Shaanxi and Shanxi, and in Liaoning, Gansu, and Inner Mongolia after the 1970s; seedbeds are planted with spring wheat, and ridges are used for planted or transplanted maize.

This region includes the northeastern and northern China maize growing areas. The northeastern provinces require moderate or early hybrids, with high yield potential and good tolerance to low temperatures. There is lower incidence of viruses such as sugarcane mosaic virus (SCMV) and maize rough dwarf virus (MRDV), and maydis leaf blight (caused by *Helminthosporium maydis*) in the northeastern provinces than in northern China, where turcicum leaf blight (*Exserohilum turcicum*) and head smut (*Sphacelotheca reiliana*) are severely epidemic. Outbreaks of Asian corn borer (*Ostrinia furnacalis*) cause dramatic yield losses in certain years. Hybrids used in this region must possess some degree of resistance to these disease and pests. The major hybrids include Zhengdan 958, Xianyu 335 (Pioneer 335), Benyu No. 9, Jidan 159, Sidan 19, Jidan 27, Dongdan 60, Suiyu 7, Zhedan 7, CAU108, and Shendan No. 7.

Virus diseases (SCMV and MRDV) and stalk rot (*Fusarium moniliforme*, *F. graminearum*, and *Pythium aphanidermatum*) are severe problems in some provinces of northern China, and hybrids in this region are required to be resistant to them.

Constraints for maize production in northern China include: (1) post-harvest constraints such as insufficient storage, processing, transportation, and marketing facilities due to lack of investment and credit; (2) problems such as early frost, low temperatures, slow grain-filling, and difficult maize dehydration degrade product quality and increase processing and energy costs; (3) insufficient irrigation systems and water resources; (4) insufficient fertilizer use due to lack of balanced fertilization technologies; and (5) lack of new hybrids and of input-saving technologies.

Future strategies for improving maize production aim to increase the maize area and maize yield potential by: (1) developing and/or introducing high performing early maturing hybrids with lodging resistance, adaptation to high population densities, and suitability for management with farm machinery. New hybrids should fill and dehydrate faster, and also possess high quality, drought tolerance, and resistance to head smut, turcicum leaf blight, grey leaf spot, and Asian corn borer; (2) increasing investments in inputs. The average fertilizer application was only 210 kg/ha in the region in 1996. In Heilongjiang Province it was only 126 kg/ha, less than in Tibet. Continuous maize cropping over many years degrades the soil, diminishes fertility, and reduces sustainability. Balanced fertilization would increase yield potential and reduce maize production costs dramatically; (3) disseminating mulching technologies. Mulching is effective for increasing yield and protecting crops from drought stress. The technique was developed and disseminated in Shanxi, Inner Mongolia, and parts of Jilin and Liaoning, an area of over 200,000 hectares. Transplanting techniques and farm machinery are also being introduced; and (4) reforming the grain trading system. It is urgent to broaden the grain trading system and invest in grain storage facilities and oven drying systems to improve grain quality and promote export of grain or grain products from the northeastern provinces. Processing capacity should be increased to stabilize maize production and prices.

2.2 The summer maize region in the Yellow, Huai, and Hai River Valleys

This region covers the middle and lower reaches of the Yellow, Huai, and Hai Rivers, including all of Shandong and Henan, most of Hebei, southern Shanxi, middle Shaanxi, and part of Jiangsu. It is the second largest maize producing region in China, comprising around 33% of the national area and 36% of the production.

This region is located in the subhumid temperate zone; its frost-free season is about 170-220 days, and it receives ample precipitation. Both surface and underground water resources are abundant in the Yellow, Huai, and Hai River Valleys, and about 50% of maize is under irrigation. Temperatures and evaporation capacity are higher, but more than 70% of rainfall occurs in the summer, often causing waterlogging in summer and drought in spring. Disasters caused by windstorms, hail damage, and many diseases are common, and saline-sodic soil is also a stress in this region. The farming system is mainly an annual double cropping rotation. Summer maize, planted after the winter wheat harvest in June, is harvested in late September. Maize and wheat intercropping is also common, i.e., maize is planted around 10 days before the wheat harvest. Intercropping maize and soybean is also common, along with intercropping or mixed cropping with green or red mung beans.

With the maize season restricted by two winter wheat crops, early or intermediate hybrids are required. Epidemics of MRDV and SCMV are common, as are turcicum leaf blight, maydis leaf blight, stalk rots, and leaf spot (caused by *Curvularia lunata*). The demand for hybrids is high, and the predominant hybrids are Zhengdan 958, Xundan 20, Ludan 981, Liaoyu 18, CAU108, Zhongke 4, and Denghai 11.

There is great demand for new hybrids that are suited to intercropping or sequenced cropping and possess high yield potential, disease and lodging resistances, and tolerance to high population densities. However, current commercial hybrids do not satisfy requirements for yield, quality, and disease resistance. Chemical fertilizer supply is sufficient in this region, where the average application is 480 kg/ha. But the multiple cropping index is higher, and the amount of fertilizer used on summer maize was estimated at less than half of the nitrogen, phosphorus, and potassium required to achieve high yields (7.5 tonnes/ha). Adoption of farm machinery for maize in this region is higher than in other regions. Without farm machinery, full-season maize hybrids could not be used in multi-cropping regimes, and would not fully utilize the abundant thermal and light energy during the summer season.

2.3 The southwestern hilly summer maize region

This region includes Sichuan, Chongqing, Yunnan, Guizhou, southern Shaanxi, parts of Guangxi, Hunan, and Gansu, and western Hubei, comprising around 18% of the national maize area and producing 13% of national production.

Almost 90% of the arable land lies in hilly or mountainous areas or highlands, 200-4,000 m above sea level (masl), necessitating the vertical distribution of crops. Plain basins account for only 5% of the arable land. This region is temperate, with subtropical wet or sub-humid climate and adequate rainfall and thermal energy, but poor light resources. The frost-free period is usually 240-330 days per year, and the maize crop season usually lasts 150-180 days. Precipitation is 800-1,200 mm annually, and most of the rainfall comes from April through October. Overcast and rainy weather is common, with more than 200 days annually. Spring and summer drought is frequent. Disease and insect infestations are very complex, and epidemics are frequent. In the highlands, the soil is infertile, and yields are lower.

There are three primary cropping regimes in this region. Wheat-maize-sweet potato, a three crop interplanting system, is common in the hilly dry areas. Spring maize is planted between the wheat rows 35-40 days before the winter wheat crop (spring wheat, planted in winter) is harvested, and sweet potato is transplanted between the maize once the wheat has been harvested. Wheat or potato can be inter-planted with maize in the cooler mountainous areas (above 800 masl), where the growing season is longer than needed for one crop, but not sufficient for two crops per year. In Yunnan Province, maize can be rotated with tobacco, pepper, and soybean, but single season maize is also common.

Hybrids in this region must be adapted to many complex diseases and pest infestations, including turcicum leaf blight, maydis leaf blight, stalk rots, grey leaf spot, virus diseases (SCMV, MRDV), rust (*Puccinia sorghii*), banded leaf and sheath blight (BLSB) (caused by *Rhizoctonia solani* f. sp. *sasaki*; *R. microsclerotia*), downy mildew (*Peronosclerospora maydis*), aflatoxin (*Aspergillus flavus*), fall army worm (*Pseudaletia unipuncta*), and Asian corn borer (*Ostrinia furnacalis*). Popular hybrids include Chengdan 14, Chuandan No. 9, Yayu No. 2, Luyu 13, Dekalb 007, Chengdan 13, and Miandan No. 1, but improved open-pollinated varieties (OPVs) and top-cross hybrids are also preferred in some mountainous areas.

Maize production could be improved by: (1) extending the area planted to hybrids. Only half of the area in this region is sown to hybrids, partly because not many hybrids are adapted to the particular stresses of the region. This region is the center for maize diversity in China, and breeders should exploit the native germplasm to develop well adapted hybrids. Improved OPVs, synthetics, and populations should continue to be disseminated in the poor mountainous areas where growing conditions are particularly harsh; and (2) continuing to disseminate throughout the region mulching and seedling transplanting techniques that increase yield by an average 30-50%.

2.4 The southern China winter maize region

This region includes Guangdong, Hainan, Fujian, Zhejiang, Jiangxi, and Taiwan; the southern parts of Jiangsu and Anhui; and the eastern parts of Guangxi, Hunan, and Hubei. It is the principal rice producing region in China, and the area sown to maize is small, about 700,000 ha, or 3.2% of the country's total area, producing 2.2% of the total output (Wu, 1997).

This tropical or subtropical humid zone has higher temperatures, high precipitation, and a crop season of 220-360 days. Annual precipitation is 1,000-1,800 mm and relatively uniformly distributed. The cumulative sunshine is 1,600-2,500 hours, and maize can be grown in any season, but the area is low-lying and production unstable. Geographical and climatic conditions are most favorable for paddy rice growing, but also suitable for fall or winter maize production.

Multi-cropping regimes have historically been the norm in this region. Maize is usually grown as a fall or winter crop. Fall maize is usually grown as the third season crop in three-crop regimes in Zhejiang, Jiangxi, and in parts of Hunan and Guangxi. It functions as a rotation between paddy and highland crops. Winter maize is predominant in Hainan, Guangdong, Guangxi, and southern Fujian. Maize seeding and transplanting techniques are advanced in this region. For instance, in Zhejiang, Jiangxi, and Hunan, fall maize seedlings are usually cultivated in a culture pan or nutritive pot and then transplanted into the field after midseason rice is harvested. This technique has been shown to increase maize yields significantly.

The area sown to subtropical maize hybrids is small, and the winter maize hybrids that are predominant elsewhere need special traits tailored to the region, including early maturity, cold tolerance, and resistance to diseases and pests such as stalk rots, rust, and BLSB. The dominant hybrids are Guiding No. 1 (top cross), Zhengda 619, Yayu No. 2, and Yundan No. 1.

The southern provinces are the principal consumers of maize products, but must transport a vast volume of maize from the northern provinces or import it from abroad. Many farmers have to feed rice to their animals or poultry, which is not ideal for the animals and also leads to reduced profits. Increased fall and winter maize production would help to meet the demand for cereal crops in the region and promote sustainable agricultural development.

Five methods are recommended for increasing maize production: (1) exploiting the fallow land in winter. At least 12 million hectares of dryland in the southern provinces are currently not being used effectively, even though more than half of it is suitable for maize production. Maize production could be promoted by modifying the cropping regimes, increasing the cropping index, and further developing intercropping and multi-planting techniques. Advanced cultivation techniques, such as maintaining high population densities, using maize seedling and transplanting methods, and using maize residue as cattle feed, should be employed to improve outputs from arid, uncultivated land; (2) rotating paddy and highland crops. Improved cropping regimes have been disseminated throughout Hunan and Hubei. The dominant regime is a rotation of spring maize, second season or early season rice, and summer maize for a total maize harvest of 6.0-7.5 tonnes and a harvest of all three crops of more than 15 tonnes/ha. This technique has also been tested and proven successful in Guangdong, Jiangxi, and Fujian; (3) intercropping regimes; maize is usually inter-planted with sweet potato, peanuts, and legumes, which still produces the 3-4 tonnes/ha of maize that would be achieved without inter-planting; (4) using mulching techniques, which can increase maize yields by 30-50% in cool mountainous areas; and (5) disseminating new, adapted elite hybrids. Hybrids from the north are not adapted to conditions in the southern hilly drylands, not ideal for intercropping, and not sufficiently stress tolerant. Increasing fertilizer supply and application and the use of improved cropping techniques would also help to increase yields in the winter maize production zone.

2.5 The northwestern irrigated spring maize region

This region includes Xinjiang, the western corridor of the Yellow River in Gansu, and the Yellow River Valley in Ningxia. It is arid with a continental climate, and annual precipitation is low. The maize area has been increasing since the 1970s, when irrigation systems were developed. Maize now covers about 700,000 ha, i.e., 3% of the national maize area (Wu, 1997).

The frost-free period is 130-180 days, sunshine is sufficient (about 2,600-3,200 hours annually), and the cumulative temperature above 0°C is 3,000-4,100°C with 2,500-2,600 effective growth degree-days (GDD) throughout the region. In general, the abundant thermal resources and wider range of daytime temperatures favor the development of maize plants, and contribute to high performance and good grain quality in the western provinces. As precipitation is less than 200 mm annually, crop production relies upon advanced irrigation systems and thawing snow. Yield potential is very high, and the predominant cropping regime is one crop of spring maize annually, and some intercropping of wheat and maize.

Because of the dry weather and wide range of daytime temperatures, disease and pest infestations are infrequent, but drought is the overwhelming problem. This region requires hybrids with very high yield potential, tolerance to high population densities, drought tolerance, and resistance to head smut. The predominant hybrids are Zhongdan No. 2, SC704, Shendan 16, Shendan 10, Yudan 8702, and Jingzao No. 8.

Maize intercropped with wheat can yield as much as 7.5-9.0 tonnes/ha of maize in the irrigated lands of the western corridor of the Yellow River in Gansu and Ningxia. A record maize yield was achieved in Xinjiang: 15.47 t/ha over 73.6 hectares. Insufficient supply and use of fertilizer and other inputs are limiting factors for maize production. Also, water-efficient management technologies must be developed to achieve a sustainable agricultural system.

3 Biotic and abiotic stresses

3.1 Biotic stresses

In the 1950s, the dominant diseases were corn smut, turcicum leaf blight, and stalk rot (*Fusarium moniliforme*), but the losses they caused were relatively low. By the time hybrids began to be widely disseminated, the maize area had increased, and disease epidemics were on the rise. Currently, the predominant diseases are virus diseases, head smut, stalk rot, turcicum leaf blight, maydis leaf blight, and ear rot. Some of these diseases have been controlled with the release of resistant hybrids, but new diseases, such as grey spot (caused by *Cercospora zeae-maydis*), southern rust, BLSB, and leaf spot (*Curvularia lunata*), are now becoming problematic.

Virus diseases such as SCMV and MRDV have caused severe losses during the past decade, due to the adoption of susceptible inbred lines and commercial hybrids. SCMV often occurs in Hebei, Beijing, Shanxi, Liaoning, Gansu, and Sichuan. The popular commercial inbred lines Mo17, Ye 107, and Shen 5003 are susceptible to virus diseases. MRDV is endemic in Shandong, Anhui, Shanxi, Hebei, Shaanxi, and Henan, where it generally causes yield losses of 10-15%, although it has been known to cause yield losses higher than 40%. Ye 107 and Ye 478 are typical susceptible lines. Breeders have developed a series of resistant lines, including Qi 319, X178, P138, CN 165, and Shen 136, that contain tropical germplasm in their pedigrees. These lines have been used commercially in northern China.

Stalk rot is usually caused by *Fusarium moniliforme*, but can also be caused by *Pythium aphanidermatum*, sometimes in tandem with *Fusarium*. Yield losses due to stalk rot may reach 10-15%. *Fusarium moniliforme* and *Pythium aphanidermatum* cause severe lodging at the late growth stage, drastically reducing yields. Breeders have developed and released for commercial use a series of resistant lines, including Qi 319, P138, X178, and Shen 137.

Turcicum leaf blight is usually endemic under humid, cool temperatures, whereas maydis leaf blight occurs in the south or in summer maize areas where temperatures are higher. In 1966, there was a turcicum leaf blight epidemic that caused severe yield losses. Since then, breeders have developed a series of resistant lines and released a number of resistant hybrids to replace susceptible hybrids (Li, 1988). Turcicum leaf blight struck again in some provinces in 1993 due to the adoption of susceptible lines and hybrids, but in general, turcicum and maydis leaf blights have been controlled by the release of resistant germplasm.

In the 1970s, head smut was a severe problem in the northeastern and northern spring maize region. It was controlled with the release of resistant hybrids Zhongdan No. 2 and Danyu 13. However, in recent years, head smut is increasing again in the northeastern provinces due to continuous maize cropping over many years and the use of new susceptible lines and commercial hybrids.

New diseases, including ear rots caused by *Fusarium moniliforme, Diplodia maydis*, and *Gibberella zeae*, maize rust, BLSB, grey spot, and leaf spot, have been affecting maize crops since the 1990s. They have caused severe yield losses in some regions and have spread to other maize growing areas.

Ear rots occur in areas with high rainfall; full-season hybrids are particularly affected. Sichuan, Yunnan, Liaoning, and Beijing have all suffered ear rot epidemics. Common or southern rust has struck the southern provinces and has spread north. The summer maize region in Shandong has experienced very severe rust epidemics in recent years; BLSB is endemic in Sichuan, Guangxi, Yunnan, and Guizhou, and less common in the northern provinces. Resistance to BLSB has not been identified. Grey spot is endemic in Liaoning, Jilin, and Yunnan where the weather is cool. Leaf blight has affected Beijing and areas with higher temperatures, spreading to northern and northeastern China. Aflatoxin (due to the presence of *Aspergillus flavus)* is a problem in the hot, humid environments of southern China. This fungus endangers maize in the field as well as in storage.

3.2 Maize pests

The Asian corn borer attacks maize most often in the northeastern provinces and then spreads to northern China and the southern provinces. In normal years, the Asian corn borer causes 7-10% yield losses,but once every 8-10 years severe infestations occur, causing up to 20% yield losses. The European corn borer (*Ostrinia nubilalis*) has been reported in Xinjiang.

Soil insects damage emerging seedlings and severely reduce field populations. The major soil insects are mole crickets (*Gryllotalpa unispina*, *G. africana*, and other *Gryllotalpa* species), wire worms (*Pleonomus canaliculatus, Agriotes subvittatus, Melanotus brannipes*), and cutworms (*Agrotis ipsilon*, *A. segetum*, *A. tokionis*). Sometimes lamellicorn beetles (*Holotrichia* spp., *Anomala corpulenta, Pentodon mongolicus*, *Trematodes tenebrioidec*) damage maize seedlings. The fall army worm (*Mythimna separata*) infests maize after silking. Insecticides are available to protect seeds from damage by soil pests, as well as corn borer and army worm, but resistant hybrids are a more effective preventive measure.

3.3 Abiotic stresses

Almost 70% of China's maize area is located in rainfed regions without reliable irrigation systems. Severe drought has caused yield losses of 20-50%, and entire crops have been lost in some years. At the provincial level, Shaanxi showed the highest yield losses (-31.8%), then Gansu (-31.3%), Liaoning (-30.9%), Jilin (-27.3%), Shandong (-25.8%), Shanxi (-22.2%), and Inner Mongolia (-21.3%). The extent of yield losses was moderate in Heilongjiang (-15.5%) and Henan (-14.3%). Efforts to minimize yield losses due to drought include the development of water-conserving methods, improved cropping systems, and drought tolerant hybrids.

Some 60% of the maize area is in the hilly and mountainous areas where infertile, acidic red loam soils limit maize production. Average fertilizer rates are quite low, especially in terms of balancing N, P, and K. Increased use of fertilizer supplements and the development of hybrids tolerant to low nitrogen and acidic soils have great potential for raising maize yields. Maize breeding research should continue to produce germplasm that is resistant/tolerant to a variety of stresses, including drought, diseases and pests, and infertile soils.

4. Progress on hybrid development and utilization

4.1 Development of hybrids

Based on the rich maize germplasm available in China (Li et al., 2002c; Yu et al., 2007), three types of maize breeding lines were characterized: open-pollinated varieties (OPVs), double-cross hybrids, and single-cross hybrids (Li, 1998). As indicated in Figure 3, these materials have contributed significantly to yield improvement.

From 1950 to 1961, all maize cultivars were OPVs, landraces, or improved OPVs. Predominant varieties in northern China were Golden Queen, White Dent, Huanong No. 2, Yinglizi (Shanxi), Hongguzi (Red Cob, Liaoning), Xiaolihong (Small Red Kernel, Shandong), Xiaojinli (Small Golden Kernel, Henan), and Yejihong (Red Pheasant, Shaanxi). Some variety-hybrids were developed, such as Fangza No. 2 (Shandong), Chunza No. 2 (northern China), Baiza No. 6 (Henan) and Changza No. 4 (Shanxi), but the areas planted to them were very samll, and they were soon replaced by double-cross hybrids. The national maize area initially increased 51.3%, from 11.7 million hectares in 1950 to 17.7 million ha in 1956. It then declined to 13 million ha with introduction of the cooperative system. During this period, yield gains were small, averaging 13.9 kg/ha/year.

After 1955, scientists in China led by Prof. Li Jingxiong introduced, developed, and tested inbred hybrids. The government promoted the dissemination of doublecross hybrids, which led to improvement of agronomic techniques, increased population densities, and fertilizer use. Yield gains

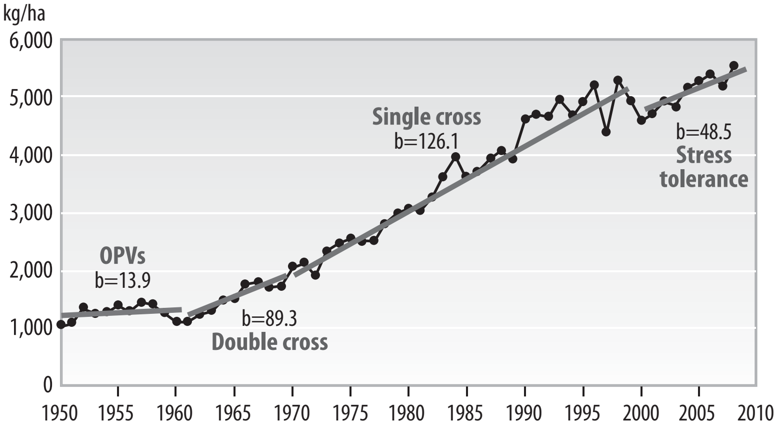

Figure 3. Maize yield gains as a result of hybrid adoption, 1950-2008.

averaged 89 kg/ha/year from 1961 to 1970 as a result of these improvements. Chinese double-cross hybrids were developed over three periods.

During the first (1960-1963), American hybrids US 13, Wisc 641, OK 24, and Iowa 4316 were introduced. During the second (1962-1966), Russian hybrids Вир 42 and Вир 156 were introduced and disseminated. The third (1964-1968) saw the introduction of Romanian hybrids HD 311, HD 405, and HD 409. The government organized scientists from 20 provinces to reproduce the parental lines of these hybrids in a winter nursery on Hainan Island. The resulting hybrids were all susceptible to turcicum leaf blight and destroyed by the disease. Hybrids resistant to turcicum and maydis leaf blights and head smut were not developed until 1970. New single-cross hybrids such as disease resistant Zhongdan No. 2 and Danyu No. 6 were then released. These new single-cross hybrids were not only disease resistant but also adapted to many provinces, and they soon became the predominant hybrids throughout the country. Since then, maize has not been attacked by large-scale disease epidemics.

The predominant hybrids in the second period (1961-1970) included BAU No. 4, Chungza 12, Xinshuang No. 1, Вир 42, and Вир 156. During that time, the maize area increased to 16 million ha, and total production increased as well. Single-cross hybrids performed well and were disseminated very quickly after 1971. Yield gains peaked at an annual rate of 126 kg/ha from 1971 through 1995, and those kinds of yields gains are still common. The maize area increased from 16 to 24 million ha and output increased threefold. The elite hybrids of the earliest periods were Xindan No. 1, Baidan No. 4, Qundan 105, Danyu No. 6, Zhengdan No. 2, and Jidan 101. Most predominant over the past three decades were Zhongdan No. 2, Danyu 13, Yedan No. 2, Yedan 13, Huang 417 (including Yandan 14 and Hudan No. 1), Benyu No. 9, CAU108, Zhengdan 958, and Pioneer 335.

At present, Zhengdan 958, developed by the Henan Academy of Agricultural Sciences, is the leading hybrid in China, covering around 5 million ha per year. These hybrids are multi-disease resistant, drought tolerant, early maturing, and adapted to a number of provinces and ecological regions. A number of elite inbred lines were also developed, such as Huangzao 4 by breeders at the Chinese Academy of Agricultural Sciences (CAAS), Zi 330 and Dan 340 by the Dandong Institute, Liaoning Academy of Agricultural Sciences, U8112 and Ye 478 by the Denghai Seed Group, and Shen 5003 by the Shenyang Agricultural Research Institute in Liaoning. Mo17 was the most widely used exotic inbred line in China until the release of Pioneer 335 and Lic 016. The other recent trend contributing to the high yields and good lodging resistance of modern Chinese hybrids was to use much higher plant densities than in the past.

After 1995, yield gains from maize improvement slowed to 48.5 kg/ha annually. It is recognized that the population density in maize production remains as low as 52,500 plants per ha, and that stress tolerance has been ignored during inbred line and hybrid development. However, breeders have modified their breeding objectives and strategies, and are now emphasizing stress tolerance under higher population densities in their breeding programs.

Hybrids increased yields dramatically, but a shortage of germplasm has resulted in some negative traits in the hybrids. Peng and Chen (1993) showed that five hybrids, Yedan 13, Danyu 13, Zhongdan No. 2, Yedan No. 2, and Yedan 12, covered 53% of the total maize area planted to hybrids. More than 61% of the total maize area relies heavily on five inbred lines: Mo17, Ye 478, Huangzao 4, Dan 340, and E28. A larger gene pool from which to derive hybrids would ensure a wider range of genetic variation to meet the challenges posed by pathogens and to withstand abiotic stresses such as drought, waterlogging, and heat. Because the narrow genetic base has reduced the probability of exploiting heterosis and enhancing stress tolerance, it will be difficult to further raise yield potential without new germplasm in the various heterotic groups and patterns in maize breeding programs.

In 1996, CAAS initiated an important national research project for maize germplasm enhancement, improvement, and development. The project was designed to introduce and improve both exotic and local germplasm in order to broaden the breeding base of maize programs, enhance the use of heterosis, and increase the yields of new hybrids. Heterotic groups and patterns among the introduced tropical, subtropical, and temperate germplasm were analyzed. Using exotic germplasm from CIMMYT, an evolutionary improvement scheme was designed for gradual adaptation of tropical and subtropical gene pools, populations, and synthetics from south to north. This is a national prebreeding activity, and will form the basis of a modern maize breeding program in the coming decades (Zhang et al., 1995, 1998).

4.2 Heterotic groups and patterns used in Chinese maize breeding

The application of heterosis in crop breeding is the most important contribution of plant genetics to the development of agricultural technology in the last century. Heterosis depends on the genetic background of parents, and is related to the lines' general combining ability (GCA) and the specific combining ability (SCA) between parents. Two groups of maize germplasm used in the U.S. Corn Belt were generalized as Reid and Lancaster germplasm. Significant heterosis was found between the groups, and heterotic patterns between Reid and non-Reid germplasm were established.

A heterotic pattern between U.S. dent×European flint maize was established in Europe based on geographic origin and kernel type. Some developing countries in tropical areas established potential patterns, such as Tuxpeno×ETO, Tuson×Tuxpeno, Cuba flint×Tuxpeno, and Suwan 1×Tuxpeno (Vasal et al., 1999).

Maize breeders in China have tried to exploit heterotic groups and patterns in the course of hybrid maize development and dissemination. Research on heterotic grouping was initiated in the late 1980s, as documented by Peng et al. (1998) and Wang et al. (1997).

Strategy adopted in heterotic grouping analysis. Since at least five potential heterotic groups have been observed in China (Peng et al., 1998; Wang et al., 1997), the strategy proposed for heterotic grouping analysis involves three steps: (1) diallel analysis to classify 15 selected typical inbreds with clearly different pedigrees into a few groups, and to distinguish the common testers; (2) design II to classify more inbreds based on SCA data with the common testers identified in (1); and (3) molecular marker technology to group many inbred lines, and lines with high frequencies of common alleles considered as belonging to the same group.

Heterotic groups and patterns predominant in China. Based on SCA data from diallel analysis, Peng et al. (1998) divided 15 predominant lines into 5 clusters: Sipingtou, Luda Red Cob, BSSS, PA, and Lancaster. RAPD data confirmed these results. Yuan et al. (2000b) tested the same set of inbred lines with RFLP, SSR, and AFLP primers, and confirmed the results. The RFLPs and SSRs showed that the genetic distance (GD) between the Sipingtou and Luda Red Cob sub-groups was short; therefore they were incorporated into one group called domestic (*Dom*.). The GD between the BSSS and PA sub-groups was also short, and they were established as group A. These groupings were consistent with breeders' experience.

This work was extended to 29 inbred lines using RFLP and SSR (Yuan et al., 2000a). Yuan et al. (2000a) and Peng et al. (1998) reported there were at least three groups among inbred lines used in China, and distinguished five common testers for the five sub-groups, respectively. The testers were Huangzao 4 for Sipingtou, Dan 340 for Luda Red Cob, Mo17 for Lancaster, B73 for BSSS, and Ye 478 for the PA sub-groups.

Maize breeders developed a number of new lines based on American hybrids, and as a result, a new sub-group is emerging. This germplasm had very good resistance to virus diseases, southern rust, stalk rot, and other foliar diseases, as well as good drought tolerance. It gave strong heterosis with the Sipingtou and PA sub-groups. This new sub-group, named the PB sub-group, was close to non-Reid germplasm.

Heterotic Group	Sub-group	Common Tester
D *(Dom)*	Sipingtou	Huangzao 4
	Luda Red Cob	Dan 340
A (Reid)	SS	B73
	PA	Ye 478
B (non-Reid)	Lancaster (NSS)	Mo17
	PB	Qi 319

Most maize breeders tend to exploit two heterotic patterns. The first is *Dom*×Lan, which expresses as two models. Late-maturing Luda Red Cob×Lan is used in the spring maize area in northern or northeastern China. Typical hybrids are Danyu 13 (E28×Mo17) and Zhongdan No. 2 (Mo17×Zi330). Sipingtou×Lan is early maturing, and an important model in the northeastern provinces and part of the summer maize area. Huangzao 4×Mo17 is a typical hybrid. Another pattern available in the summer maize area is *Dom*×PA, which expresses as two models: one is PA×Sipingtou, and typical hybrids are Zhengdan 958 (Zheng58×Chang7-2), and an older hybrid, Yedan No. 4 (U8112×Huangzao 4). The other is Luda Red Cob×PA, and a typical hybrid is Yedan 13 (Ye 478×Dan 340). A lot of recycled lines and hybrids based on this pattern are used in commercial maize production.

Pattern	Model	Typical hybrid
D×*B*	Luda Red Cob×Lan	Mo17×Zi 330 (Zhongdan No. 2) E28×Mo17 (Danyu 13)
	Sipingtou×Lan	Huangzao 4×Mo17 Ji 853×Mo 17 (Jidan 180)
A×*D*	PA×Sipingtou	Zheng 58×Chang 7-2 (Zhengdan 958)
	PA×Luda Red Cob	Ye 478×Dan 340 (Yedan 13)

New patterns between A×B are becoming available with the development and dissemination of PB germplasm. A typical hybrid is CAU108 (HC×178). Another new line of PB germplasm, Qi 319, is being disseminated throughout the country. This germplasm will promote the adoption of A×B and *A×D* patterns. The heterotic patterns of predominant hybrids in China are presented in Table 3.

Table 3. Heterotic patterns of predominant hybrids sown in China.

Hybrid	Combination	Heterotic pattern	Heterotic pattern type
Zhongdan No. 2	Zi 330×Mo17	Luda Red Cob×Lan	*D*×*B*
Danyu 13	E28×Mo17	Luda Red Cob×Lan	*D*×*B*
Yandan 14	Huangzao 4×Mo17	Sipingtou×Lan	*D*×*B*
Ludan 981	Qi 319×LX9801	PB×Sipingtou	*B*×*D*
Shendan No. 7	Shen 5003×E28	PA×Luda Red Cob	*A*×*D*
Yedan 13	Ye 478×Dan 340	PA×Luda Red Cob	*A*×*D*
Yedan No. 2	Ye 107×Huangzao 4	PA×Sipingtou	*A*×*D*
Yedan No. 4	U8112×Huangzao 4	PA×Sipingtou	*A*×*D*
CAU108	HC×X178	A×PB	*A*×*B*
Zhengdan 958	Z58×C7-2	PA×Sipingtou	*A*×*D*
Pioneer 335	PH6WC×PH4CV	SS×NSS	*A*×*B*

Heterotic patterns and technology for developing inbred lines. Maize breeders have been trying to exploit heterotic patterns to facilitate development of inbred lines and hybrids. Yuan et al. (2000a) have argued that Sipingtou and Luda Red Cob can be incorporated into one group, called *Dom*. The Denghai Seed Group located in Shandong Province derived a recycled line, Ye 502, from the combination Huangzao 4×Dan 340 (Sipingtou×Luda Red Cob), and then derived a series of modified lines from it. A number of hybrids used in the summer maize area were developed from Ye 502 and its derivatives.

Breeders' experience has shown that new lines can be derived from crosses between sub-groups within the same heterotic group, and that it is more efficient to develop hybrids between groups. For example, good lines were derived from Sipingtou×Luda Red Cob, and also from crosses between the SS and PA sub-groups. Good hybrids can be developed from *Dom*×Lan, such as Luda Red Cob×Lan or Sipingtou×Lan in the spring maize area, and also from PA×*Dom*.

Heterotic patterns and technology for germplasm improvement. Maize breeders have been developing and improving populations using recurrent selection procedures since 1978, but only a few lines have been derived from the improved populations. The chaotic germplasm background makes it difficult to derive elite lines from the populations. The base populations should be comprised of germplasm from the same or closely related sub-groups. The heterotic responses of the germplasm should then be assessed.

Heterotic groups are complex, and at least six common testers have been identified in China. We have tried to simplify the main heterotic groups used in commercial maize production, especially when tropical and subtropical germplasm has been used in temperate maize breeding programs. Heterotic patterns also need to be simplified.

The technology used for population improvement is influenced by heterotic patterns. Reciprocal recurrent selection (RRS) in inter-population crosses will replace selection in intra-population crosses, such as modified ear-to-row, half-sib, full-sib, S1 or S2 selections, although these methods played an important role in increasing GCA in the early stages of germplasm improvement. The purpose of population improvement is to derive new lines with greater combining ability and, ultimately, to produce superior hybrids. As a basis of hybrid development, intra-population germplasm improvement is not enough for SCA, and inter-population RRS is necessary for developing elite lines and hybrids.

Maize breeders have developed a number of populations and synthetics, but the history of most of them is chaotic, and heterotic patterns among them have not been established. It is recommended that RRS should be used in hybrid maize breeding. Combining ability analysis is urgently needed to evaluate the potential of many populations, synthetics, and OPVs in hybrid maize breeding programs.

Heterotic patterns and germplasm enhancement. A prebreeding project for maize germplasm enhancement, improvement, and development financed by the Ministry of Agriculture was initiated in 1996. Pools and populations from CIMMYT and other sources were introduced to broaden the genetic base of hybrid maize breeding, and to develop new lines with greater combining ability and hybrids with superior performance and good resistance to biotic and abiotic stresses (Zhang et al., 1998; Li et al., 2005).

The heterotic reactions among populations were tested with quantitative genetic technology. Design II was adopted for producing crosses between 27 populations (14 from CIMMYT, and 13 domestic) and 4 common testers (Huangzao 4, Dan 340, Ye 478, and Mo17). Evaluation trials were conducted at five sites in 2001 and eight sites in 2002. Semi-exotic composites were produced based on the heterotic groups among populations. A group of CAAS maize breeders did not produce composites between domestic and exotic germplasm until genetic diversity analyses were performed.

Chinese scientists should try to improve elite local germplasm such as Luda Red Cob, Sipingtou, and Golden Queen, and evaluate heterotic groups and patterns in cross combinations. Composites and/or populations between exotics and adapted germplasm in northern China have to be developed before heterotic patterns can be used to strengthen hybrid maize breeding efforts in that region.

More than 20 tropical and subtropical germplasms were improved under temperate day-length conditions using the bi-parental mass selection method to improve adaptation with little loss of genetic diversity. The use of semi-exotic germplasm is another approach to utilizing tropical germplasm in temperate areas. Tropical inbred lines were crossed with domestic lines based on heterotic patterns. The improved semi-exotics were released to breeders after one season of selfing and at least two cycles of bulk pollination. In this way, we are trying to broaden the genetic diversity used in hybrid maize breeding in China.

4.3 Progress in breeding specialty corn

The lysine content in normal maize kernels is approximately 0.23%, but animal diets require 0.6%-0.8%. The deficit is usually covered by adding lysine, bean meal (oilseed residue), or fish meal to animal feed. However, available amounts of these supplements are not enough to support the development of the feed and livestock industries in China. A solution to this problem could be quality protein maize (QPM), which has lysine and tryptophan contents as high as 0.35-0.40%. Animals such as pigs gain weight much faster and grow much larger when fed QPM as opposed to normal maize. China's QPM breeding project, also part of the national initiative, has been led by Prof. Li Jingxiong since it began in 1973. Although CAAS and China Agricultural University (CAU) worked collaboratively with the Shandong, Sichuan, Xinjiang, Guizhou, and Yunnan academies of agricultural sciences to develop a number of QPM hybrids, most of them did not perform well and were not widely adopted. Shandong AAS developed an elite QPM line, Qi 205, which promoted QPM development and improved hybrid performance. CAAS also derived a series of QPM lines from improved subtropical germplasm from CIMMYT. CA335, CA339, and CA375 are important QPM lines; CA375 was crossed with Qi 205 to produce Zhongdan 9409, a good QPM hybrid that gives high yields while retaining its high lysine content. Zhongdan 9409 and other QPM hybrids established a QPM heterotic pattern that occurs in Qi 205×CA375 and G14×G13. This knowledge will facilitate future QPM breeding efforts.

The government has encouraged research on maize with high oil content, and a series of inbred lines and hybrids with good performance have been developed. CAU introduced high oil maize synthetics from the USA and then developed their own high oil maize synthetics based on Chinese germplasm. A series of high oil maize inbred lines and hybrids with good performance were developed. The oil content of these hybrids is 5-8% higher than that of normal maize, and their disease and lodging resistances are also much improved.

Maize breeding activities and priorities have changed and diversified with the development of China's economy over the last decade. Breeding research increased, and the sweet corn and waxy maize processing industry has developed rapidly. Shanghai AAS, Huanan Agricultural University (South China AU), the Genetics Institute of the Chinese Academy of Sciences (CAS), Guangdong AAS, and the Zhejiang Maize Institute all work on breeding sweet corn and have released a number of hybrids, including normal sweet (susu), improved sweet (aeae susu), and super sweet (btbt) genotypes. Typical sweet corn hybrids include Tianyu No. 4 and Tianyu No. 6 (CAAS), the Ketian series (CAS), and the Yuetian series. CAAS, Jiangsu AAS, Shanxi AAS, and Beijing AAS, developed and released a number of waxy corn hybrids, such as the white grain hybrids Zhongnuo No. 1 (CAAS) and Suyunuo No. 1 (Jiangsu AAS). CAAS and Shenyang AU also develop and produce popcorn hybrids, but the market for this product is still small due to the lack of modern processing facilities.

5. Maize biotechnology research

China is interested in the application of biotechnology in agricultural production. Modern science and technology have been the catalysts of China's economic development over the last 50 years, and will help meet the challenge of producing enough food for the 1.6 million people who will live in China in the near future. The government has invested significantly in biotechnology research, as indicated by the increasing number of research staff from 1986 to 2005 (Table 4), a period when funds for conventional plant breeding programs has declined.

Table 4. Numbers of high level researchers involved in plant biotechnology in China since 1986.

Year	Staff
1986	740
1990	1,067
1995	1,447
2000	2,128
2005	5,200

Source: MOST, AgBioforum.

Biotechnology research in China focuses mainly on transgenics, tissue culture (including dihaploidization), and transfers to breeding materials, with increasing emphasis on gene cloning, modification, and chemosynthesis. Transgenic research, in particular, is attractive to scientists and policy makers alike (Wang et al., 2001; Li et al., 2001), but progress is limited due to the lack of efficient transformation systems and the shortage of cloned genes.

A number of scientists and breeders are already working on molecular-marker assisted selection and other methods that combine biotechnology with conventional breeding, with the purpose of accelerating the plant breeding process and reducing input use. Critical to plant breeding is identifying desirable genotypes by linking them to phenotypes, but many of the current techniques for identifying desirable phenotypes are unreliable, costly, and influenced by the environment. For example, the techniques used for identifying drought tolerance, pest resistance, and certain quality characteristics are not very accurate, but certainly very expensive. Molecular technologies should identify desirable traits and genes more reliably, with significant savings in costs and labor. Marker-assisted selection is also environmentally friendly.

Maize biotechnology research in China is currently focusing on the following areas: (1) heterotic groupings of maize germplasm and inheritance of heterosis (Yuan et al., 2000a, b; Liu et al., 2002; Li et al., 2002b, c; Fan et al., 2004; Xie et al., 2007); (2) gene mapping of resistance to the main virus diseases of maize in China, SCMV and MRDV (Wu et al., 2002); (3) inheritance and gene mapping of resistance to head smut, BLSB, stalk rots, rust, and ear rots, and marker-assisted selection strategies (Chen et al., 2008) for transferring superior traits to breeding lines; (4) gene and QTL mapping for drought tolerance (Qin et al., 2003; Li et al., 2007; Zheng et al., 2009); (5) transgenic research for herbicide resistance (Li et al., 2002a); and (6) resistance/tolerance to other biotic and abiotic stresses (Wang et al., 2003; Yin et al., 2003; Xiao et al., 2007; Zhou et al., 2007).

Institutions involved in maize biotechnology research include China Agricultural University, the Center for Biotechnology Research (CAAS), Crop Science Institute (CAAS), Genetics Institute (CAS), Institute of Botany (CAS), Central China Agricultural University in Hubei Province, and other universities. A few provincial academies of agricultural science and private companies have also established biotechnology laboratories.

In December, 2009, China released its first genetically modified (GM) maize carrying a modified phytase gene. This was the result of cooperation between CAAS and Origin Agritech Ltd. Further developments with other genes, including the *Bt* gene for insect control, are expected in the next few years.

6. Other key factors affecting maize breeding and production

Three factors are beginning to have a strong impact on maize breeding and will become increasingly important in the future. First, cereal genomics is currently undergoing a revolution. After 2005, the completion of the rice genome sequence radically changed how scientists and breeders approach challenges in rice genetic improvement. Having a high-quality reference sequence of rice led to many genetic discoveries that should improve the efficiency of rice selection and breeding, and synteny between the rice and maize genomes provides new perspectives for maize, especially following the recent publication of the B73 inbred maize sequence (Schnable et al., 2009) and new developments in bioinformatics. New gene shuttle research between maize, rice, and other cereals will soon be a routine activity. Future maize geneticists will have to become cereal geneticists. However, there are two remaining bottlenecks that still challenge scientists and breeders: (1) high-quality routine trait phenotyping to link sequences to phenotypes; and (2) new IT tools and specialists to process genetic data and transform them into formats suitable for breeders.

Second, changes in climatic variability will definitely affect China, and especially northern China, in the next century (Wu and Wang, 1999). The entire maize scientific community will have to deal with the consequences of water scarcity, higher, more variable temperatures, and changing biotic stresses.

Third, maize used for feed currently accounts for more than 65% of the total production; 40 to 45% of that amount is fed directly to livestock and poultry with tremendous amounts of waste. Given the rapidly increasing meat and milk consumption in China, increasing amounts of maize grain, cobs, and possibly stalks will be processed into more digestible formulated products. In addition, the processing industries will use increasing amounts of maize to produce starch, alcohol, sugar, maize oil, glutamate, xylitol, and other derived products. While China is the second most important producer of this cereal globally (after the USA), its maize processing industry, although growing rapidly, still lags far behind those of North America and Europe. There are many maize processing enterprises in China, but few are large-scale operations capable of competing at the international level. Hence, downsizing to a lower number of more efficient enterprises is likely. These will probably also encompass other emerging applications in medicine (mannitol), industry (biodegradable plastics), and energy production (alcohol).

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References

Chen, Y.S., Chao, Q., Tan, G.P., Zhao, J., Zhang, M.J., Ji, Q., and Xu, M.L. 2008. Identification and fine-mapping of a major QTL conferring resistance against head smut in maize. Theoretical and Applied Genetics 117: 1241-1252.

Fan, X.M., Tan, J., Li, M.S., Yang, J.Y., and Chen, H.M. 2004. Genetic diversity of Chinese temperate and exotic tropical, subtropical quality protein maize inbreds by SSR markers. Agricultural Sciences in China 3(2): 94-100.

Li, J.X. 1988. Hybrid maize breeding in China. Proceedings of the Third Asian Regional Maize Workshop, Kunming and Nanning, China. pp. 36-45.

Li, Y. 1998. Development and germplasm base of maize hybrids in China. Maydica 43: 259-269.

Li, G., Yang, A.F., Zhang, J.R., Bi, Y.P., and Shan, L. 2001. Genetic transformation of calli from maize and regeneration of herbicide-resistant plantlets. Chinese Science Bulletin 46: 563-565 (in Chinese).

Li, H.F., Li, X.G., Liu, X., Chang, T.J., Xiao, G.F., and Zhu, Z.Z. 2002a. Maize transformation of the *cry1Ac3* gene and insect resistance of their transgenic plants. Acta Botanica Sinica 44: 684-688 (in Chinese).

Li, H.M., Hu, R.F., and Zhang, S.H. 2005. The impacts of US and CGIAR germplasm on maize production in China. Scientia Agricultura Sinica 38: 2189-2197 (in Chinese).

Li, H.Y., Huang, S.H., Shi, Y.S., Song, Y.C., Zhao, J.R., Wang, F.G., Wang, T.Y., and Li, Y. 2007. Isolating soil drought-induced genes from maize seedling leaves through suppression subtractive hybridization. Agricultural Sciences in China 6: 647-651.

Li, M.S., Zhang, S.H., Li, X.H., Pan, G.T, Bai, L., and Peng, Z.B. 2002b. Study on heterotic groups among maize inbred lines based on SCA. Scientia Agricultura Sinica 35: 600-605 (in Chinese).

Li, Y., Shi, Y., Cao, Y.S., and Wang, T.Y. 2002c. A phentotypic diversity analysis of maize germplasm preserved in China. Maydica 47: 107-114.

Liu, J., Liu, G.S., Zhu, Z.Q., and Chen, G. 2002. Assessment on genetic relationships among 15 maize (*Zea mays*) elite inbred lines of China using SSR markers: comparisons with data from heterosis and pedigree. Acta Botanica Boreali-Occidentalia Sinica 22: 741-750 (in Chinese).

Meng, E.C.H., Hu, R.F., Shi, X.H., and Zhang, S.H. 2006. Maize in China: Production systems, constraints, and research Priorities. Mexico, D.F.: CIMMYT.

Peng, Z.B., and Chen, Z.H. 1993. Current status of maize hybrid breeding and its strategies in China. Proceedings of the Fifth Asian Regional Maize Workshop, Hanoi, Vietnam. pp.31-41.

Peng, Z.B., Liu, X.Z., Fu, J.H., Li, L.C., and Huang, C.L. 1998. Heterotic groups and patterns of maize inbred lines established by RAPDs. Acta Agronomica Sinica 24: 711-717 (in Chinese).

Qin, F., Li, J., Zhang, G.Y. Zhao, J., Chen, S.Y., and Liu, Q. 2003. Isolation and structural analysis of DRE-binding transcription factor from maize (*Zea mays* L.). Acta Botanica Sinica 45: 331-339 (in Chinese).

Schnable, P.S., Ware, D., Fulton, R.S., Stein, J.C., Wei, F.S. et al. 2009. The B73 maize genome: complexity, diversity, and dynamics. Science 326: 1112-1115.

Tong, P.Y., and Zhao, G.P. 1988. The History of Maize. China Agriculture Press, Beijing (in Chinese).

Uchibayashi, M. 2005. Maize in pre-Columbian China. Yakugaku Zasshi 17: 583-586.

Vasal, S.K., Cordova, H., Pandey, S., and Srinivasan, G. 1999. Tropical maize and heterosis. In: J.G. Coors and S. Pandey (eds.). Genetics and Exploitation of Heterosis in Crops. ASA, CSSA, SSSA, Madison, WI, USA. pp. 363-373.

Wang, J.X., Sun, Y., Cui, G.M., and Ju, J.J. 2001. Transgenic maize plants obtained by pollen mediated transformation. Acta Botanica Sinica 43: 275-279 (in Chinese).

Wang, Y.B., Wang, Z.H., Lu, L.X., Wang, Y.P., and Zhang, X. 1997. Studies on heterosis utilizing models of main maize germplasms in China. Scientia Agricultura Sinica 30(4): 16-24 (in Chinese).

Wang, Z.H., Li, X.H., Yuan, L.X., Han, X.Q., and Zhang, S.H. 2003. Genetic diversity of elite maize germplasm for resistance to SCMV. Acta Agronomica Sinica 29: 391-396 (in Chinese).

Wu, J., 1997. Maize Production and Technology Strategy in 2010 in China. The Development and Strategy of Crop and Animal Production in 2010 in China, China Agricultural Science and Technology Press, Beijing. pp.25-35 (in Chinese).

Wu, J. D., and Wang, F.T. 1999. Changes in climatic variability and maize yield in northeast China. The Journal of Chinese Geography 9: 237-247 (in Chinese).

Wu, J.Y., Ding, J.Q., Du, Y.X., and Chen, W.C. 2002. Identification and molecular tagging of two complementary dominant resistance genes to maize dwarf mosaic virus. Acta Genetica Sinica 29: 1095-1099 (in Chinese).

Xiao, W., Zhao, J., Fan, S., Li, L., Dai, J., and Xu, M.L. 2007. Mapping of genome-wide resistance gene analogs (RGAs) in maize (*Zea mays* L.). Theoretical and Applied Genetics 115: 501-508.

Xie, C.H., Zhang, S.H., Li, M.H., Li, X.H., Hao, Z.F., Bai, L., Zhang, D.G., and Liang, Y.H. 2007. Inferring genome ancestry and estimating molecular relatedness among 187 Chinese maize inbred lines. Journal of Genetics and Genomics 34: 738-748.

Yin, X.Y., Wang, Q.H., Yang, J.L., Jin, D.M., Wang, F., Wang, B., and Zhang, J. 2003. Fine mapping of the *Ht2* (*Helminthosporium turcicum* resistance 2) gene in maize. Chinese Science Bulletin 48: 165-169 (in Chinese).

Yu, Y., Wang, R., Shi, Y., Song, Y., Wang, T., and Li, Y. 2007. Genetic diversity and structure of the core collection for maize inbred lines in China. Maydica 52: 181-194.

Yuan, L.X., Fu, J.H., Liu, X.Z., Peng, Z.B., Zhang, S.H., Li, X.H., and Li, L.C. 2000a. Study on prediction of heterosis in maize (*Zea mays* L.) using molecular markers. Scientia Agricultura Sinica 33(6): 6-12 (in Chinese).

Yuan, L.X., Fu, J.H., Warburton, M., Li, X.H., Zhang, S.H., Khairallah, M., Liu, X.Z., Peng, Z.B., and Li, L.C. 2000b. Comparison of genetic diversity among inbred lines based on RFLPs, SSRs, AFLPs, and RAPDs. Acta Genetica Sinica 27: 725-733 (in Chinese).

Zhang, S.H., Shi, D.Q., Xu, J.S., Yang, Y.F., Kang, J.W., and Wang, L.M. 1995. Effects of mass selection on adaptive improvement of exotic quality protein maize populations. I. Direct response to selection for early silking. Acta Agronomica Sinica 21: 271-280 (in Chinese).

Zhang, S.H., Shi, D.Q., and Li, J.S. 1998. Maize production and research for the next century in China: progress, challenges and priority areas. In: S.K. Vasal et al. (eds.). Proceedings of the Seventh Asian Regional Maize Workshop, PCARRD, Los Baños, Philippines. pp. 474-481.

Zheng, H.J., Wu, A.Z., Zheng, C.C., Wang, Y.F., Cai, R., Shen, X.F., Xu, R.R., Liu, P., Kong, L.J., and Dong, S.T. 2009. QTL mapping of maize (*Zea mays*) stay-green traits and their relationship to yield. Plant Breeding 128: 54-62.

Zhou, C.J., Chen, C.X., Cao, P.X., Wu, S.W., Sun, J.W., Lin, D.M., and Wang, B. 2007. Characterization and fine mapping of *RppQ*, a resistance gene to Southern corn rust in maize. Molecular and General Genomics 278: 723-728.

Wheat improvement in China

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1. Introduction

China is the largest wheat producer and consumer in the world and wheat ranks as the third leading crop in China after rice and maize. Table 1 lists the production of the three major cereal crops in China, Asia, and the world.

Table 1. Cereal production in millions of tonnes, 2008-2009.

Region	Rice	Maize	Wheat
China	137	152	110
Asia	605	179	278
World	688	787	677

In China, agricultural reform in the early 1980s stimulated wheat production, and a peak of 123 million tonnes was recorded in 1997. Wheat production, however, declined substantially from 2000 to 2005, largely due to the policy of increasing crop diversity, elimination of protected pricing policies in the Yangtze and spring wheat regions, and the lower profitability of wheat production compared with cash crops. Wheat area and production were stable for the period 2005-2009 since several policies aimed at increasing grain production were put in place. In 2008, wheat area, average yield, and production in China were 23.6 million ha, 4,762 kg/ha, and 112 million tonnes, respectively. Durum wheat is planted only in very limited areas in Xinjiang and Yunnan.

There is a long history of wheat cultivation in China, starting about 5,000 years BC. In the 1930s, wheat accounted for about one third of China's cultivated area and about 25% of all cereal production. From the establishment of People's Republic of China in 1949 to the present, wheat continues to play an important role in food production. Great progress has been achieved in Chinese wheat production over the last 60 years (Figure 1): average wheat

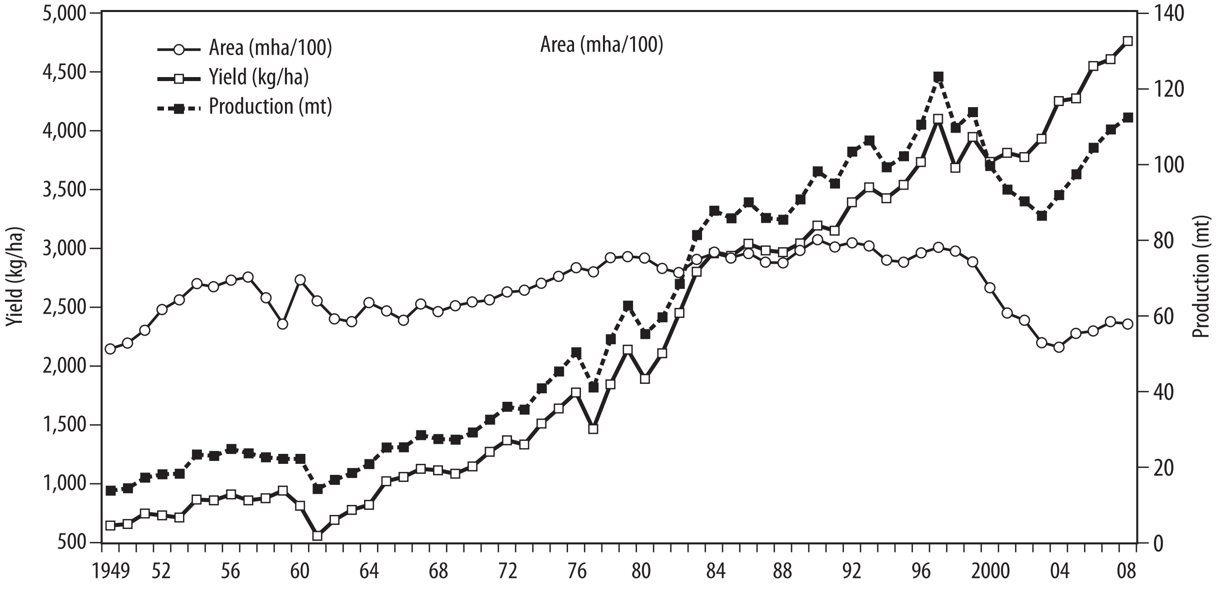

Figure 1. Wheat area, average yield, and production in China, 1950-2008.

yield increased annually by 1.9%, and production increased more than sixfold. Many factors contributed to the significant increase in average yield, including adoption of improved cultivars, expansion of high yielding cultivation technologies, increased use of fertilizers and irrigation, increased farm mechanization, and improved rural policies. Farmers in the major wheat areas have replaced their wheat cultivars six to eight times during the past 60 years. Wheat breeding in China was documented by He et al. (2001) in English and by Zhuang (2003) in Chinese.

1.1 Agro-ecological zones

The wheat area in China is divided into 10 major agro-ecological zones (Figure 2) and 26 sub-zones, based on wheat types, varietal response to temperature, moisture, biotic and abiotic stresses, and growing seasons (He et al., 2001). Very little wheat is produced in zone V at present. Based on sowing dates, autumn-sown wheat accounts for more than 90% of production and area. Winter and facultative wheat, sown on the Northern China Plain (zone I) and the Yellow and Huai River Valleys (zone II), contributes around 65-70% of the wheat area and production. Autumn-sown, spring habit wheat, planted both in the Middle and Lower Yangtze Valleys (III) and southwestern China (zone IV), contributes around 20-25% of production. Spring-sown spring wheat is mostly planted in northeastern and northwestern China (zones VI, VII, and VIII), making up about 7% of the wheat area.

The molecular characterization of vernalization genes in Chinese wheat has provided very useful information on the vernalization requirements in various zones (Zhang et al., 2008). Although wheat is produced in 30 of the 31 provinces, more than 65% of Chinese wheat is produced in just five provinces: Henan, Shandong, Hebei, Anhui, and Jiangsu. Table 2 lists the wheat area and production in 2007 by province.

Zone I: Northern winter wheat region. True winter-habit wheat cultivars are grown in this zone, which has a wheat production area of around 1.5 million ha. It includes Beijing, Tianjin, and northern Hebei Province, including Tangshan and Langfang prefectures, the northern parts of Baoding and Cangzhou prefectures, central and southeastern Shanxi Province, North Wei Plateau, Yanan prefecture in Shaanxi Province, and Qingyang and Pingling prefectures in Gansu Province. Wheat is planted in late September or early October and harvested in mid- to late June.

Zone II: Facultative wheat region in the Yellow and Huai River Valleys. This is the most important wheat producing region, where 12 million ha are sown to

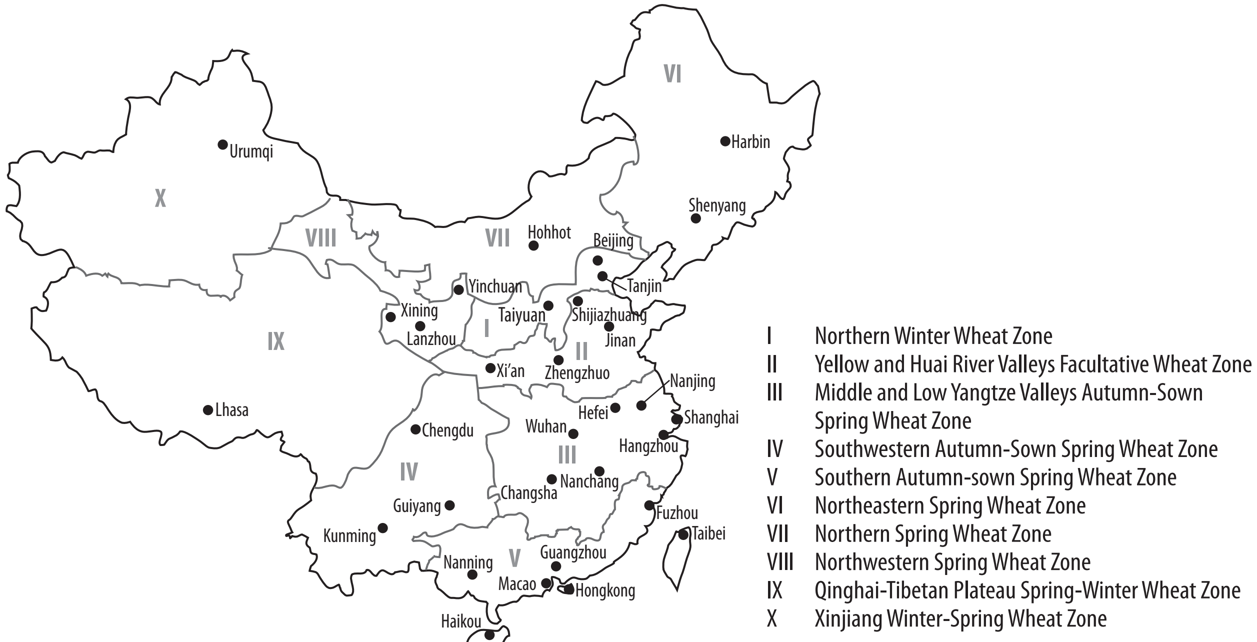

Figure 2. Main wheat production areas, China.

wheat each year. It accounts for about 65% of the total wheat area and production. Zone II covers most of Henan and Shandong, southern Hebei, central parts of Shaanxi and southern Shanxi, and northern parts of Jiangsu and Anhui. Wheat is sown from early to mid-October and harvested in early June.

Zone III: Autumn-sown spring wheat region in the Middle and Lower Yangtze Valley. This zone covers 15% of the wheat area, including the southern parts of Henan, Anhui, and Jiangsu Provinces, plus Hunan, Hubei, Jiangxi, Zhejiang, and Shanghai. Wheat is planted in late October and harvested from late May to early June.

Zone IV: Southwestern autumn-sown spring wheat region. This zone accounts for 10% of China's wheat area and includes most parts of Sichuan and Chongqing, and all of Yunnan and Guizhou Provinces. Wheat is sown from late October to early November and harvested in mid-May.

Table 2. Chinese wheat area, production, and average yield by province, 2007.

Province	Area (000 ha)	% area	Production (000 t)	% production	Yield (kg/ha)
Henan	5213.3	22.0	2980.2	27.3	5717
Shandong	3519.1	14.8	1995.6	18.3	5671
Hebei	2414.2	10.2	1193.7	10.9	4948
Anhui	2330.3	9.8	1111.3	10.2	4769
Jiangsu	2039.1	8.6	973.8	8.9	4776
Sichuan	1316.8	5.6	451.7	4.1	3430
Shaanxi	1144.6	4.8	359.1	3.3	3137
Hubei	1096.3	4.6	353.2	3.2	3222
Gansu	982.1	4.1	237.4	2.2	2417
Shanxi	712.3	3.0	220.2	2.0	3091
Xinjiang	605.8	2.6	341.3	3.1	5634
Inner Mongolia	533.4	2.2	175.6	1.6	3292
Yunnan	426.8	1.8	91.2	0.8	2137
Guizhou	242.7	1.0	47.9	0.4	1972
Ningxia	233.7	1.0	61.6	0.6	2634
Heilongjiang	233.0	1.0	68.8	0.6	2952
Chongqing	199.7	0.8	61.1	0.6	3058
Qinghai	154.0	0.6	61.4	0.6	3986
Tianjin	104.9	0.4	50.6	0.5	4825
Zhejiang	49.3	0.2	18.4	0.2	3731
Beijing	41.4	0.2	20.4	0.2	4931
Tibet	40.3	0.2	26.5	0.2	6572
Shanghai	37.5	0.2	14.6	0.1	3900
Hunan	13.6	0.1	3.2	0.0	2353
Liaoning	12.4	0.1	5.3	0.0	4236
Jiangxi	11.2	0.0	2.0	0.0	1768
Jilin	5.4	0.0	1.6	0.0	2876
Fujian	4.5	0.0	1.5	0.0	3332
Guangxi	3.9	0.0	0.6	0.0	1534
Guangdong	1.0	0.0	0.3	0.0	3000
Total	23720.6	100.0	10929.6	100.0	4608

Source: Chinese Agricultural Statistical Data Collection 2007, Ministry of Agriculture.

Zone V: Southern autumn-sown spring wheat region. In this zone, which includes Fujian, Guangdong, and Guangxi Provinces, very little wheat is planted at present. Wheat is sown in mid-November and harvested in mid- to late April.

Zone VI: Northeastern spring wheat region. This zone, representing 2% of China's wheat area, includes Heilongjiang Province, eastern parts of Inner Mongolia, and small areas in Jilin and Liaoning Provinces. Wheat is planted in early April and harvesting occurs from late June to August.

Zone VII: Northern spring wheat region. This zone represents 2% of China's wheat area and covers most of Inner Mongolia, and parts of Shaanxi, Shanxi and Hebei Provinces. Wheat is planted in late March and harvested in late July.

Zone VIII: Northwestern spring wheat region. This zone also has a 2% share of the wheat area and includes Ningxia and parts of Gansu and Qinghai Provinces. Wheat is planted mostly in mid March and harvested from mid- to late July.

Zone IX: Qinghai-Tibetan Plateau spring-winter wheat region. This zone has less than 1% of China's wheat area. It includes all of Tibet, parts of Qinghai, and small portions of Yunnan and Sichuan. Spring wheat is planted in late March and winter wheat in mid-September; both are harvested in September.

Zone X: Xinjiang winter-spring wheat region. Winter and spring wheat share about 60% and 40% of the wheat area in this zone, respectively. Zone X comprises less than 3% of the national wheat area. Spring wheat is sown in early April and harvested in late July; winter wheat is sown in late September and harvested in late June.

1.2 Soil types

Drab and loess soils predominate in zones I and II, and saline-alkaline soils are present in the coastal areas. Paddy soil, red soil, and yellow soil are present in the Middle and Lower Yangtze Valley, while in the southwestern region, purple, red, and yellow soils are dominant in Sichuan, Yunnan, and Guizhou, respectively. In the spring-sown spring wheat region, black and chestnut soils occur more frequently. Oasis soil is widely distributed in the rainfed area, particularly in Gansu and Xinjiang.

1.3 Temperature, rainfall, and irrigation

Temperature and rainfall data for the various wheat zones from 1950-1980 are presented in Table 3.

Full or supplemental irrigation is available in 60-70% of the wheat area in zones I and II. Irrigation is not provided in southern China, not even in hilly areas where drought is a constraint to wheat production. In the spring-sown spring wheat area, 30-40% of wheat is irrigated, mostly in the Yellow River areas concentrated in Bayan Nur Meng of Inner Mongolia, and the Hexi corridor including Wuwei, Jinchang, and Zhangye prefectures in Gansu Province, and Xinjiang. Mostly, 3-4 irrigations are provided, but the number of applications has declined in recent years due to lower wheat prices.

1.4 Main pests and abiotic stresses

Powdery mildew [caused by *Blumeria graminis* f. sp. *tritici*], yellow or stripe rust [caused by *Puccinia striiformis* f. sp. *tritici*], and Fusarium head blight [caused by *Gibberella zeae* (Sacc.) Petch] are the three major wheat diseases in China. However, take-all [caused by *Gaeumannomyces graminis* (Sacc) Arx & D. Olivier var. *tritici* J. Walker] and sharp eyespot [caused by *Rhizoctonia cerealis* Van der Hoeven] are becoming more serious and increasingly important. Powdery mildew was established first in humid areas, such as Yunnan and Guizhou, but has spread to all parts of China since the early 1980s, particularly in zones II, III, IV, and VI. Breakdowns in resistance to yellow rust were the main factors for varietal replacements in zones II and IV from the 1950s to the 1980s. Yellow rust is the most important disease in Shaanxi and Gansu Provinces (zone II), and Sichuan and Yunnan Provinces (zone IV). It is also a major disease in zones VIII, IV, and V. Leaf rust (caused by *Puccinia triticina*) is not as important as yellow rust. Stem rust (caused by *Puccinia graminis* f. sp. *tritici*) has been controlled in the northeastern spring wheat region (zone VI) for many years.

Fusarium head scab is most predominant in the Middle and Lower Yangtze Valley (zone III) and in Heilongjiang and Fujian Provinces. It is also a problem in parts of Sichuan, central Shaanxi, and southern Henan. Take-all has become increasingly important in Shandong Province (zone II) and in the spring wheat region (zones VII and VIII). *Rhizoctonia cerealis* is reported mainly in zones II and III. Barley yellow dwarf virus (BYDV) occurs in zones VI, VII, and VIII, but sometimes also in the rainfed areas of zones I and II. Red stunt transmitted by leafhoppers, and blue stunt transmitted by a mycoplasm, are major concerns in the Loess Plateau of zone I: Pingliang and Qinyang prefectures in Gansu, and northern Shaanxi. Aphids [predominantly *Macrosiphum avenae* (E.)] are present in all major wheat regions, and blossom midge [*Sitodiplosis mosellana* (Gehin)] can also be a major problem.

Major abiotic stresses include drought, high temperature, waterlogging, preharvest sprouting, poor soil fertility, and alkaline soils. Drought is a limiting factor for wheat production in the rainfed areas of zones I and II, hilly areas of zone IV, and especially in the spring-sown spring wheat regions. High temperatures and hot winds during the grainfilling stage are common in most autumn-sown wheat areas (zones I, II, and III), and in the

Table 3. Temperature and rainfall in the wheat areas of China.

Zone	Latitude[1]	RF1[2] (mm)	RF2 (mm)	RF3 (mm)	TEMP1[3] <0°C (day)	TEMP2 >30°C (day)	Frost-free days
I	37°47-39°48	578	109.9	40.7	140.3	13.2	168
II	34°18-38°04	734	121.1	70.8	105.4	14.5	190
III	30°19-32°	1335	292.5	214.7	--	5.4	255
IV	25°01-30°40	1108	91.1	146.0	--	1.9	268
V	22°49-26°	1542	81.3	145.6	--	1.1	346
VI	45°41-48°03	617	74.9	177.4	1.6	7.4	128
VII	40°49	349	65.6	101.1	4.9	11.2	118
VIII	36°06-38°14	267	70.3	73.9	3.5	8.6	140
IX	29°41	128	120.8	325.2	6.0	--	150
X	43°54	489	115.4	36.0	147.8	26.7	66

[1] Latitude is the range of latitudes in the representative breeding station(s).

[2] RF1, RF2, and RF3 are the average annual rainfall, rainfall before heading (from sowing) and after heading (to maturity), respectively. They are average data from representative breeding stations in each zone.

[3] TEMP1 and TEMP2 are the number of days with temperatures below 0°C before heading, and temperatures above 30°C from heading to maturity, respectively. They are average data from representative breeding stations.

spring-sown spring wheat areas (zones VI, VII, VIII, and X). Waterlogging is common in zones III, IV, and VI. Winter hardiness is needed in zone I to avoid winterkilling, although temperatures have been increasing over the last 20 years. Although preharvest sprouting is more common in zones III, IV, and VI, it is also an occasional problem in zone I and the spring-sown spring wheat areas. Poor soil fertility is of particular concern in the hilly areas of zones IV and VII. Salt tolerance is needed in the coastal areas of zone I and in Xinjiang. Lodging limits wheat production in high yielding areas such as zones I and II, and shattering is a concern in Xinjiang and Heilongjiang, since most Chinese wheat cultivars have poor tolerance to shattering.

1.5 Main end-uses of wheat

Currently, around 80% of wheat is used for food, 10% for feed, 5% for seed, and the remaining 5% for industrial use. About 45% of Chinese wheat is traded (i.e., it is mainly sold to state grain stations), and the remaining 55% is retained and consumed by farmers. Traditional products such as steamed bread, Chinese noodles, and dumplings comprise about 85% of wheat food products, and just 3-5% is used to make western bread and soft wheat products such as cookies and cakes. Steamed bread or *mantou* is widely consumed in China. The earliest record of steamed bread is from the Han dynasty, about 1,500 years ago. The two main types of steamed bread, the northern and southern styles, differ in size, appearance, structure, elasticity and cohesiveness, and stickiness. Northern style steamed bread is predominant on the market, particularly in northern China, and southern style is mostly consumed in southern China where rice is the major staple food. Steamed bread is mostly home-made, particularly in rural areas, but in the cities, semi-mechanized and mechanized processes are increasingly being used for steamed bread production.

Noodles, which originated in China about 2,000 years ago, may be consumed three times daily in northern China, although they are mostly eaten at midday and in the evening. In southern China, noodles are generally served at breakfast. Many types of noodles are produced and consumed in China; home-made fresh noodles are very common, followed by dry white and instant noodles, of which around 4.1 million tonnes and 3.6 million tonnes are produced, respectively.

With rapidly increasing urban populations and changing lifestyles, it is projected that in the near future the consumption of home-made steamed bread and fresh noodles will decrease in favor of industrial equivalents and of Western-type breads and pastries, as has previously happened in other Asian countries such as Japan, Singapore, and Korea.

2. Wheat based multi-cropping systems

More than 75% of the Chinese wheat area is under multi-cropping systems. The advantages of these systems include improved total land productivity to meet the increasing grain demand; fewer inputs used for wheat production; and avoidance of the negative effects of continuous wheat cropping. The strategy for adopting multi-cropping systems in China is to delay harvesting of the crop planted after wheat and the planting of wheat, with the harvest time of wheat remaining basically unchanged. This requires farmers to adopt early maturing wheat cultivars with good tolerance to late sowing. Because wheat harvesting is completed within 3-5 days in most areas, the availability of labor and machinery may be limiting factors for continuation of multi-cropping systems in which harvesting of wheat and planting of a second crop normally take place within a short time-frame (1-2 days in some areas). Chinese farmers refer to this season as "taking food from the dragon's mouth" to illustrate the busy season. Furthermore, timely planting of wheat after harvesting the second crop is important because wheat yields can be reduced significantly by planting delays of only 7-10 days beyond optimum planting dates. Such delays require increased seeding rates and adjustments in fertilization and irrigation management in order to maintain high wheat yields. For a review of wheat cropping systems and technologies in China, see Wang et al. (2009a).

The multi-cropping systems that include wheat as the main crop vary with different regions (for detailed information on the subject, see Jin, 1996). In the Northern China Plain (zone I) and the Yellow and Huai River Valleys (zone II), at least 50% of wheat is planted under full or supplemental irrigation. The wheat-maize rotation system is predominant, particularly under irrigated conditions, although wheat/maize relay cropping is also practiced. Under the wheat/maize relay system, a 40-60-cm space is left after every second row of wheat to allow planting of maize 15-20 days before the wheat harvest. However, wheat yield reductions of 5-10%, combined with the difficulties of planting and harvesting, have diminished the extent of the wheat/maize relay planting system. The development of early maturing wheat cultivars with good tolerance to late sowing, combined with adjustments in seeding rate, fertilization, and irrigation practices, have promoted the rapid adoption of sequence cropping of wheat and maize. Other cropping systems include wheat-soybean or wheat-peanut rotations in Henan and Shandong, wheat-cotton rotations in Hebei, Henan, Shandong, and northern parts of Jiangsu and Anhui, and wheat-sweet potato rotations in Shandong and northern Jiangsu.

In the Middle and Lower Yangtze Valley (zone III) and in southwestern China (zone IV), including the southern parts of Anhui, Jiangsu, Hubei, Zhejiang, Sichuan, and Yunnan, wheat is grown under rainfed conditions, since no irrigation is needed in the Chengdu Plain due to high rainfall conditions. There, wheat-rice rotations take a dominant position. However, waterlogging and delayed planting of wheat are limiting factors for production. Consequently, direct sowing of wheat without tillage is commonly practiced. In hilly areas with poor soil fertility, wheat/maize/sweet potato relay planting is commonly practiced, where wheat is planted in early November and harvested in late April or early May, maize is planted in late March or transplanted in late April and harvested in August, and sweet potato is transplanted in June and harvested in late October to early November. Based on data from multi-location trials, shared total yields for wheat, sweet potato, and maize are 24-27%, 31-35%, and 39-43%, respectively, higher than for each crop grown in monoculture. Wheat-maize or wheat-potato rotations are also practiced in some areas.

In the spring-sown spring wheat areas, including Heilongjiang, Inner Mongolia, Gansu, and Ningxia, only a single wheat crop is planted. However, in irrigated areas, the wheat/maize relay is the most popular cropping system.

Sowing and harvesting is done mostly by machine in irrigated areas, but sowing by hand or with animals and hand-harvesting is still common in rainfed areas. In zones I and II, and the spring-sown spring wheat region, land is plowed before sowing wheat. In zones III and IV, minimum or zero tillage is popular for wheat sowing, and broadcasting is encouraged; bed planting is used to reduce waterlogging. In rainfed fields of southern China, pot planting and subsequent transplanting by hand is the norm. In the autumn-sown wheat regions, seeding rates range from 60 to 120 kg/ha, depending on sowing time, soil fertility, and availability of irrigation, whereas in spring-sown spring wheat regions, seeding rates are much higher, from 225 to 375 kg/ha. Both chemical fertilizer and organic manure are used, but the use of organic manure is declining. Fertilizers (N, P, K) are usually applied three times (at sowing, stem elongation, and flowering) in irrigated environments, but only once (at sowing time) in rainfed areas. Herbicide use is becoming popular, although manual weed control is still commonly practiced in the rainfed and less developed areas.

3. Wheat genetic improvement

3.1 Introduction of wheat

The oldest finding in Shaan County of Henan Province indicates that wheat (*mai* or *xiaomai* in Chinese) was cultivated in China about 7,000 years ago. In the sixth century BC, or earlier, wheat was widely cultivated in the lower valleys of the Yellow River, i.e., in Gansu, Shanxi, Shaanxi, Henan, Hebei, and Shandong. Chou-li records from the third century indicate that in addition to the Yellow and Huai Valleys, wheat was grown in southern Inner Mongolia and the northern part of the North China Plain. During the Han dynasty (202-220), both spring and winter wheat were documented; winter-planted wheat extended to the middle Yangtze Valley and spring wheat was cultivated in northern Hebei. Wheat production then spread to southern China. During the Ming dynasty (1368-1644), wheat was grown in all parts of China. Wheat's long history and wide distribution in China generated many landraces adapted to different regions.

The introduction of foreign cultivars started in the 1920s. Some 300 lines were introduced from 1920-1925. More than 1,700 accessions of world wheat collections were obtained from John Percival at Reading University in 1932, and about 2,000 lines were introduced from Kansas State University in 1946 (Zhuang, 2003). Cultivars introduced from Italy, USA, the former Soviet Union, Romania, Mexico (CIMMYT), Australia, Canada, Chile, and other countries were used to improve local cultivars or were used directly by farmers.

Introduced cultivars have played an important role in Chinese wheat production. Outstanding introductions include Mentana, Abbondanza, Funo, Ardito, Villa Glori, and St 1472/506 from Italy; CI 12203, Early Premium, and Minn 2761 from USA; Ukraine 0246, New Ukraine 83, and Red Star from the former Soviet Union; Penjamo 62, Cajeme F71, and Mexipak 65 from CIMMYT; Quality (a synonym of Florence) from Australia, and Orofen from Chile. Early maturing hard red winter wheat cultivars from USA were mostly used in breeding programs in zone I, whereas hard red spring wheats from the USA were well adapted to zone VI. Italian cultivars performed very well in zones II, III, IV, and VIII. Cultivars from the former Soviet Union were disseminated mainly in Xinjiang, and CIMMYT wheats were well suited to Yunnan, Xinjiang, and zone VIII. Few introductions were widely grown in China after 1980, when much progress was made in local wheat breeding.

Introductions used as crossing parents also contributed greatly to Chinese wheat improvement programs, and today most commercial cultivars have one foreign parent in their pedigrees. The major introductions used in developing new cultivars include Orofen, Lovrin 10, Abbondanza, Funo, Predgornaia 2, Lovrin 13, Mentana, Alondra's', Kavkaz, Aurora, Tanori F71, St 2422/464, Early Premium, Yecora F70, and Quality. They contributed resistance to lodging and rust, and high yield potential to Chinese wheats.

3.2 Landraces and historical breeding records before 1949

Chinese landraces are characterized by good adaptation to local conditions, early maturity, good fertility, tall plant height, poor lodging resistance, low yield potential (1.5 t/ha), and susceptibility to major diseases such as stripe rust and stem rust. Landraces with tolerance to low temperatures, heat, drought, waterlogging, salinity, acidic soils, and low soil fertility, and resistance to Fusarium head scab have been identified.

In the early 1950s, large numbers of landraces were collected and evaluated, and the top landraces with better yield potential and disease resistance were recommended for production. Re-selections were also made for improving landraces. In total, 13,930 accessions of Chinese wheat landraces were collected and stored at the national crop germplasm bank located at the Chinese Academy of Agricultural Science (CAAS) in Beijing. Well-known landraces include Jiangdongmen, Hechuanguangtou, Chengduguangtou, Mazhamai, Yanda 1817, and Youzimai.

According to Zhuang (2003), Chinese wheat improvement activities before 1943 were documented in a paper titled "Thirty Years of Wheat Breeding in China," co-authored by Jin Shanbao and Cai Xu in 1943 (original reference not available). Wheat breeding at the University of Nanking and Central University began in 1915 and 1919, respectively. A regional yield trial was established in 1932 and hybridization breeding started in the early 1930s. In total, 34 cultivars were released from 1924 to 1943. Six cultivars were introduced from other countries, including Quality and Faun (wrongly spelled Fawn in China) from Australia; Ardito, Villa Glori, and Mentana from Italy; and Akagomughi from Japan. Five cultivars were developed through re-selection, including Zhongda Jiangdongmen, Peixian Xiaohongmang, Huiyin Dayuhua, Jinda Jingyanglanmangmai, and Chengdu Guangtumai. Twenty-two cultivars (including Zhongda Nankingchike, Jinda Suzhou 1419, Jinan 1195, Dingxian 72, Dingxian 73914, Mingxian 169, Shaannong 7, Mazhamai, Xibei 60, Xibei 302, and Zhechang 4) were developed through pure line selection. Mozi 101 was developed through hybridization. However, promotion and use of these improved cultivars were limited, and most farmers still used landraces.

3.3 Breeding objectives and general progress

Chinese wheat breeding has progressed rapidly since the founding of the People's Republic of China in 1949. In general, breeding objectives included yield potential improvement, plant height reduction, early maturity to fit multi-cropping systems, and broad adaptation. Breeding for resistance to major diseases such as yellow rust, stem rust, powdery mildew, and Fusarium head scab, and to aphids has always been important; however, priorities differ in different regions. In the last 10 years, sharp eyespot (*Rhizoctonia cerealis*), common root rot (*Bipolaris sorokiniana*), and take-all have become common diseases in the major wheat regions. Waterlogging and pre-harvest sprouting in the Yangtze region, high temperatures during grainfilling, and spring droughts are the major abiotic stresses limiting wheat production. Quality improvement has been neglected for many years and Chinese wheats have poor processing quality for breads, noodles, and cookies/cakes.

Chinese wheat breeding can be divided into six periods: (1) selection of top landraces and their re-selection starting in the early 1950s, followed by introductions and the development of the first improved cultivars in the mid 1950s; (2) in the early 1960s, dissemination of improved cultivars with rust resistance, high yield potential, and early maturity; (3) in the early 1970s, cultivars with better yield potential, short stature, good lodging resistance, and rust resistance were used in production; (4) improved cultivars with the 1B.1R translocation took leading roles in the 1980s and 1990s; (5) good quality cultivars were introduced after 2000; and (6) today cultivars with high yield potential and improved quality are taking a leading role.

During the last 60 years, great progress was achieved in yield potential, rust resistance, earliness, lodging resistance, and quality improvement. Plant height was reduced from 110-120 cm in the early 1950s to less than 90 cm currently. Semidwarf cultivars cover most of the wheat area in the Yellow and Huai River Valleys (zone II), and most commercial cultivars possess good lodging resistance and are around 80 cm tall. Harvest index has increased from 0.33 to approximately 0.42, and 1000-kernel weight has risen from less than 30 g to 40 g or more. From 1960 to 2000, the average annual genetic gain in grain yield ranged from 32.07 kg/ha to 72.11 kg/ha or from 0.48% to 1.23% in different provinces in the Yellow and Huai River Valleys (zone II), and from 13.96 kg/ha to 40.80 kg/ha or from 0.31% to 0.74% in different provinces in the southern China autumn-sown spring wheat region (zones III and IV), respectively (Zhou et al., 2007a, 2007b). Reduced plant height and increased harvest index achieved with the use of dwarfing genes such as *Rht8*, *Rht1* (*Rht-B1b*), and *Rht2* (*Rht-D1b*), and the use of the 1B.1R translocation were the major factors contributing to improving yield potential. Milestone cultivars in various zones, identified mainly by Jin (1986, 1997), He et al. (2001) and Zhuang (2003), are described below.

3.4 Milestone cultivars in zone I

Leading breeding programs in zone I include the Chinese Academy of Agricultural Science (CAAS), China Agricultural University (once called Beijing Agricultural University, abbreviated as BAU), and the Beijing Academy of Agricultural Science. All three are located in Beijing.

Nongda 183 and Nongda 311 were developed from Yanda 1817/Triumph by BAU in 1957 and 1963, respectively. Nongda 183 was characterized by good yellow rust resistance, cold and drought tolerance, early maturity, white kernel color, and high yield potential (outyielding the reference cultivar by more than 10% in regional trials). It became a leading cultivar in zone I and covered 170,000 ha annually in the early 1960s. Nongda 311's performance was similar to that of Nongda 183, but it matured 1-2 days later. It replaced Nongda 183 because its resistance to yellow rust withstood a severe epidemic in 1964. Its area of production expanded rapidly, reaching 330,000 ha in the late 1960s.

Dongfanghong 3, a re-selection of Nongda 45 developed from Nongda 17//Wheat-Agropyron Hybrid 16/Early Premium, was released by BAU in 1967. It possessed good winter hardiness, yellow rust resistance, lodging resistance (due to strong stems), and high yield potential. It was the leading cultivar in zone I until the 1980s and occupied 500,000 ha at its peak.

Nongda 139 was developed from Nongda 183/Virgilio//Yanda 1817/30983 by BAU in 1969. Due to its short stature, lodging resistance, stripe rust resistance, high tillering ability, good winter hardiness, white kernels, and high productivity, it was extensively sown in the irrigated area of zone I until the early 1980s with an annual sowing area of 370,000 ha.

Beijing 10 was released from Huabei 672/Xinshi14//Skorospslka L-1/Huabei 672 by CAAS in 1965. This white grained wheat had a good combination of yield components and produced 3,750-5,250 kg/ha under good irrigation conditions. It took a leading position in production, and its sowing area peaked at 570,000 ha in 1978. Tangmai 2, a re-selection of Beijing 10, was a leading cultivar in southern Xinjiang with an area of 270,000 ha in 1990.

Fengkang 8 was selected from Youmanghong 7/Lovrin 10 by CAAS in collaboration with the Beijing Academy of Agricultural Sciences and released in 1983. It showed good resistance to rusts and powdery mildew, high yield potential (14.3% higher than Nongda 139 in regional yield trials), large grain size, good winter hardiness, and broad adaptation. It was the leading cultivar until the 1990s and covered 330,000 ha annually in this region.

Jingdong 8 was selected from Aurora/5238-016//Hongliang 4/3/Youmanghong 7/Lovrin 10 by the Beijing Academy of Agricultural Science in

1995. It was characterized by high yield potential (outyielding the reference cultivar by 6.0%), broad adaptation (largely due to good tolerance to high temperatures during grainfilling), and good performance under reduced irrigation or rainfed conditions. It had red kernels and showed good resistance to pre-harvesting sprouting compared to cultivars with white kernels. It has been the leading cultivar since 1995 to the present, mostly in Tianjin, northern Hebei, and Shanxi. However, its yield potential and lodging resistance need further improvement, particularly in high yielding environments.

3.5 Milestone cultivars in zone II

Most of the outstanding cultivars in zone II were developed by the wheat breeding programs in Shaanxi, Shandong, Henan and Hebei Provinces.

Northwestern Agricultural University (Northwestern AU) in Yangling, Shaanxi Province, released Bima 1 and Bima 4 selected from Mazhamai/Quality in 1947. Mazhamai was a local cultivar from central Shaanxi and Quality was introduced from Australia. Bima 1 and Bima 4 marked the first milestone in the history of wheat breeding in China, since they were the first two distinguished improved cultivars developed for commercial production through hybridization between a local Chinese landrace and an introduction. They were popularized after a severe stripe rust epidemic in 1950. Bima 1 was characterized by large heads, high 1000-kernel weight, good yield potential, white grain, early maturity, stripe rust resistance, and wide adaptability. Based on data collected from 36 counties in 1951 and 1952, it outyielded local cultivars by an average 30%, and consequently its production area rapidly expanded. The leading cultivar in the 1950s and early 1960s, Bima 1 was sown in almost every part of zone II, and its annual sowing area peaked at 6 million ha in 1959. Bima 4 was less broadly adapted, but its maximum seeding area reached 1.1 million ha in 1960.

In 1966, Northwestern AU crossed Denmark 1 with Xinong 6028 to produce Fengchan 3. It had high yield potential, short stature, lodging resistance, drought tolerance, stripe rust resistance, and broad adaptation. It was promoted in the central Shaanxi Plain in 1966, and subsequently spread to other parts of zone II. Its production area reached over 1.9 million ha in 1977. Xiannong 39 was developed by crossing Xinong 6028 with Suwon from Korea. It measured around 65 cm in height and was highly resistant to lodging, but susceptible to leaf rust, Septoria tritici blotch, and Fusarium head blight. It matured late and suffered severely from premature senescence at the late ripening stage. Fengchan 3 was crossed with advanced line Xiannong 39/58(18) to produce Aifeng 3, released by Northwestern AU in 1971. Aifeng 3 was characterized by high yield potential (6 t/ha) under optimum conditions, short stature, and improved resistance to lodging and diseases. It was grown in Shaanxi and Henan, covering 330,000 ha annually in the late 1970s.

Xiaoyan 6, developed from Italian introduction St 2422/464 crossed with Xiaoyang 96, a derivative of *Agropyron elongatum*, was released by the Northwestern Botanical Institute, Yangling, in 1980. Among cultivars generated from alien gene transfer, it is the most successful, apart from 1B.1R derivatives. It has been widely grown in the western parts of zone II for more than 20 years and was the leading cultivar in central Shaanxi for most of the 1980s, with an annual sowing area of 400,000 ha. Xiaoyan 6 was characterized by high yield potential (outyielding the reference cultivar by 15%), wide adaptability, yellow rust and Septoria tritici blotch resistance, and good quality for making bread, steamed bread, and Chinese noodles. Cytological examination showed that it carried two translocations between two small *A. elongatum* chromosomes and two wheat chromosomes (Li Zhengsheng, pers. comm.).

Jinan 2, Beijing 8, and Shijiazhuang 54 were developed from Bima 4/Early Premium by the Shandong Academy of Agricultural Sciences (Shandong AAS) in Jinan, CAAS in Beijing, and the Hebei Academy of Agricultural Sciences (Hebei AAS) in Shijiazhuang in 1959, 1963, and 1964, respectively. They showed good resistance to yellow rust, high yield potential, early maturity, and broad adaptation. They were the leading cultivars in the 1960s and early 1970s in zone II, with annual sowing areas of 2.0 million, 1.3 million, and 1.3 million ha, respectively.

Taishan 1, developed from 54405/Orofen by the Shandong AAS in 1971, was the second most popular cultivar in the winter and facultative area of China, just behind Bima 1. It was also the leading cultivar in zone II from 1975 to 1983. Due to its broad adaptation, its production area extended to the southern border of zone I. Its annual sowing area reached 3.8 million ha in the early 1980s. Taishan 5, developed by the Shandong AAS in 1974 from a cross between an advanced line of Huixianhong/Abbondanza and White Orofen (a selection from Orofen), was characterized by short stature, high yield potential, good lodging resistance, early maturity, and outstanding performance under optimum conditions. It covered 400,000 ha in 1980. Jinan 13, also developed by the Shandong AAS in 1977 from the reciprocal cross used to produce Taishan 5, outyielded Taishan 1 by 15.8% in regional yield trials in zone II. It was widely grown in the eastern part of zone II for many years and covered about 1.3 million ha in 1985.

Improved lines with similar traits, called Aimengniu 2, 4, and 5 (for the three Chinese characteristics of their three parents), were developed from Aifeng 3//Mengxian 201/Neuzucht by Shandong Agricultural University in Taian in the early 1980s. They had short stature and good disease resistance, but were a little late maturing. A group of cultivars, including Lumai 1, Lumai 5, Lumai 8, Lumai 11, Lumai 215953, and Lumai 15, was developed from Aimengniu. They were all characterized by short stature (about 80 cm), excellent resistance to stripe rust, moderate resistance to powdery mildew, high, stable yields, and good appearance at ripening. They became the leading cultivars in Shandong from the early 1980s to the early 1990s.

Jinan 17 and Jimai 19 were selected from Linfen 5064/Lumai 13 by the Shandong AAS in 1999 and 2001, respectively. Jinan 17 was characterized by good bread and steamed-bread making quality and high yield potential, 4.5% better than that of the reference cultivar in provincial yield trials. It covered 600,000 ha in the 1999-2001 seasons. Jimai 19 was broadly adapted and had excellent noodle quality (noodle scores from 86 to 93), yield potential 5.7% higher than that of the reference cultivar in provincial yield trials, short stature, good lodging resistance, and resistance to powdery mildew and yellow rust. It became a leading cultivar in zone II after 2000, occupying 800,000 ha in 2001, mostly in Shandong, Henan, Jiangsu, and Anhui. Jimai 20, selected from Lumai 14/Shandong 884187 by the Shandong AAS in 2003, was registered in Shandong, Henan, and Anhui Provinces, and in Tianjin. Shandong 884187, with excellent pan bread making quality, was derived from the USA cultivar Lancota. Jimai 20 was characterized by strong gluten quality and excellent flour color, and was used for making pan bread and Chinese noodles for many years across locations. It was also high yielding (equalling reference cultivar Lumai 14) and broadly adapted due to its drought and cold tolerance and sprouting resistance. It was a leading cultivar from 2004 to 2008, covering 1.5 million ha in 2007. Jimai 22, derived from a cross of two advanced lines, 935024 and 935106, by the same program in 2006, was characterized by high yield potential (outyielding the reference cultivar by 10%), short stature, good lodging resistance, tolerance to high temperatures during grainfilling, and resistance to yellow rust and powdery mildew. Jimai 22 is currently the leading cultivar in Shandong, with a sowing area of more than 1.5 million ha in 2009, and also widely grown in Hebei and Jiangsu Provinces.

Yannong 19, previously named Yanyou 361, was selected from Yan 1933/Shaan 82-29 by the Yantai Agricultural Research Institute in Yantai, Shandong Province, in 2001. It was broadly adapted largely due to its strong tillering ability and showed good performance under reduced irrigation and high temperatures during grainfilling, and under low fertility conditions. It possessed improved gluten quality and was equal to the reference cultivar in provincial yield trials. Yannong 19 has been a leading cultivar since 2003, with an annual sowing area of over 1.5 million ha, and is grown mostly in northern parts of Anhui and Jiangsu, and southern Shanxi Province. However, it is not widely grown in high yielding environments due to its average lodging resistance.

Neixiang 5 was developed from Nanda 2419/(Quality+Baimangmai+Baihuomai) in Henan Province and was the leading cultivar in the southern part of zone II and parts of the Yangtze Valley (zone III) with an annual sowing area of 1.4 million ha. Boai 7023, a re-selection of Funo, was released by a state farm in Boai County, Henan Province, in 1969. It was a major cultivar in southern Hennan and northern Anhui in the 1970s, covering 1.3 million ha in 1980. Baiquan Agricultural College (Baiquan AC) in Xinxiang, Henan Province, developed Bainong 3217 from Funo/Neixiang 5//Xiannong 39/3/Xinong 64(4)3/Yanda 24 in 1975. It showed stable and high yield potential (15.8% better than Zhengyin 1 in provincial yield trials), broad adaptation, early maturity, and yellow rust resistance. It was the leading cultivar in zone II in the 1980s, mostly in Henan, with a peak sowing area of 2 million ha.

Italian cultivar St1472/506, renamed Zhengyin 1 in Henan Province, was grown in zone II with an annual sowing area of 1.1 million ha in 1979. Zhengzhou 761, a derivative of Zhengyin 1, was crossed with Yanshi 4 (Fengchan 3/Zhengzhou 5//St 2422/464/Zhengzhou 17) to produce Yumai 18 (previously named Aizao 781), released in 1990. Yumai 18, characterized by semidwarf stature, early maturity, fast grain-filling rate, tolerance to hot winds, and resistance to yellow and leaf rust, was well-suited for the wheat/maize rotation system. It was a leading cultivar from 1990 to 2008 in Henan and Anhui Provinces, covering more than 1.5 million ha annually for more than 10 years.

Yumai 21, developed from Bainong 791/Yumai 2//Lumai 1/Yanshi 4 by the Zhoukou Agricultural Research Institute in Zhoukou, Henan Province, in 1992, was a leading cultivar in Henan in the 1990s with an annual sowing area exceeding 2 million ha. Its production area decreased rapidly after 2000 due to its poor quality and susceptibility to yellow rust and powdery mildew. It was characterized by short stature, high yield potential, early maturity, and tolerance to hot winds. Zhoumai 18, developed from Neixiang 185/Yumai 21 by the same program in 2004, was characterized by high and stable yields, outyielding the reference cultivar by 7.1% in the provincial yield trial. It has short stature (80 cm), good lodging resistance, and large white kernels (1000-kernel weight: 50 g). It has excellent adaptability, good performance under high temperatures during grainfilling and in rainfed conditions, and showed resistance to yellow rust, leaf rust, powdery mildew, leaf blotch, and false eyespot. At present, Zhoumai 18 is a leading cultivar in Henan, covering around 500,000 ha in 2009, and serves as check cultivar in provincial yield trials. Aikang 58 from Zhoumai 11//Wenmai 6/Zheng 8960 was released in 2005 by the Baiquan AC. It became a leading cultivar in Henan and northern parts of Jiangsu and Anhui, with a harvested area of 800,000 ha in 2009. Aikang 58 is characterized by high yield potential, excellent lodging resistance, resistance to yellow rust and powdery mildew, and broad adaptation.

Zhengmai 9023, released from Xinong 881/Shaan 213 by the Henan Academy of Agricultural Science in Zhengzhou in 2001, has average yield, similar to reference cultivar Yumai 18, but is earlier maturing and more broadly adapted. It is also tolerant to high temperatures during grainfilling and resistant to yellow rust, powdery mildew and Fusarium head scab. Zhengmai 9023 was registered in the Yellow and Huai Valleys and Lower Yangtze regions, and was widely adopted in southern Henan, northern parts of Anhui and Jiangsu, and in Hubei Province. It has been a leading cultivar since 2000, with the largest sowing area of 1.5 million ha from 2003 to 2006.

Jimai 30, previously known as Ji5418, was released from Shi 4144 crossed with line 78-347 derived from Aurora by the Hebei Academy of Agricultural Science (Hebei AAS) in Shijiazhuang in 1988. It showed good disease resistance, broad adaptation, early maturity, high yield potential, and suitability for cultivation in favorable environments. It took a leading position in zone II from late the 1980s to late 1990s and covered more than 1.2 million ha in 1990 in Hebei, Henan, northern Jiangsu, and Anhui.

Han 6172, produced from Han 4032/Zhongyin 1 (CIMMYT introduction) by Handan Agricultural Research Institute in Handan, Hebei Province, in 2001, is characterized by high yield potential and broad adaptation, outyielding reference cultivars by more than 7% in regional trials in the northern and southern parts of Yellow and Huai Valleys. It is tolerant to low temperatures in winter and spring, high temperatures during grainfilling, and is resistant to yellow rust. It shows outstanding performance under reduced irrigation and at various levels of soil fertility. It has been a leading cultivar in northern China, with more than 700,000 ha annually from 2003 to the present, mostly in Hebei, Shanxi, and Jiangsu Provinces.

Jinmai 33 was selected from Pingyang 79391/Pingyang 76262 by Shanxi Wheat Research Institute in Linfen in 1990. It had high and stable yields and strong drought tolerance, and became the leading cultivar in the rainfed areas of southern Shanxi and neighboring regions, covering 500,000 ha in 1993.

3.6 Yangmai cultivars derived from Italian wheats in zone III

Nanda 2419 was reselected from Italian cultivar Mentana, which was introduced into China in 1934 and recommended as a leading cultivar in 1939. It outyielded cultivars by 4.0-46.3% in 32 locations for three years in Jiangsu, Zhejiang, and Anhui, and showed early maturity, good resistance to stripe rust, and very broad adaptation. Nanda 2419 was the leading cultivar from the mid-1950s to mid-1960s and its sowing area throughout China reached 4.7 million ha in 1958.

Funo, introduced into China in 1956, reached its peak area of 1.1 million ha in 1977, mainly in Anhui, Jiangsu, Hubei, and Henan. Yangmai 1 was reselected from Funo by the Yangzhou Agricultural Research Institute (Yangzhou ARI) in Yangzhou, Jiangsu Province. It retained most of Funo's desirable traits, but had better disease resistance and yield potential. Released in 1967, it was the leading cultivar in the lower Yangtze Valley in the late 1960s and 1970s, covering 420,000 ha in 1978. Yangmai 2 and Yangmai 3 were reselected from Yangmai 1 by the Yangzhou ARI and released in 1976. They became the leading cultivars in zone III from the late 1970s to the early 1980s. The Yangzhou ARI developed Yangmai 5 and Yangmai 158 by crossing an F4 line of Nanda 2419/Triumph//Funo with St 1472/506 in 1986, and Yangmai 4, a sister line from Nanda 2419/Triumph//Funo crossed with St1472/506, in 1993. Yangmai 5 showed a 7-15% yield increase, and produced stable yields over a range of sowing dates; it was widely adapted, with improved tolerance to lodging, cold, and heat, and moderate resistance to powdery mildew, yellow rust, and Fusarium head blight. It became the leading cultivar in the lower Yangtze Valley from the mid-1980s to the early 1990s; its sowing area reached 1.4 million ha in 1992. Yangmai 158 was widely adapted, had stable performance, and outyielded Yangmai 5 by 10-20% in regional yield trials. It was the leading cultivar from 1994 until 2006, occupying over one million ha annually from 1997 to 2000.

3.7 Fan 6 and its derivatives in zone IV

Shannong 205, developed from Villa Glori/Hechuan Guangtou by the Wanxian Prefectural Agricultural Research Institute in Sichuan Province in 1956, was a leading cultivar from the late 1950s to the late 1960s, covering 530,000 ha in 1966, mostly in Sichuan, Guizhou, Hunan, Zhejiang, and Shanghai. Fan 6 was developed from a series of complex crosses: IBO1828/NP824/3/Wuyimai//Chengduguangtou branched wheat /Zhongnong483/4/Zhongnong 28B branched wheat/IBO1828//NP 824/Funo, by Sichuan Agricultural University in Yaan in 1969. Fan 6 was broadly adapted and had short stature, good lodging resistance, high yield potential, photoperiod insensitivity, tolerance to late sowing, and good resistance to yellow rust and root rot. It was the leading cultivar from the early 1970s to the early 1980s in zone IV and covered an area of 800,000 ha in 1979. Mianyang Agricultural Research Institute (Mianyang ARI) in Sichuan Province was very successful in developing cultivars from Fan 6, and most leading cultivars in Sichuan Province after the late 1970s were Fan 6 derivatives. Mianyang 11, developed from 70-5858/Fan 6 in 1979, outyielded Fan 6 by 11.3% based on data from provincial yield trials. It was broadly adapted and had short stature (80-85 cm), good lodging resistance, and good powdery mildew and yellow rust resistance, and escaped Fusarium head scab due to its early heading. It was the leading cultivar in the 1980s, reaching 1.5 million ha in 1984 in zones III and IV. Mianyang 15, Mianyang 19, Mianyang 20, and Mianyang 21 were developed through reselection of Mianyang 11 in 1984, 1984, 1987, and 1989, respectively. All four showed a 10% yield advantage and a 3-5 g improvement in 1000-kernel weight. Mianyang 15 was grown on more than 700,000 ha annually from 1988 to 1990, and Mianyang 19 reached about 400,000 ha in 1992. Mianyang 20 was sown on 330,000 ha annually for several years after 1989, and Mianyang 21 covered 300,000 ha in 1993. Mianyang 26 was developed by the Mianyang ARI from Mianyang 20/Chuanyu 9. It outyielded Mianyang 11 and its sister lines by 10-30% and showed improved disease resistance. It became the leading cultivar in Sichuan after 1996, covering 800,000 ha in 1998. A reselection of Fan 6, 808 was released by Zuqiao Township in Chengdu, Sichuan Province in 1989. It became a leading cultivar in Sichuan after 1990 and covered 400,000 ha in 1991.

3.8 Milestone cultivars in the spring wheat region

Introduced into Gansu Province in 1944, CI 12203 was called Gansu 96 in China. It was resistant to yellow and stem rust, common bunt, loose smut, and blossom midge; it was also broadly adapted and had good lodging resistance. Gansu 96 became the leading cultivar in the spring-sown spring wheat areas (zones VI, VII, and VIII), and covered 670,000 ha in 1959. Abbondanza, introduced into the northwestern spring wheat region in 1957, outyielded Quality and Gansu 96 by 15-25%, and was a leading cultivar in the mid 1960s, when it reached its peak area of 400,000 ha in zone III. Ganmai 8 was developed from Wuyimai/Abbondanza by the Gansu Academy of Agricultural Sciences, (Gansu AAS) in Lanzhou in 1964. It became the leading cultivar in spring wheat areas in Gansu and Ningxia in the early 1970s, covering 670,000 ha in 1975. Ningchun 4, another name for Yongliang 4, was developed from Sonora 64/Hongtou by the Seed Station in Yongliang County, Ningxia, in 1981. It had short stature (80 cm), good lodging resistance, broad adaptation, and high yield potential, represented by a 15% advantage over Doudi 1. It also had excellent noodle-making quality. Ningchun 4 has been the leading cultivar in zones VII and VIII since 1988 to the present, with annual sowing areas of 330,000 ha mostly in the irrigated areas of Ningxia, Gansu, and Inner Mongolia.

Hezou 2 and Hezou 4 were developed from Reward 137-8/Mangou 335A-531 and Mangou 335A-531/Marquillo, respectively, in the early 1950s. Hezou 2 showed tolerance to waterlogging during grainfilling, early maturity, and resistance to stem rust and spot blotch, whereas Hezou 4 had relatively strong stems, large spikes, and stem rust resistance. They became the leading cultivars in the 1950s. Kehan 6 and Kehan 7 were developed from Kezhen/Kehong by the Keshan Wheat Research Institute (Keshan WRI) in Keshan, Heilongjiang Province around 1970, and covered 310,000 ha and 230,000 ha, respectively. Kefeng 3, developed from Ke71F1370-7/Nadodores 63 by the Keshan WRI in 1982, outyielded the check by 17%. It was broadly adapted, around 80 cm tall, and showed good lodging resistance; it also possessed good resistance to stem and leaf rust, spot blotch, and Fusarium head scab, and tolerance to drought and waterlogging. Kefeng 3 was suitable for irrigated environments and became the leading cultivar in the 1980s, occupying 700,000 ha in 1987. Kehan 9 and Xinkehan 9 were developed from Kefeng 2/Ke74F5249-3 by the Keshan WRI in 1984 and 1988, respectively. They were high yielding under drought conditions, and were 80-100 cm in height. They were leading cultivars from the mid-1980s to the late 1990s and occupied 500,000 ha and 430,000 ha, respectively, in 1996. Kehan 10, developed from Ke 68-88/Ke 68F4-585-13//T808/Ke69-513 by Keshan WRI in 1988, outyielded the check by 13% in regional yield trials, had broad adaptation, drought tolerance at the seedling stage, and waterlogging tolerance at the late growth stage; it was also resistant to stem and leaf rust, and moderately susceptible to spot blotch and Fusarium head scab. Kehan 10 was suitable for eastern Heilongjiang and parts of Inner Mongolia, and became the leading cultivar in 1990, covering 512,000 ha in 1996.

4. Application of biotechnology in wheat breeding

China was a pioneer in the application of in vitro culture and somaclonal variation in several crops, including wheat. For example, the invention of the N6 medium by the Institute of Botany, Chinese Academy of Science in Beijing, allowed real progress in the early use of double haploids (Chu, 1978). A few released wheat cultivars, such as Jinghua 1, Beijing 8686, and Huapei 764, were derived from anther culture. Somatic variation obtained in vitro was also used for selecting new cultivars. For example, wheat lines 894013 and 894037 are new germplasm sources with high levels of resistance to Fusarium head scab, developed by the Jiangsu Academy of Agricultural Sciences in Nanjing. Tissue culture was also used to make numerous wide crosses in China for creating new genetic stocks tolerant to biotic and abiotic stresses, or materials for genetic studies.

Molecular markers have great potential for improving breeding efficiency when integrated into conventional breeding programs. In addition to validating molecular markers from other programs around the world, the CAAS-CIMMYT joint wheat program plays a leading role in molecular marker development and application, in close collaboration with the Shandong AAS in Jinan, the Sichuan Academy of Agricultural Science in Chengdu, and the Gansu Academy of Agricultural Science in Lanzhou. The approach is to clone genes such as the *Psy 1* genes on chromosomes 7A and 7B associated with yellow pigment content in flour and polyphenol oxidase (PPO) genes on chromosomes 2A and 2D, develop functional markers based on the allelic variants, and then validate them on Chinese wheat cultivars. Molecular markers developed in this manner can be used efficiently in breeding programs. Around 80 available markers, including those developed by other programs around the world, target such traits as quality, disease resistance, plant height, and adaptation (Table 4). Currently, molecular markers are used to characterize crossing parents, improve selection efficiency in segregating populations of backcrosses, and confirm the presence of targeted genes in advanced lines.

Table 4. Molecular markers available in the CAAS-CIMMYT wheat program.

Marker	Target gene/allele	Type	Trait Trait	Reference
gluA3a	*Glu-A3a*	STS	LMW-GS, gluten quality	Wang et al., 2010
gluA3b	*Glu-A3b*	STS	LMW-GS, gluten quality	Wang et al., 2010
gluA3ac	*Glu-A3a/c*	STS	LMW-GS, gluten quality	Wang et al., 2010
gluA3d	*Glu-A3d*	STS	LMW-GS, gluten quality	Wang et al., 2010
gluA3e	*Glu-A3e*	STS	LMW-GS, gluten quality	Wang et al., 2010
gluA3f	*Glu-A3f*	STS	LMW-GS, gluten quality	Wang et al., 2010
gluA3g	*Glu-A3g*	STS	LMW-GS, gluten quality	Wang et al., 2010
gluB3a	*Glu-B3a*	STS	LMW-GS, gluten quality	Wang et al., 2009b
gluB3b	*Glu-B3b*	STS	LMW-GS, gluten quality	Wang et al., 2009b
gluB3c	*Glu-B3c*	STS	LMW-GS, gluten quality	Wang et al., 2009b
gluB3d	*Glu-B3d*	STS	LMW-GS, gluten quality	Wang et al., 2009b
gluB3e	*Glu-B3e*	STS	LMW-GS, gluten quality	Wang et al., 2009b
gluB3fg	*Glu-B3f/g*	STS	LMW-GS, gluten quality	Wang et al., 2009b
gluB3g	*Glu-B3g*	STS	LMW-GS, gluten quality	Wang et al., 2009b
gluB3h	*Glu-B3h*	STS	LMW-GS, gluten quality	Wang et al., 2009b
gluB3i	*Glu-B3i*	STS	LMW-GS, gluten quality	Wang et al., 2009b
Ax2*	Ax1/ Ax-null/ Ax2*	STS	HMW-GS, gluten quality	Ma et al., 2003
Ax2*	Ax2*	STS	HMW-GS, gluten quality	Ma et al., 2003
Bx17	Bx17+By18	STS	HMW-GS, gluten quality	Ma et al., 2003
Bx7	Bx7	STS	HMW-GS, gluten quality	Ma et al., 2003
TaBAC1215C06-F517— TaBAC1215C06-F517/R964	Bx7^{OE}	STS	HMW-GS, gluten quality	Ragupathy et al., 2007
ZSBy8F5/R5	By8	STS	HMW-GS, gluten quality	Lei et al., 2006
ZSBy9aF1/R3	By9	STS	HMW-GS, gluten quality	Lei et al., 2006
ZSBy9F7/R6	By9	STS	HMW-GS, gluten quality	Lei et al., 2006
ZSBy9F2/R2	Bx14+By15	STS	HMW-GS, gluten quality	Lei et al., 2006
ZSBy9F2/R2	Bx13+By16	STS	HMW-GS, gluten quality	Lei et al., 2006
Mar	Bx20	STS	HMW-GS, gluten quality	Butow et al., 2004
Dx5	Dx5	STS	HMW-GS, gluten quality	D'Ovidio and Anderson, 1994
Dx5	Dx5	STS	HMW-GS, gluten quality	Ma et al., 2003
P1/P2	Dx2, Dx5	STS	HMW-GS, gluten quality	Ahmad, 2000
P3/P4	Dy10, Dy12	STS	HMW-GS, gluten quality	Ahmad, 2000
P5/P6	Bx7	STS	HMW-GS, gluten quality	Ahmad, 2000
Wx-A1	*Wx-7AS*	STS	Synthesis of amylase	Nakamura et al., 2002
Wx-B1	*Wx-4AL*	STS	Synthesis of amylase	Nakamura et al., 2002
Wx-D1	*Wx-7DS*	STS	Synthesis of amylase	Nakamura et al., 2002
PPO18	*Ppo-A1a/b*	STS	PPO activity, bright color	Sun et al., 2005
PPO16	*Ppo-D1a/b*	STS	PPO activity, bright color	He et al., 2007
PPO29	*Ppo-D1a/b*	STS	PPO activity, bright color	He et al., 2007
PPO33	*Ppo-A1a/b*	STS	PPO activity, bright color	He et al., 2007
YP7A	*Psy-A1a/b*	STS	PSY gene in 7A, bright color	He et al., 2008
YP7A-2	*Psy-A1a/b/c*	STS	PSY gene, bright color	He et al., 2009
YP7B-1	*Psy-B1a/b*	STS	PSY gene in 7B, bright color	He et al., 2009
YP7B-2	*Psy-B1c*	STS	PSY gene in 7B, bright color	He et al., 2009
YP7B-3	*Psy-B1d*	STS	PSY gene in 7B, bright color	He et al., 2009
YP7B-4	*Psy-B1e*	STS	PSY gene in 7B, bright color	He et al., 2009
Pinb-D1b	*Pinb-D1b*	STS	Grain texture	Giroux and Morris, 1997
Wgwm261	*Rht 8*	SSR	Plant height	Worland et al., 1998
Rht-B1b	*Rht-B1b (Rht1)*	STS	Plant height	Ellis et al., 2002
Rht-D1b	*Rht-D1b (Rht2)*	STS	Plant height	Ellis et al., 2002
Ppd-D1	*Ppd-D1a/b*	STS	Photo period response	Beales et al., 2007
Vp1B3	*Vp-1B*	STS	Pre-harvest-sprouting	Yang et al., 2007
Vrn-A1	*Vrn –A1*	STS	Vernalization	Yan et al., 2004
Vrn-B1	*Vrn-B1*	STS	Vernalization	Fu et al., 2005
Vrn-D1	*Vrn-D1*	STS	Vernalization	Fu et al., 2005
Vrn-B4	*Vrn-B4*	STS	Vernalization	Dubcovsky, pers. comm.
Lr19	7Ag.7DL	STS	7Ag.7DL translocation	Prins et al., 2001

Table 4. Molecular markers .... cont'd.

Marker	Target gene/allele	Type	Trait Trait	Reference
ω-sec-p1/ω-sec-p2	1B/1R	STS	1B/1R translocation	Chai et al., 2006
ω-sec-p3/ω-sec-p4	1B/1R	STS	1B/1R translocation	Chai et al., 2006
O11B3/O11B5	1B/1R	STS	1B/1R translocation	Froidmont, 1998
SECA2/SECA3	1B/1R	STS	1B/1R translocation	Froidmont, 1998
AF1/AF4	1B/1R	STS	1B/1R translocation	Francis et al., 1995
NOR	1B/1R	STS	1B/1R translocation	Koebner, 1995
cssfr1	*Yr18/Lr34/Pm38*	STS	Multi-resistance genes	Lagudah et al., 2009
cssfr2	*Yr18/Lr34/Pm38*	STS	Multi-resistance genes	Lagudah et al., 2009
cssfr3	*Yr18/Lr34/Pm38*	STS	Multi-resistance genes	Lagudah et al., 2009
cssfr4	*Yr18/Lr34/Pm38*	STS	Multi-resistance genes	Lagudah et al., 2009
cssfr5	*Yr18/Lr34/Pm38*	STS	Multi-resistance genes	Lagudah et al., 2009
Xwgp-17	*Yr5*	RGA	Resistance to yellow rust	Yan et al., 2003
Xwgp-18	*Yr5*	RGA	Resistance to yellow rust	Yan et al., 2003
Xgwm295.1	*Yr18*	SSR	Resistance to yellow rust	Suenaga et al., 2003
csLV34	*Yr18*	STS	Resistance to yellow rust	Lagudah et al., 2006
CYS-5	*Yr26*	RGA	Resistance to yellow rust	Wen et al., 2008
Xcfa2040/Xbarc32	*YrZH84*	SSR	Resistance to yellow rust	Li et al., 2006b
Xgwm498/Xbarc187	*YrZH42*	SSR	Resistance to yellow rust	Li et al., 2006a
Xpsr113, Xpsr10	*Pm12*	RFLP	Resistance to powdery mildew	Jia et al., 1996
Xgwm159	*Pm16*	SSR	Resistance to powdery mildew	Chen et al., 2005
Xpsp3029	*Pm31*	SSR	Resistance to powdery mildew	Xie et al., 2003
gwm533	*Sr2*	SSR	Resistance to stem rust	Spielmeyer et al., 2003
Gb	*Sr25/Lr19*	STS	Resistance to stem rust	Prins et al., 2001
Iag95	*Sr31*	STS	Resistance to stem rust	Mago et al., 2002

Chinese scientists started working on genetically modified (GM) wheat in the early 1990s, and a national GM wheat project was initiated in 2008 with the participation of major breeding programs. This 15-year project has excellent funding and targets such traits as drought tolerance and pre-harvesting sprouting resistance, improved gluten strength and starch parameters, and high yield potential. Significant progress has been made in improving drought tolerance and resistance to pre-harvesting sprouting. Field trials are being conducted in several institutes, and it is expected that rapid progress will be achieved in the near future.

5. Future prospects

The area under wheat in China has stayed at 23.5 million ha over the last four years, and it is not likely to expand. Given the continuing increase in population and living standards, production needs to reach 120-130 million tonnes by 2030. In the meantime, Chinese wheat producers are facing great challenges such as reduced soil fertility, water scarcity, environmental contamination, and increased incidence of high temperatures and drought caused by global climate change, combined with increasing labor shortages and land-use shifts from grain production to cash crops. Although breeding high yielding cultivars remains the first priority, those cultivars will need to be properly managed to reach their full potential (see a review of crop management strategies in Wang et al., 2009a). The future challenge of wheat breeding in China is to raise or maintain genetic gains in grain yield and improve processing quality, without increasing inputs for the wheat-based double cropping system in the main wheat growing regions. Chinese scientists have worked on hybrid wheat for around 40 years, but no significant progress has been achieved in farmer adoption of hybrid wheat. Thus, conventional breeding in combination with increased biotechnology will play a leading role in future cultivar development.

The significant genetic improvements in grain yield in China can be attributed primarily to increased kernel weight per spike, reduced plant height, and increased harvest index, and also to the combination of Chinese and foreign germplasm. Large kernel size is generally preferred in China and it is associated with rapid grainfilling under high temperatures, which are very common in northern China after anthesis. Therefore, thousand kernel weight (TKW) is an important selection criterion for Chinese wheat breeding programs. Considering the limited potential to further increase TKW in Chinese environments, and the trend towards reducing spike number per unit area, it is generally believed that further increases of kernels per spike (even 2-3 kernels) could offer an opportunity for increasing grain yield potential. Experience in developing new cultivars such as Zhoumai 18 and Zhongmai 175 supports this approach.

The significant increase in grain yield in China occurred mainly in the early 1980s, largely due to the successful utilization of dwarfing genes and the incorporation of the 1B.1R translocation. However, it is very unlikely that further reduction in plant height will benefit yield progress in zones I and II. It is generally believed that the optimum plant height in zone II is around 80 cm, based on the experience of Chinese wheat breeders (Zhuang, 2003). Most current leading cultivars in zones I and II have plant heights of around 75-85 cm, suggesting that combinations of *Rht-B1b* or *Rht-D1b* with *Rht 8* confer optimal plant height for those regions. Combining *Rht-B1b* with *Rht 8* is suggested for zone III. The GA-insensitivity genes *Rht-B1b* and *Rht-D1b* have pleiotropic effects on plant growth, causing reduction in coleoptile length and seedling leaf area. Other dwarfing genes such as *Rht 8* and *Rht 9* that do not confer GA insensitivity may therefore be more suitable for reducing final plant height without compromising early plant growth.

In addition to powdery mildew and yellow rust, Fusarium head blight is now endemic in the main wheat regions, and sharp eyespot and take-all are also present. It is important that foreign germplasm and alien genes from wild relatives of wheat be explored as potential sources of multiple disease resistance. Introduced cultivars have played an important role in Chinese wheat breeding and production in the past. Over 200 synthetic hexaploid wheat accessions from CIMMYT have been introduced into China in recent years. Elite synthetics were crossed and backcrossed with Chinese commercial wheat cultivars to improve yellow rust resistance and yield potential. Four synthetic derivatives, Chuanmai 38, Chuanmai 42, Chuanmai 43, and Chuanmai 47, have been released in zone IV in recent years. Of these, Chuanmai 42, with large kernels and yellow rust resistance, had higher average yields (> 6 t/ha) than any other cultivar over two years in Sichuan provincial yield trials, outyielding the commercial reference cultivar Chuanmai 107 by 22.7%. Chuanmai 42 has increased yields in farmers' fields by 0.45-0.75 t/ha and is currently a leading cultivar in Sichuan Province.

To reduce inputs used in wheat production, it is essential to breed cultivars with higher water, nitrogen (N), and phosphorus (P) use efficiencies. Cultivars with drought tolerance and better water use efficiency are urgently needed in rainfed areas. Initially, most wheat breeding programs in China developed cultivars for optimum environments, and few paid attention to drought tolerance before the 1990s even though around 40% of the country's wheat area is rainfed, particularly in the spring-sown spring wheat region (zones VI, VII and VIII). Today the national program gives priority to breeding drought tolerant cultivars, such as Jinmai 47, Luohan 2 and Shijiazhuang 8 with high water use efficiency, which are already in production. Cultivars with higher N and P use efficiency have been identified, including Xiaoyan 6, Zhoumai 9, Chuangwu 134, Shi 5418, and Henong 341. They will be used to breed cultivars combining higher P and N use efficiencies in the future.

Demand for good quality wheat is expected to rise given the rapidly increasing consumption of fast foods, such as instant and frozen noodles, and western products, such as bread and cookies. It is estimated that there already is market demand for more than 20 million tonnes of good quality wheat suitable for making noodles, dumplings, western breads, cookies, and cakes. This represents around 20% of the national production and over 50% of commercial wheat production. For this reason, development of good quality wheat in northern China has been a national strategy for several years (He et al., 2002). In addition to good quality cultivars, the industry requires appropriate production systems, improved quality testing, and adequate grain segregation and storage capacity. Experience has shown that it is possible to combine high grain yield and excellent industrial quality, as exemplified by Jimai 20 and Yumai 34, leading cultivars in Shandong and Henan, respectively.

For decades, repeated attempts have been made to develop hybrid wheat systems, and China remains a major, if not the main, world player in this sense (Zhang et al., 2001; Yuan et al., 2007). Several breeding teams used to work with various types of cytoplasmic male sterility systems based on alien cytoplasm, genetic male sterility, and gametocides.

Following the success of hybrid rice, hybrid wheat breeders are trying to develop two-line hybrid wheat systems that exploit differential plant responses to different thermo-and photo-period environments (Guo et al., 2006). Even with further progress in the science, commercial hybrid wheat will be delayed as we will need to bridge the gap between the breeding nursery and farmers' fields. However, if successfully developed, hybrid wheat would undoubtedly contribute a significant production increase.

With a significant investment in wheat biotechnology, both molecular marker-assisted selection and genetic transformation are expected to play increasingly important roles in the future. In 2008 the Chinese government decided to fund a GM wheat project for 15 years. It is crucial to integrate the advances in biotechnology into leading conventional breeding programs. Biotechnology offers new tools for breeding programs, and international cooperation may accelerate their use. More training is needed for breeders to take advantage of available markers in practical breeding programs.

Clearly, widening the use of elite wheat germplasm (i.e., synthetic wheat) and close collaboration in the use of molecular markers, genetic transformation technology, and conventional and hybrid breeding will be essential to developing the next generation of improved cultivars in China. It is important to ensure that the necessary biological materials and technological tools are available so that wheat production may keep up with the increasing population and living standards.

References

Ahmad, M. 2000. Molecular marker-assisted selection of HMW glutenin alleles related to wheat bread quality by PCR-generated DNA markers. Theoretical and Applied Genetics 101: 892–896.

Beales, J., Turner, A., Griffiths, S., Snape, J.W., and Laurie, D.A. 2007. A pseudo-response regulator is misexpressed in the photoperiod insensitive *Ppd–D1a* mutant of wheat (*Triticum aestivum* L.). Theoretical and Applied Genetics 115: 721–733.

Butow, B.J., Gale, K.R., Ikea, J., Juhász, A., Bedö, Z., Tamás, L., and Gianibell, M.C. 2004. Dissemination of the highly expressed Bx7 glutenin subunit (*Glu-B1al* allele) in wheat as revealed by novel PCR markers and RP-HPLC. Theoretical and Applied Genetics 109: 1525–1535.

Chai, J.F., Zhou, R.H., Jia, J.Z., and Liu, X. 2006. Development and application of a new codominant PCR marker for detecting 1BL·1RS wheat-rye chromosome translocations. Plant Breeding 125: 302–304.

Chen, X.M., Luo, Y.H., Xia, X.C., Xia, L.Q., Chen, X., Ren, Z.L., He, Z.H., and Jia, J.Z. 2005. Chromosomal location of powdery mildew resistance gene *Pm16* in wheat using SSR marker analysis. Plant Breeding 124: 225–228.

Chu, C.C. 1978. The N6 medium and its application to anther cultures of cereal crops. In: Proceedings of Symposium on Plant Tissue Culture, Beijing Science Press, pp. 45-50.

D'Ovidio, R., and Anderson, O.D. 1994. PCR analysis to distinguish between alleles of a member of a multigene family correlated with wheat bread-making quality. Theoretical and Applied Genetics 88: 759–763.

Ellis, M.H., Spielmeyer, W., Rebetzke, G.J., and Richards, R.A. 2002. "Perfect" markers for the *Rht-Blb* and *Rht-Dlb* dwarfing genes in wheat. Theoretical and Applied Genetics 105: 1038–1042.

Francis, H.A., Leitch, A.R., and Koebner, R.M.D. 1995. Conversion of a RAPD generated PCR product, containing a novel dispersed repetitive element, into a fast and robust assay for the presence of rye chromatin in wheat. Theoretical and Applied Genetics 90: 636–642.

Froidmont, D.D. 1998. A co-dominant marker for the 1BL·1RS wheat-rye translocation via multiplex PCR. Journal of Cereal Science 27: 229–232.

Fu, D., Szücs, P., Yan, L., Helguera, M., Skinner, J.S., Von Zitzewitz, J., Hayes, P.M., and Dubcovsky, J. 2005. Large deletions within the first intron in VRN-1 are associated with spring growth habit in barley and wheat. Molecular and General Genomics 273: 54–65.

Giroux, M.J., and Morris, C.F. 1997. A glycine to serine change in puroindoline b is associated with wheat grain hardness and low levels of starch-surface friabilin. Theoretical and Applied Genetics 95: 857–864.

Guo, R.X., Sun, D.F., Tan, Z.B., and Rong, D.F. 2006. Two reccesive genes controlling thermophoto period-sensitive male sterility in wheat. Theoretical and Applied Genetics 112: 1271-1276.

He, Z.H., Rajaram, S., Xin, Z.Y., and Huang, G.Z. 2001. A History of Wheat Breeding in China. Mexico, D.F.: CIMMYT.

He, Z.H., Lin, Z.J., Wang, L.J., Xiao, Z.M., Wan, F.S., and Zhuang, Q.S. 2002. Classification of Chinese wheat regions based on quality. Scientia Agricultura Sinica 35: 359-364 (in Chinese).

He, X.Y., He, Z.H., Zhang, L.P., Sun, D.J., Morris, C.F., Furerst, E.P., and Xia, X.C. 2007. Allelic variation of polyphenol oxidase (*PPO*) genes located on chromosomes 2A and 2D and development of functional markers for the *PPO* genes in common wheat. Theoretical and Applied Genetics 115: 47–58.

He, X.Y., Zhang, Y.L., He, Z.H., Wu, Y.P., Xiao, Y.G., Ma, C.X., and Xia, X.C. 2008. Characterization of a phytoene synthase 1 gene (*Psy1*) located on common wheat chromosome 7A and development of a functional marker. Theoretical and Applied Genetics 116: 213–221.

He, X.Y., He, Z.H., Ma, W., Appels, R., and Xia, X.C. 2009. Allelic variants of phytoene synthase 1 (*Psy1*) genes in Chinese and CIMMYT wheat cultivars and development of functional markers for flour colour. Molecular Breeding 23: 553–563.

Jia, J., Devos, K.M., and Chao, S. 1999. RFLP-based maps of the homoeologous group-6 chromosomes of wheat and their application in the tagging of *Pm12*, a powdery mildew resistance gene transferred form *Aegilops speltoides* to wheat. Theoretical and Applied Genetics 98: 941–946.

Jin, S.B. 1986. Chinese Wheat Cultivars and Their Pedigrees (1962-1982). Beijing, China Agriculture Press (in Chinese).

Jin, S.B. 1996. Chinese Wheat Science. Beijing, China Agriculture Press (in Chinese).

Jin, S.B. 1997. Chinese Wheat Cultivars and Their Pedigrees (1983-1993). Beijing, China Agriculture Press (in Chinese).

Koebner, R.M.D. 1995. Generation of PCR-based markers for the detection of rye chromatin in a wheat background. Theoretical and Applied Genetics 90: 740–745.

Lagudah, E.S., McFadden, H., Singh, R.P., Huerta-Espino, J., Bariana, H.S., and Spielmeyer, W. 2006. Molecular genetic characterization of the Lr34/Yr18 slow rusting resistance gene region in wheat. Theoretical and Applied Genetics 114: 21–30.

Lagudah, E.S., Krattinger, S.G., Herrera-Foessel, S., Singh, R.P., Huerta-Espino J., Spielmeyer, W., Brown-Guedira, G., Selter, L.L., and Keller, B. 2009. Gene-specific markers for the wheat gene Lr34/Yr18/Pm38 which confers resistance to multiple fungal pathogens. Theoretical and Applied Genetics 119: 889-898.

Lei, Z.S., Gale, K.R., He, Z.H., Gianibelli, C., Larroque, O., Xia, X.C., Butow, B.J., and Ma, W. 2006. Y-type gene specific markers for enhanced discrimination of high molecular weight glutenin alleles at the *Glu-B1* locus in hexaploid wheat. Journal of Cereal Science 43: 94–101.

Li, G.Q., Li, Z.F., Yang, W.Y., Zhang, Y., He, Z.H., Xu, S.C., Singh, R.P., Qu, Y.Y., and Xia, X.C. 2006a. Molecular mapping of stripe rust resistance gene *YrCH42* in Chinese wheat cultivar Chuanmai 42 and its allelism with *Yr24* and *Yr26*. Theoretical and Applied Genetics 112: 1434–1440.

Li, Z.F, Zheng, T.C., He, Z.H., Li, G.Q., Xu, S.C., Li, X.P., Yang, G.Y., Singh, R.P., and Xia, X.C. 2006b. Molecular tagging of stripe rust resistance gene *YrZH84* in Chinese wheat line Zhou 8425B. Theoretical and Applied Genetics 112: 1098–1103.

Ma, W., Zhang, W., and Gale, K.R. 2003. Multiplex-PCR typing of high molecular weight glutenin alleles in wheat. Euphytica 134: 51–60.

Mago, R., Speilmeyer, W., Lawrence, G.J., Lagudah, E.S., Ellis, J.G., and Pryor, A.J. 2002. Identification and mapping of molecular markers linked to rust resistance genes located on chromosome 1RS of rye using wheat rye translocation lines. Theoretical and Applied Genetics 104: 1317–1324.

Nakamura, T., Vrinten, P., Saito, M., and Konda, M. 2002. Rapid classification of partial waxy wheat using PCR-based markers. Genome 45: 1150–1156.

Prins, R., Groenewald, J.Z., Marais, G.F., Snape, J.W., and Koebner, R.M.D. 2001. AFLP and STS tagging of *Lr19*, a gene conferring resistance to leaf rust in wheat. Theoretical and Applied Genetics 103: 618–624.

Ragupathy, R., Naeem, H.A., Reimer, E., Lukow, O.M., Sapirstein, H.D., and Cloutier, S. 2007. Evolutionary origin of the segmental duplication encompassing the wheat *Glu-B1* locus encoding the overexpressed Bx7 (Bx7^{OE}) high molecular glutenin subunit. Theoretical and Applied Genetics 116: 283–296.

Spielmeyer, W., Sharp, P.J., and Lagudah, E.S. 2003. Identification and validation of markers linked to broad spectrum stem rust resistance gene *Sr2* in wheat (*Triticum aestivum* L.). Crop Science 43: 333–336.

Suenaga, K., Singh, R.P., Huerta-Espino, J., and William, H.M. 2003. Microsatellite markers for genes *Lr34*/*Yr18* and other quantitative trait loci for leaf rust and stripe rust resistance in bread wheat. Phytopathology 93: 881–890.

Sun, D.J., He, Z.H., Xia, X.C., Zhang, L.P., Morris, C.F., Appels, R., Ma, W.J., and Wang, H. 2005. A novel STS marker for polyphenol oxidase activity in bread wheat. Molecular Breeding 16: 209–218.

Wang, F.H., He, Z.H., Sayre, K., Li, S.D., Si, J.S., Feng, B., and Kong, L.H. 2009a. Wheat cropping systems and technologies in China. Field Crop Research 111: 181-188.

Wang, L.H., Li, G.Y., Peña, R.J., Xia, X.C., and He, Z.H. 2010. Identification of novel allelic variants at *Glu-A3* locus and development of STS markers in common wheat (*Triticum aestivum* L.), Journal of Cereal Science 51: 301-312.

Wang, L.H., Zhao, X.L., He, Z.H., Ma, W., Appels, R., Peña, R.J., and Xia, X.C. 2009b. Characterization of low-molecular-weight glutenin subunit *Glu-B3* genes and development of STS markers in common wheat (*Triticum aestivum* L.). Theoretical and Applied Genetics 118: 525–539.

Wen, W.E., Li, G.Q., He, Z.H., Yang, W.Y., Xu, M.L., and Xia, X.C. 2008. Development of an STS marker tightly linked to *Yr26* against wheat stripe rust using the resistance gene-analog polymorphism (RGAP) technique. Molecular Breeding 22: 507–515.

Worland, A.J., Borner, A., Korzun, V., Li, W.M., Petrovic, S., and Sayers, E.J. 1998. The influence of photoperiod genes on the adaptability of European winter wheats. Euphytica 100: 385–394.

Xie, C., Sun, Q., Ni, Z., Yang, T., Nevo, E., and Fahima, T. 2003. Chromosomal location of a *Triticum dicoccoides* derived powdery mildew resistance gene in common wheat by using microsatellite markers. Theoretical and Applied Genetics 106: 341–345.

Yan, G.P., Chen, X.M., Line, R.F., and Wellings, C.R. 2003. Resistance gene-analog polymorphism markers co-segregating with the *Yr5* gene for resistance to wheat stripe rust. Theoretical and Applied Genetics 106: 636–643.

Yan, L., Helguera, M., Kato, K., Fukuyama, S., Sherman, J., and Dubcovsky, J. 2004. Allelic variation at the VRN-1 promoter region in polyploidy wheat. Theoretical and Applied Genetics 109: 1677–1686.

Yang, Y., Zhao, X.L., Xia, L.Q., Chen, X.M., Xia, X.C., Yu, Z., He, Z.H., and Röder, M. 2007. Development and validation of a Viviparous-1 STS marker for pre-harvest sprouting tolerance in Chinese wheats. Theoretical and Applied Genetics 115: 971–980.

Yuan, M.L., Wang, S.H., and Zhou, K.J. 2007. Advances in research of generation heterosis utilization of spring wheat in Gansu province. Journal of Gansu Agricultural Science and Technology 7: 32-34.

Zhang, A.M., Nie, X., Liu, D., and Guo, X. 2001. Advances of hybrid wheat breeding in China. Cereal Research Communications 29: 343-350.

Zhang, X.K., Xiao, Y.G., Zhang, Y., Xia, X.C., Dubcovsky, J., and He, Z.H., 2008. Allelic variation at the vernalization genes *Vrn-A1*, *Vrn-B1*, *Vrn-D1* and *Vrn-B3* in Chinese wheat cultivars and their association with growth habit. Crop Science 48: 458-470.

Zhou, Y., He, Z.H., Sui, X.X., Xia, X.C., Zhang, X.K., and Zhang, G.S. 2007a. Genetic improvement of grain yield and associated traits in the northern China winter wheat region from 1960 to 2000. Crop Science 47: 245-253.

Zhou, Y., Zhu, H.Z., Cai, S.B., He, Z.H., Zhang, X.K., Xia, X.C., and Zhang, G.S. 2007b. Genetic improvement of grain yield and associated traits in the southern China winter wheat region: 1949 to 2000. Euphytica 157: 465-473.

Zhuang, Q.S. 2003. Wheat Improvement and Pedigree Analysis in Chinese Wheat Cultivars. Beijing, China Agriculture Press (in Chinese).

Chapter 5.

Barley breeding and production in China

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1. Introduction

Barley is the fourth most important cereal crop in the world after wheat, rice, and maize in terms of both production and area. It is not only a good feed crop, but also the leading malting crop and is gaining importance as a health food. Naked barley is a staple food for Tibetans.

Barley is more tolerant to cold, drought, salinity, and low fertility than other major cereal crops. It can be grown in all provinces of China, even at altitudes as high as 4,700 m above sea level, making it the most adaptable and widely distributed of the cereal crops. The average land area per person in China is among the lowest in the world. Today the Chinese population is more than 1.4 billion, and that land area is continuing to decrease given the expansion of cities and new infrastructure such as roads and housing. On the other hand, there are also many wasteland areas in the north, saline areas near the sea, and fallow field areas in the south, totaling more than 6.7 million ha (m ha). If such areas could be sown to barley, it would not only resolve a barley demand problem, but also significantly enhance farm income and agricultural development.

The demand for processing barley in China is more than 10 million tonnes (mt) per year. With domestic production less than 4 mt per year, there is a huge deficit which must be met by imports from international markets.

1.1 History of barley production

Barley is an ancient crop in China. It is mentioned in texts such as hieroglyphs from 2000 BC (Xu and Feng, 2001) and appears in inscriptions on bones and tortoise shells from the Yinshang dynasty (1600-1046 BC). There has been a formal Chinese word for barley, i.e., *da mai*, since 300 BC (Lu, 1996).

A century ago, China was the world's largest barley producer. From 1914 to 1918, the area sown to barley was 8.0 m ha, representing about 23.6% of the world's barley area, and production was 9.0 mt. In 1936, barley area and production were 6.54 m ha and 4.05 mt, accounting for 13.6% and 8.4% of world levels, respectively. The average yield per ha was 619.2 kg, about 61.8% of the world average. This level of production remained stable until the mid-1940s, when barley area and production were 6.1 m ha and 6.3 mt, accounting for 13.4% and 12.6% of world levels, respectively (Huang, 2001). During this period, China remained the leading barley producing country. As shown in Table 1, there were large fluctuations in production beginning in the 1950s, and with the development of modern

Table 1. Barley production and imports in China.

Year	Area (m ha)	Production (mt)	Yield (kg/ha)	Beer production (mt)	Malting production (mt)	Imports for malting (mt)
1950s	3.87	3.45	891	na	na	na
1960s	3.53	3.71	1,052	na	na	na
1970s	6.50	9.90	1,523	na	na	0.24
1980s	3.33	7.00	2,102	0.69	0.12	0.40
1990s	2.00	4.64	2,321	6.92	1.15	0.89
2000	0.79	2.65	3,347	22.31	1.60	2.12
2001	0.77	2.89	3,760	23.01	1.50	2.20
2002	0.92	3.33	3,640	24.18	1.80	1.91
2003	0.90	3.27	3,626	25.46	2.18	1.37
2004	0.79	3.20	3,760	28.75	2.16	1.71
2005	1.07	4.19	3,916	31.89	2.29	2.18
2006	1.31	4.78	3,655	36.22	2.79	2.15
2007	1.04	3.54	3,619	38.24	2.35	0.91
2008	1.61	5.83	3,630	41.03	3.44	1.08

Source: China Agricultural Data Collection.
na = Data not available.

agriculture and improved irrigation and fertilization practices, along with the increasing demand for food, there was a gradual decline in the area of barley production.

In 1957, the barley growing area increased to 5.4 m ha, accounting for 9.1% of world production. After that, it went down again because of the increase in the maize and wheat areas. In the 1970s and 1980s, it peaked again with the expansion of multiple cropping systems and better cultivars. However, production only accounted for 7.44% and 5.74% of the world levels due to the rapid development of the brewing and feed industries in developed countries. With the increased central control of crop planting and prices set by the government in the 1980s, there was little demand for barley, and very low benefits for producers. The barley area consequently decreased to 3.3 m ha, and production was 7.0 mt, accounting for 6.3% and 4.12% of world totals. With the development of the brewing industry in the mid-1980s and the corresponding increase in the demand for malting barley, production increased mainly in Jiangsu, Zhejiang, Gansu, Xinjiang, and Heilongjiang. There was also a very significant increase in barley imports because the imported product had better malting quality.

By the early 1990s, the barley area was 2.0 m ha, accounting for only 2.75% of world production. In 2008, area and production were 1.6 m ha and 5.8 mt, respectively. The largest provincial planting areas were in Inner Mongolia (0.25 m ha), Jiangsu (0.23 m ha), Tibet (0.21 m ha), Yunnan (0.19 m ha), Gansu (0.17 m ha), Hubei (0.12 m ha), Sichuan (0.09 m ha), Qinghai (0.08 m ha), Xinjiang (0.08 m ha), Heilongjiang (0.05 m ha), Henan (0.04 m ha), Guizhou (0.03 m ha), and Zhejiang (0.03 m ha). Based on 2009 data, production of winter barley, used both for malting and feed, was 980,000 tonnes. Jiangsu is the largest producer with 650,000 tonnes, followed by Yunnan with 150,000 tonnes, then by Hubei and Zhejiang which together produce 150,000 tonnes; the remaining provinces account for 30,000 tonnes. Production of spring malting barley was 1.1 million tonnes; Gansu, Inner Mongolia, and Xinjiang are the three largest producers, with 450,000 tonnes, 350,000 tonnes and 240,000 tonnes, respectively. Other provinces, including Ningxia, Hebei, and Qinghai, together produced 60,000 tonnes of spring barley.

There were several reasons for the decline in barley production: firstly, research on barley improvement was lagging; at the same time, the gap between the malting quality of local and imported cultivars was increasing. There was also a lack of infrastructure for mechanized production, drying, storage, transportation, and marketing of malting barley. Consequently, it was much simpler for processors to import the grain directly to the processing facilities than to buy it on the local market. Secondly, there was little research on barley as a feed grain, again a huge difference from what was occurring in western and northern Europe. In China, most of the barley continues to be fed directly to animals; very little is marketed or used in processed feeds. There is a shortage of feed grains in southern China, but no real market for feed barley. Thirdly, barley prices were so low that farmers gained little benefit from growing and marketing the crop. In sum, the development of barley as a significant crop in China was hindered on multiple fronts: lack of genetic improvement, especially in the cost-beneficial areas of malting quality and other special uses, lack of mechanization and transport, and lack of a suitable marketing system for grain products.

1.2 Barley demand in China

Beer consumption in China has increased rapidly in recent years. In 2001, consumption was 17 liters per capita, and it increased to 24 liters per capita by 2007. In 2001, more than 2.2 mt of malting barley were imported, mainly from Canada and Australia. This represented 53% of the international trade in that commodity and accounted for 60% of China's needs (Yang et al., 2003).

The main factors affecting China's beer industry are insufficient local malting barley (largely due to the effects of abiotic and biotic stresses on malting quality and production) and dependence on an unstable world market. It is therefore important to develop a modern national breeding program for malting barley, but such a program would not succeed if the storage, transport, and marketing infrastructure is not greatly improved.

Barley is also a good feed crop, with a nutritional value similar to that of maize. China imports about 15 mt of feed barley per year, or about 70% of the world trade in feed barley. However, a large proportion of the imported feed barley is used to make beer. The greatest demand for feed grain is in southern China. To meet this demand, there are three options. One is to use locally produced rice, the second is to obtain feed grains from northern China, and the third is to import feed grains from the international market. There has also been a rapid increase in the feed use of barley. Recently, there was significant progress in research on additives such as β-glucanase at the Zhejiang Academy of Agricultural Science (Zhejiang AAS) stationed in Hangzhou (Xu et al., 2004). For example, an assorted barley feed with an added enzyme was developed that cost 5-10% less than maize feed. To address the demand for feed barley in southern China, it is necessary to select good quality, high yielding feed barley, build a feed barley production base, and use winter fallow fields and alkaline soils to produce feed barley. Current opportunities for barley production are not attractive, and they will not improve unless new infrastructure is developed and national markets for feed grains improve.

Barley is still a major staple food in several highland regions of China, including Tibet, Qinghai, and small parts of Sichuan, Yunnan, and Gansu. These regions are characterized by harsh living conditions and low production systems. In 2007, naked barley area and production in these regions were 0.35 m ha and 0.99 mt, respectively, according to the China Agricultural Annual Data Collection. Most naked barley is consumed in Tibet, where it accounts for 56% of the total food production. About 2.1 million people consume barley. The main product of naked barley is roasted barley flour known as *zangpa*. Alcohol made from naked barley (*qingke jiu* in Chinese) is the major alcoholic beverage in Tibet. Barley is also used in traditional dishes such as *kasha, miso*, and popped barley.

Today barley is a potential health food, and as a source of soluble fiber it is considered important in preventing hypocholesterolemia and hypoglycaemia in non-insulin-dependent diabetics. The potential benefit of soluble dietary fiber in lowering cholesterol levels and postprandial blood glucose and insulin response was reported by Brennan and Cleary (2005). Tocols (tocopherols and tocotrienols) present in barley are also reported to lower total cholesterol and low density lipoprotein cholesterol (Wang et al., 1993).

2. Distribution of barley production

The types of barley grown in China and their distribution are determined by various factors such as photoperiod and temperature response, rainfall, latitude, altitude, and cropping system, plus the benefits barley may generate. Regions are classified based largely on sowing time, whereas subregions are classified based mainly on maturity and ecotypes. In general, three geographical regions, including 12 subregions, are recognized (Lu, 1996). However, the middle and lower Yangtze Valley accounts for around 70% of the area and 80% of national production. At present, naked barley is planted on less than 200,000 ha, spring barley on about 200,000 ha, and winter barley on 1 m ha.

2.1 The naked barley region

Naked barley is grown in the Qinghai-Tibetan highlands in Tibet, Qinghai, Gannan Autonomous Region in Gansu, Aba and Ganzhi Autonomous Regions in Sichuan, and Diqing Autonomous Region in Yunnan. Altitude ranges from 2,200 to 4,750 m, with cumulative temperatures (above 0°C) during the barley growing season of 1,200-1,500°C. The frost-free period lasts 4-6 months, and there are about 800 hr of sunshine. Rainfall during the barley growing season ranges from 200 to 800 mm. Barley accounts for 60% of the cropping area, with one crop per year. Spring barley, which is the dominant type, is planted in March and April, and winter barley is planted in October. Most cultivars are multi-row, photoperiod-sensitive naked spring types. These regions are the center of origin of wild barley.

2.2 The spring barley region (five subregions)

Spring barley is sown in the northeastern plain subregion, which includes Heilongjiang, Jilin, and Liaoning, plus Huluengbeier, Xingan, and Zhelimushanger in eastern Inner Mongolia. Altitude is 40-600 m in the plains and 1,000 m in the mountains, and cumulative temperature is about 1,500°C during the barley growing season. The area receives 200 mm of rain and about 1,400 hr of sunshine, which allows one crop per year, sown in mid-April and harvested in mid- to late August. There is priority for multi-rowed spring types with long awns and sparse spikes.

The spring barley area in the northern China plain subregion includes northern Hebei, Beijing, and Tianjin; Jincheng, Gaoping, Xinshui, Linfen, and northern Hejin in Shanxi Province; and the southern part of Liaoning Province. It is a lowland area with cumulative temperatures of 1,600-1,800°C during the barley growing season, a frost-free period of 4-6 months, 50-100 mm of rainfall, severe spring droughts, 950-1,000 hr of sunshine, and two crops per year. Barley is sown in early March and harvested in mid-June to early July; irrigation is needed for good production. Maize, sweet potato, or soybean may be planted after the barley harvest. Cultivars are mainly multi-rowed, two-rowed, and naked types.

Spring barley is grown in the Inner Mongolia highland subregion, which includes the middle and western parts of Inner Mongolia, and Zhangjiakuo and Chengde prefectures in Hebei. Altitude in the subregion ranges from 1,000 to 2,400 m; there is cumulative temperature of 1,400-1,600°C during the barley growing season, 150-300 mm of rainfall, severe spring drought, 800-900 hr of sunshine, and one crop per year. Barley is sown in mid-March to early April, and harvested from mid-July to mid-August. Cultivars include two-row and six-row types, as well as naked and semi-winter types.

Spring barley is planted in the northwestern China subregion, which includes Ningxia, parts of Shaanxi, and Gansu. Altitude in the area ranges from 800 to 2,240 m. There are 1,500°C of cumulative temperature during the barley growing season, 150-300 mm of rain, 800-1,000 hr of sunshine, and one crop per year. Barley is sown from early March to late April, and harvested in mid- to late July. Cultivars include multi-rowed and two-rowed types; they are mainly spring types, but some semi-winter types are also grown.

Spring barley is planted in the Xinjiang dryland subregion comprising Xinjiang and Jiuquan prefecture in Gansu. The subregion is at an altitude of 200-1,000 m, with 1,500°C of cumulative temperature during the barley growing season. Southern Xinjiang is characterized by high temperatures and low rainfall, whereas low temperatures and higher rainfall are the norm in northern Xinjiang. The subregion receives a total of 800 hr of sunshine, sufficient for one crop per year. In northern Xinjiang, barley is sown from early to mid-April and harvested in mid- to late July, whereas in southern Xinjiang, it is sown in early March and harvested in early July. Cultivars include two-rowed and multi-rowed hulled spring types.

2.3 The winter barley region (six subregions)

Winter barley is sown in the Yellow and Huai River Valley subregion, comprising Shandong, northern Jiangsu and Anhui, southern Hebei, Henan, central Shaanxi, south Shanxi, and parts of Gansu. Altitude the subregion ranges from 500 to 1,300 m, and there are 1,600-2,000°C of cumulative temperature during the barley growing season. Average rainfall is 100-200 mm, and there are 1,000-1,400 hr of sunshine and two crops per year. Barley is sown in late October to early November, and harvested in late May to early June. Barley matures around 7-10 days earlier than wheat. Cultivars are multi-rowed semi-winter and winter types.

Winter barley is cropped in the Qingba Hilly subregion, which includes the southern parts of Shaanxi, and parts of Sichuan and Gansu. Altitude is 500-2,000 m, cumulative temperature 1,600-1,800°C during the barley growing season, rainfall 200-300 mm, and total sunshine less than 1,000 hr. The cropping system is either one crop per year or three crops every two years. Barley is sown in mid-October and harvested in mid to late May. Cultivars are multi-rowed semi-winter types.

In the middle and lower Yangtze Valley subregion, winter barley is grown in Shanghai, southern Jiangsu, Anhui, Zhejiang, Hunan, Hubei, and Jiangxi. Altitude is less than 100 m in the plains and 300-700 m in the mountains. There are 850-1,350 hr of sunshine, cumulative temperature of 1,600-1,800°C during the barley growing season, 200-300 mm of rain, and two or three crops per year. The crop is sown in late October to early November, and harvested at the end of May. The major cropping system is barley-rice-rice. Barley matures 7-10 days earlier than wheat, and early harvesting of barley benefits the early planting of rice. Cultivars are semi-winter and spring types.

In the Sichuan Basin subregion, winter barley is planted in Chongqing and major parts of Sichuan. The area has an altitude of 500-1,000 m, cumulative temperature of 1,900°C during the barley growing season, 400 mm of rain, 500 hr of sunshine, and mainly two crops per year. Sowing occurs in early November and harvesting at the end of April. The cultivars are all spring and semi-winter, two-rowed improved types.

In in the southwestern highland region, winter barley is sown in Guizhou, Yunnan, and parts of Sichuan and Hunan. The area lies at an altitude of 1,000-2,000 m, and has 1,800°C of cumulative temperature during the barley growing season, 130-150 mm of rain, 1,200 hr of sunshine, and two crops per year. Sowing is from late September to early November and harvesting from February to May. The cropping system is barley followed by rice. Cultivars are multi-rowed and two-rowed, spring and semi-winter types.

The southern China winter barley subregion includes Fujian, Guangdong, Guangxi, Hainan, Taiwan, Wenzhou in Zhejiang, and Ganzhou in Jiangxi. The area is characterized by an altitude less than 100 m in the plains, 200 m in the hills, and 1,000 m in the mountains. There are 2,000°C of cumulative temperature during the barley growing season, 150-400 mm of rain, 400-600 hr of sunshine, and three crops per year. Barley is sown at the beginning of November and harvested in March to April. Cultivars are two-rowed and multi-rowed early maturing spring types.

3. Major biotic stresses

There are no serious disease and pest problems in the naked barley areas. In the warmer, more humid areas, diseases such as leaf rust, stem rust, Fusarium head blight, and powdery mildew can be significant. In the spring barley areas, barley yellow dwarf virus and root (crown) rot caused by *Fusarium graminearum* can be extremely serious, and barley leaf stripe and loose smut can also become epidemic. Epidemics of barley yellow mosaic, Fusarium head blight, and powdery mildew are common in the winter barley areas, especially in the mid- and lower Yangtze Valley.

The main pests of barley are non-specific soil inhabitants such as mole crickets, grubs, and wireworms. Aphid infestations can become extremely high at the seedling stage. Aphids can cause either considerable direct damage or early and damaging infections of barley yellow dwarf disease. Resistant cultivars and chemical treatments are used to manage these diseases and pests.

4. Genetic resources

4.1 Barley collection and preservation

The collection of barley germplasm in China progressed in three stages. At the beginning of the farm cooperative system in the mid-1950s, many landraces were collected for preservation. By 1958, 3,249 landrace accessions were available and their characteristics identified. Some landraces were evaluated and promoted as superior cultivars. During the mid-1960s to late 1970s, little was done due to the Cultural Revolution, and the number of accessions actually declined to 2,713 in 1974. During the third stage, which began after the first national barley germplasm congress held in 1979, further collections were made, and the number of accessions increased to 5,137. This collection expanded greatly in subsequent years especially with samples from Tibet.

From 1985 to 1995, a total of 16,188 accessions were collected. Of these, 6,351 were from foreign countries, 9,837 were local landraces and cultivars, and 6,026 were hull-less types. Local landraces accounted for 54% of the collection (Sun et al., 1995). Today China holds one of the most important collections of barley germplasm, especially naked barley, in the world. Many naked barley accessions (4,400) came from the Qingzang Highlands in Tibet (Ma and Li, 1999), and many of them are useful sources of resistance to cold, drought, and other abiotic stresses. More than 2,000 accessions, most of them two-rowed types, are from the middle and upper Yangtze Valley. More than 1,300 six-rowed accessions came from the winter barley region in the Yellow and Huai River Valleys, whereas 620 multi-rowed and long awned entries are from the Yungui Highlands in southwestern China. Foreign accessions come from 46 countries, including Canada, Denmark, France, USA, Japan, and the former USSR, as well as from CIMMYT and ICARDA.

4.2 Evaluation and utilization

At this stage, the agronomic traits of barley collections have been identified. A four-volume compilation titled *Catalogue of Barley Resources in China* summarizes the agronomic traits of up to 16,251 cultivated barleys. In the Catalogue, Chapter 6 on Chinese Barley Science focuses on germplasm resources (Lu, 1996). A number of accessions (12,500) have been assessed for responses to barley yellow mosaic virus, Fusarium head blight, barley yellow dwarf virus, and barley leaf stripe. Among the abiotic stresses, 12,949 accessions were tested for salt tolerance, 7,000 for drought tolerance, and 8,000 for waterlogging tolerance. Protein, starch, and lysine contents of 9,840 genotypes were also determined. Two dwarfing types were identified, including Xiaoshanlixiahuang from China and Aiganqi introduced from Sweden with the whorl gene *uz*, and Zhepi 1 with a new unnamed dwarfing gene that arose from mutation.

Notable Chinese germplasm with resistance to barley yellow mosaic virus includes 8-2, Sandunjiangsileng, Shanghailulengzi, Humai No. 1, Humai No. 10, Lixin No. 1, Nantongtiemai, Shengxianwumangluleng, Yiwuzao, Mushigang No. 3, and Cangzhou naked barley. Twenty-three accessions with resistance to Fusarium head blight (diseased spikes less than 5%) were identified from 8,166 accessions. Among them, 19 were Chinese cultivars, mostly two-rowed types. They were mainly from Zhejiang, Jiangsu, or Hubei, and notable accessions included Shangyuhongerleng, Yiwuerleng, and Yongkangerleng.

In the early stages of barley breeding in China, many important materials were used as breeding parents. Xiaoshanlixiahuang and Chiba barley were high yielding dwarf types, Zaoshu No. 3 was early maturing and high yielding, and Zhangqingluo, Baiyuzhimang, and Dulihuang were hull-less barleys. More recently, accessions with good quality were used, such as Pu 829019, Pu 895067, Suyin 24, and Suyin 21 with high resistance to powdery mildew and Fusarium head blight; S-096 and Ping 567 with large grain size; and Ganmuertiao, Harrington, and Daner with good malting quality. Xiyin 2 was a source of dwarf stature and high yield, while Hiproly, Ziguangmangluoerleng, Kuangyingluomai, Huangchuangguang, and Huaiansanyuehuang had high protein content.

5. Barley breeding in China

Despite barley's long history in China, no systematic barley improvement was conducted prior to the 1950s. Barley cultivars were landraces. During the 1940s, there were only two cultivars, Zhenongguangmangerleng and Taizhong No. 1, selected by introduction and domestication.

After the 1950s, the use of feed barley declined, and barley improvement targeted only the main production areas. It was only after the mid-1970s that the demand for malting and feed barley began to increase. In 1979, a national barley genetic resource congress was convened in Hangzhou. In 1980, a national barley breeding group was established at the Zhejiang AAS. In 1986, barley breeding was listed as a national priority project for science and technology. The history of barley improvement is described below, and the leading cultivars from the 1950s to the present are listed in Table 2.

5.1 The landrace period

From the early 20th century until the 1950s, all barley cultivars were landraces. Because of low productivity, low multiple-cropping index, and the high likelihood of lodging, cultivars with good resistance to Fusarium head blight and lodging were selected. These cultivars were suited to two crops per year, and had a yield potential of 1,500 kg/ha. They had special characteristics such as large vegetative mass, early maturity, low grain yield, and tolerance to abiotic stresses. No cultivar was planted over a large area; the area planted to individual cultivars covered no more than several thousand hectares and cultivars were long-lived. For example, cv. Tianmenzao in Hubei had a 70-year planting history. Most cultivars were multi-rowed or hull-less, and rarely two-rowed. Different areas had spring and winter types. Along the middle and upper Yangtze Valley, and the Yellow and Huai Valleys, the main cultivars were semi-winter and winter types. Spring cultivars were grown in the autumn-sowing area in southern China, the Qinghai-Tibetan highlands, and the spring barley area in the north. Many landraces had good quality and other attributes. For example, cv. Xiaoshanlixiahuang in Zhejiang was 85-90 cm in height, Aibaiyang had a yield potential of 4,500 kg/ha, Luonanhuosuotaoluren in Shanxi had 20% grain protein content, Menyuanlianglan in Qinghai could be grown in environments with a 40-day frost-free period, Chaguolan in Tibet could be planted at an altitude of 4,200 m and a full growing cycle of 80 days, and Qianqian in Guizhou was resistant to powdery mildew.

5.2 The early period of cultivar improvement

After the 1950s, with the development of modern agriculture, good landraces were selected and promoted. Cultivars with high yield, good quality, high disease resistance, and wide adaptability included Heisileng and Heiliuleng in Sichuan, Fupinglao in Shanxi, Silenggumai in Hunan, Jianglingsanyuehuang in Hubei, Runanchangmang in Henan, Taiannongzhong in Shandong, Tadamai in

Hebei, Funingshidamai and Changliuleng in Jiangsu, Dongyangsanyuehuang and Xiaoshancimangerleng in Zhejiang, Bailiuleng in Shanghai, Bailangsan in Qinghai, and Luocihongmangdamai in Yunnan.

Cross-breeding in the 1960s led to the release of cultivars such as Hull-less 757 and Zhenong 12 in Zhejiang, Chiba and Lixin 1 in Jiangsu, Fengaierleng and Humai 1 in Shanghai, Ximala 2 in Tibet, and Ganzi 809 in Sichuan.

5.3 The middle period of cultivar improvement

During the 1970s and 1980s, great efforts were made to increase the multiple-cropping index and improve agronomic practices. Suitable cultivars were needed to better fit the changing conditions. The two-row trait was seen as an important source for malting and resistance to Fusarium head blight.

Crossbreeding programs in Jiangsu, Zhejiang, Shanghai, Qinghai, and Tibet led to the selection and release of cultivars such as Mimai 114, Su 2-14, Cunnongyuanmai, Humai No. 4, Kunlun, Qingzhang, Ximala No. 6, Ximala No. 8, and Yanfuaizaosan.

Introduced cultivars also played an important role in barley production. In 1966, Zaoshu 3 was introduced from Japan by the Zhejiang AAS (Zhao, 1993). It had high yield potential, was broadly adapted, and could be grown in almost the entire country. The area planted to Zaoshu 3 along the Yangtze Valley reached 0.9 m ha in 1977, the largest planting area in China. Zaoshu 3 was also widely used as a breeding parent. In addition, the multi-row, hull-less cultivar Aiganqi was introduced from Sweden. It had short stems, lodging resistance, early maturity, and high yield, and the area it covered reached 333,000 ha in the late 1970s. During this period, the rate of cultivar replacement began to accelerate.

5.4 The improved cultivar period

From 1985 to 1990, many cultivars were developed with key support from the central government. They included the ZAU (Zhejiang Agricultural University) and Zhepi (Zhejiang Malting Barley) series in Zhejiang; the Humai series in Shanghai; Supi No. 1, Suyinmai No. 2, and Sunong 21 in Jiangsu; Jipi 1 in Jilin; the Xiangmai series in Hunan; the Emai series in Hubei; the Pudamai series in Putian, Fijian

Table 2. Leading barley cultivars in China from the 1950s to the present.

Cultivar	Cross	Type	Year of release	Area of adaptation
Zhenong 12	Zhenongguangmangerleng/Beinongda 18	two-row	1963	Zhejiang
Zaoshu 3	Guandongertiao 3	two-row	1966	Zhejiang, Jiangsu, Hubei, Shanghai, Fujian
Ximala 8	Handiziqingke/Ximala 1	six-row	1977	Tibet
Humai 4	Zheza 12/Zaoshu 3	two-row	1979	Shanghai, Zhejiang, Jiangsu, Hubei, Sichuan, Hunan
Yanfuaizao 3	Zaoshu 3 60Coγ	two-row	1979	Jiangsu, Fujian, Jilin, Shanxi
Xiyin 2	Qianjianmai	six-row	1980	Kuan-chung Plain
Pudamai 4	Zaoshu 3/Roumania earliness	two-row	1982	Fujian
Zhepi 1	73-142/Zaori 19	two-row	1982	Zhejiang
V 24	From Mexico	six-row	1986	Sichuan,Yunnan
Suyinmai 2	Gang 2	two-row	1991	Jiangsu
Shan 2	Nasu Nijo/Kinugutaka	two-row	1992	Jiangsu
Zhepi 4	Humai 8/Zhepi1	two-row	1996	Zhejiang
Kenpimai 2	Robust/Azure	six-row	1996	Heilongjiang
Ganpi 3	S-3/Fawaweit	two-row	1997	Gansu, Inner Mongolia
Kenpimai 3	86-1/Gimple	two-row	1999	Heilongjiang, Inner Mongolia
Supi 3	Kinuyu Taka/Kanto Nijo 25//Hu 94-043	two-row	2001	Jiangsu, Hubei
Zhudamai 3	Zhu 8909/TG4	two-row	2001	Henan
Zangqing 25	815078/Qinghai1 039	six-row	2001	Tibet
Ganpi 4	Fawaweit/Banong 862659	two-row	2002	Gansu, Inner Mongolia
Kenpimai 7	Ant90-2/Hong92-25	two-row	2004	Heilongjiang, Inner Mongolia
Supi 4	Shen6/Meinianghuangjin//Shan2/3/Shan2/Yanmai 3	two-row	2005	Jiangsu, Hubei
Yangnongpi 5	Rudong 6109/Sunong 22	two-row	2006	Jiangsu
Zhepi 33	(Gang 2/Xiumai 3//Xiumai 3)/Gang 2	two-row	2006	Zhejiang
Yunpi 2	Aoxuan 3/S500	two-row	2006	Yunnan
Mengpimai 1	Bowman/91Dong27//91G318	two-row	2008	Inner Mongolia

Province; and Chuanluo 1 in Sichuan. Most of these cultivars had improved quality and strong resistance to barley yellow mosaic. Some of them had malt extracts of 76-78%, and some of them outyielded the control by more than 10%. ZAU No. 3 had the largest planting area among these cultivars.

Many cultivars were introduced from other countries to meet the increasing demand for malting barley production in the northern spring barley region. They included Hungary 84 (Favavit) introduced from Hungary to Gansu Province in 1984, Conquest introduced from Canada to Heilongjiang in 1982, Xiyin 2 introduced from Japan to Shaanxi, and V 24 introduced from Mexico to Sichuan.

5.5 Quality improvement

In the 1980s, it was realized that specialized cultivars must be developed for malting, feed, and food uses. The choice of parents was then based on high yield potential, good end-use quality, and resistance to Fusarium head blight and barley yellow mosaic. Although some progress was made, quality improvement was hindered by an inadequate definition of quality traits and selection methods. As a result, locally developed cultivars were unable to compete with imported grain, which represented 20% of consumption in the mid-1980s and increased to 68% in the mid-1990s. Recently, improved cultivars with outstanding malting quality have become available, such as ZAU No. 7, Zhepi No. 4, Daner, Kenpi No. 2, Ganpi No. 2, and Supi No. 3. The malt extract of Daner was higher than 80%, and that of Supi No. 3 was higher than 81%. The protein content of some feed barleys such as Zheyuan 18 and Yangsi No. 1 was higher than 13%. Currently, Daner is the quality standard for malting cultivars, and Zheyuan 18 is the standard for feed cultivars.

5.6 Exploration of heterosis

Male sterility started being applied to barley in the 1940s. Nucleo-cytoplasmic interaction type male sterile lines were first obtained by crossing wild barley and cultivated barley at the Chinese Academy of Science (CAS) (Shao et al., 1991). Scientists at Sichuan Agricultural University (Sun et al., 1995) reported that nucleo-cytoplasmic interaction type male sterility from wild and cultivated barley crosses was quantitatively inherited, and thus distinctly contrasting sterile and restorer lines were extremely difficult to develop. Other approaches (Zhang et al., 1998; Feng et al., 2001) such as separable small and large grains obtained through nucleo-cytoplasmic interaction at Zhejiang University, and a photo-thermo-sensitive nuclear sterile line system discovered by the Crop Research Institute in Chongqing were investigated, but were not very successful in production due to the low yield in seed production.

6. China's national breeding program and future strategies

From 1985 to the present, barley breeding led by the Zhejiang AAS was listed as a key project by the Chinese Ministry of Science and Technology. The Hangzhou National Barley Improvement Center, established at the Zhejiang AAS in 2001, has greatly promoted barley breeding in China. Other major institutes involved in barley breeding include Zhejiang University (formerly Zhejiang Agricultural University) in Hangzhou, Nantong Agricultural Research Institute, Yancheng Agricultural Research Institute and Yangzhou University in Jiangsu Province, Shanghai Academy of Agricultural Science, Tibetan Agricultural and Animal Husbandry Academy in Lasa, Qinghai Academy of Agricultural Science in Xinning, Gansu Academy of Agricultural Science in Lanzhou, and Hongxinnong Agricultural Research Institute in Heilongjiang. The Chinese Academy of Agricultural Science is responsible for germplasm collection and characterization.

The mission of the National Barley Improvement Center includes:

(1) Collection, preservation, and documentation of barley genetic resources, both local and introduced, and establishment of a barley genetic resources database.

(2) Genetic resource evaluation and analysis; identification and evaluation of the main characteristics of barley resources; genetic analysis and evaluation of potential parents.

(3) Exchange and creation of new genetic resources among all barley breeding groups and creation of elite materials for cultivar assessment.

(4) Improvement of breeding methods, including research on heterosis, improvement of traditional breeding methods, identification of disease resistance, early generation

determination of quality, improved mutation induction technology, and biotechnology.

(5) Selection and promotion of new cultivars: selection of malting and feed barley cultivars with good quality, high yield potential, disease resistance, and stress tolerance, and their promotion in appropriate cultivation areas.

(6) Industrialization of new cultivars as a sound base for malting and feed barley production; establishment of mechanisms for combining cultivar selection, seed production, processing, and promotion and marketing of new cultivars.

(7) Training and international collaboration for the exchange of local and foreign barley germplasm; establishment of a national barley network.

6.1 Malting quality improvement

The aim of breeding high quality malting barley is to increase malt extract, diastatic power, and amylase activity, and to decrease protein content while improving grain appearance and physical characteristics. In the near future, malt extract is expected to reach 82%, diastatic power will reach 280-300 WK, and the protein content of malting barley grown in northern China will be less than 12%.

6.2 Feed barley

The primary aim of the feed barley breeding program is high yield and quality with emphasis on increasing grain protein and lysine contents while decreasing beta-glucan and fibrin contents. In the near future, feed barleys are expected to have protein content approaching 13-15%, lysine content up to 0.5%, and beta-glucan content less than 2.5%.

6.3 Yield potential

Research will focus on traits likely to produce high yields, such as short stature, multi-spike characteristics (including large spikes and large grain), and high harvest index. Multi-rowed and naked feed barley genotypes with high yield potential will be important, as naked types with high protein and low fibrin contents are well suited for feed. In the near future, the yield potential of feed barley should reach 1,200-9,000 kg/ha.

6.4 Disease resistance

Resistance to Fusarium head blight, barley yellow mosaic, and powdery mildew are essential for the production of high yielding malting and feed barleys. Fusarium head blight is the greatest constraint to the production of malting barley. Resistance is quantitatively inherited and strongly influenced by environment; fortunately, it is easier to achieve in two-row than in six-row genotypes.

6.5 Tolerance to abiotic stress

Barley is more tolerant to salt, waterlogging, drought, and acidity than other cereals. There is huge potential to develop tolerant cultivars for the under-utilized eastern and southern areas of China that are subject to one or more of these constraints.

6.6 New breeding methods

The methods used to improve barley are typical of self-pollinated crop breeding programs. Conventional methods may include pedigree, mutation, backcross, intercross bulk-population, doubled haploid, single seed descent, and hybrid approaches. With developments in molecular biology, marker-assisted selection and genetic transformation are beginning to be used in breeding. Combining these new methods with conventional methods will provide further genetic gains.

Barley is an under-utilized crop in China. Barley improvement is relatively new, but it has already contributed to the malting and feed industries, while retaining its traditional role as a minor food crop. It is now recognized that the qualities required for each of these end-uses are very different, and that separate improvement programs are required for each. There are also areas where barley production could expand without replacing or competing with other crops, and breeders should exploit barley's special attributes of abiotic stress tolerance and promote its use in areas where such stresses limit other cereal crops. Increased production will meet the rapidly expanding demand for malting and feed barley, as living standards improve, and perhaps even reduce the current high reliance on imported grain for both uses. However, this will be achieved only with competitive, high yielding, high quality cultivars, and well organized grain handling, storage, marketing, and transport infrastructure.

References

Brennan, C.S., and Cleary, L.J. 2005. The potential use of cereal (1→3,1→4)-β-D-glucans as functional food ingredients. Journal of Cereal Science 42: 1-13.

Feng, Z.Y., Zhang, Y.Z., Li, M., Kuang, S.F., and Xu, T.W. 2001. Review of studies on barley nucleo-cytplasmic interaction type male sterility in China. Barley Science in China 5: 13-17 (in Chinese).

Huang, Z.R. 2001. Review of barley production and scientific research in China in the 20th century. Collections of Barley Research Papers in China 5: 1-6 (in Chinese).

Lu, L.S. (ed.). 1996. Chinese Barley Science. China Agriculture Press, Beijing, China (in Chinese).

Ma, D.Q., and Li, Y.Q. 1999. Excellent wild barley relatives' resources in Tibet and Qinghai plateau in China. Collections of Barley Research Papers in China 4: 1-5 (in Chinese).

Shao, Q.Q., Rong, J.K., Li, A.S., Deng, W.Q., and Lin, X.Y. 1991. Study on relationship between inheritance of male sterility and genetic distance between crossed species of barley. Collections of Barley Research Papers in China 2: 53-54 (in Chinese).

Sun, D.F., Xu, T.W., Jiang, H.R., and Zhao, L. 1995. Selection and genetic analysis of nucleo-cytoplasmic male sterile l1ne 88bcms in barley**.** Scientia Agricutura Sinica 28(3): 1-36 (in Chinese).

Wang, L., Xue, Q., Newman, R.K., and Newman, C.W. 1993. Enrichment of tocopherol, tocotrienol, and oil in barley by milling and pearling. Cereal Chemistry 70: 499-501.

Xu, T.W., and Feng, Z.Y. 2001. Origin of cultivated barley in China with reference to the explanations of the Chinese classical words Lai Mu. Collections of Barley Research Papers in China 5: 18-22 (in Chinese).

Xu, Z.W., Deng, B., Liu, M.H., Fei, D.B., Li, Y.M., and Xu, Y. 2004. Effects of different enzymes on reducing the viscosity of barley, wheat and rye. Acta Agriculturae Zhejiangensis 16: 21-24 (in Chinese).

Yang, J.M., Shen, Q.Q., Wang, J.M., and Zhu, J.H. 2003. The production, demand and strategy of barley in China. Barley Science 1: 1-6 (in Chinese).

Zhang, M.S., Zhang, J.Y., Jiang, X.P., Wang, J.R., Wu, C., and Guo, J. 1998. Current situation and tendency of research on exploitation of barley (*Hordeum vulgare*) heterosis. Acta Agriculturae Jiangxi 10: 81-85 (in Chinese).

Zhao, L.Q. 1993. Review on barley improvement in Zhejiang province. Barley Science 3: 1-3 (in Chinese).

Chapter 6.

Development of triticale in China

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1. Introduction

Triticale is a synthetic species created by combining the genomes of wheat and rye. Its creation was inspired by wheat's own evolution. Hexaploid wheat (genomic formula: 2n=42=AABBDD) evolved through two natural inter-specific hybridization events followed each time by spontaneous chromosome doubling. This brought together the genomes of three diploid wild species, namely *Triticum uratu* (genome AA); a representative of the *Aegilops* group (genome BB) not unlike *Aegilops speltoides*; and *Aegilops tauschii* Cosson. (genome DD) (Wilson, 1876; Meister, 1921; Gustafson et al., 2009). The addition of each genome resulted in marked improvements in both yield and nutritional quality.

Allopolyploid triticale can be produced through man-made crosses between wheat (AABB if tetraploid wheat is used, or AABBDD if hexaploid wheat is used) and rye (RR). The resulting hexaploid (AABBRR) or octoploid (AABBDDRR) triticales are characterized by large, complex genomes (Blakeslee, 1937; Muntzing, 1979). Because of potentially high biological yields, good nutritional quality, high levels of disease resistance, and wide adaptability, triticale has shown great potential as a new cereal crop in China and elsewhere (Zillinsky and Borlaug, 1971; Sun and Zhang, 1996; Sun, 2002; Sun et al., 2002).

In China, triticale research started in the 1950s. The first variety was exhibited around the country in 1970, and released for commercial production in 1976 (Bao, 1981; Bao and Yan, 1993; Sun and Wang, 1986). Before 1995, triticale was used mainly as a food crop planted in high altitude, cold mountainous areas of southwestern and northwestern China because of its stress tolerance and disease resistance. After 1995, with changes in the Chinese agricultural structure and adjustments in cereal breeding objectives (from breeding cultivars only for food, to developing green forage cultivars and dual-purpose forage and grain cultivars for food and feed), triticale began to be used as a fodder crop (Table 1) as its high biological yields and good nutritional qualities became increasingly known (Sun et al., 1996; Wang and Sun, 2002, 2003a, 2003b).

The area sown to triticale in China was around 73,000 ha in 2008. Today triticale is an important fodder crop throughout the country, and is expanding rapidly in the Yellow and Huai Valleys, northern China plain, southern and lower reaches of the Yangtze River, and northwestern China.

2. Development and evolution of triticale as a cereal crop

2.1 Early triticale testing (1970-1975)

Triticale testing began in 1970. The grain yields of the first triticale cultivars tested in the mountain areas were higher than those of existing crops, with a

Table 1. Area sown to triticale and its utilization in China, 1975 to 2008.

Year	Food (ha)	(%)	Fodder (ha)	(%)	Total (ha)
1975	467	100.0	0	0	467
1976	733	100.0	0	0	733
1977	5,866	100.0	0	0	5,866
1980	53,333	100.0	0	0	53,333
1981	2,000	100.0	0	0	2,000
1985	866	100.0	0	0	866
1990	3,400	100.0	0	0	3,400
1991	10,000	99.9	66	0.7	10,066
1995	29,000	96.7	1,000	3.3	30,000
2000	12,000	11.1	96,000	88.9	108,000
2002	12,666	4.3	290,667	95.7	303,333
2005	3,744	3.5	102,923	96.5	106,667
2008	2,787	3.8	70,546	96.2	73,333

9-23% advantage over wheat. Replicated yield trials conducted between 1972 and 1975 in the mountain regions of Guizhou Province (altitude: 1,700-2,600 m) indicated that eight of the ten triticale cultivars tested had yields higher than those of either common wheat or rye. The average yield of triticale cultivars was 2.5 t/ha, representing a 41-142% advantage over wheat, and 31-98% over rye. Octoploid cultivars Triticale N°2 (developed from AD20/WR32 with 10 generations of selection) and N°3 (developed from WR18/AD20 with 9 generations of selection) were the best intermediate cultivars among the triticale genotypes tested. Under conditions in which wheat crops failed, these triticales produced yields of up to 1.5 t/ha due to their better cold tolerance and overall stress resistance. As farmers in high-altitude, cold mountain areas became aware of these advantages, the area planted to triticale reached 733 ha in 1976.

2.2 Early triticale development (1976-1980)

The first national triticale workshop was held in Guizhou in June 1976 to demonstrate triticale fields to researchers and farmer delegates from 15 provinces. Field visits involved surveying the growth stages of triticale planted at different altitudes, sowing dates, and within different cropping systems, as well as estimating yields in different fields. The demonstrated cultivars and their pedigrees are as follows: Triticale N°1 developed from AD20/WKC1 with 8 generations of selection, Triticale N°2 developed from AD20/WR32 with 10 generations of selection, Triticale N°3 developed from WR18/AD20 with 9 generations of selection, Triticale N°8 developed from WRC/AD20 with 8 generations of selection, Triticale N°9 developed from WR18/AD20 with 8 generations of selection, Triticale N°16 and N°17, both developed from WR56/31258h42F_4 with 8 generations of selection, Triticale N°19 developed from WR56/31258h42F_4 with 8 generations of selection, Triticale N°30 developed from WR565/31258h42F_4 with 8 generations of selection, Triticale N°36 developed from 40278WAF8/41739h42F_6 with 8 generations of selection, Triticale N°52 and N°54, both developed from WR165/41737h42F_6 with 8 generations of selection, and Triticale N°73 developed from WR565/31258h42F_4 with 8 generations of selection.

Results from these demonstration plots indicated that triticale, with an average yield of 3.5 t/ha, had a 30% grain yield advantage over wheat, 40% over rye, and 50% over oats. The meeting enthusiastically endorsed triticale development in China and contributed to an initial rapid increase in its area of cultivation from 5,866 ha in 1977 to 53,333 ha in 1980, a 10-fold increase over three years. Because of its adequate cold resistance, good performance in poor soils, resistance to prevailing diseases, good quality, and potential to meet urgent food requirements, octoploid triticale developed quickly in the areas of the Wumeng Mountains (northeastern Yunnan, western Guizhou), the Liang Mountains (western Sichuan), the Qinling Mountains (southern Gansu, northwestern Sichuan), the Daba Mountains (eastern Sichuan, western Hubei, southern Shaanxi), the Funiu Mountains (southwestern Henan, southeastern Shaanxi), the Liupan Mountains (southern Ningxia, eastern Gansu) and the Yin Mountains (middle Shaanxi, middle Shanxi, northern Henan).

2.3 Decline of the triticale area (1980-1985)

Octoploid Triticale N°2 and N°3, bred by the Institute of Crop Breeding and Cultivation (renamed the Crop Science Institute) of CAAS, were the first two cultivars to be disseminated around the country. However, they were not well adapted to some of the new agro-ecological areas in which they were being planted. Even though they exhibited high fertility and traits such as grain plumpness, plant height, maturation, and cold tolerance, they were not always satisfactory. In addition, shriveled seed and low test weight prevented reaching competitive grain prices as grain supplies became increasingly available. By 1981, the triticale area had declined to 2,000 ha, and in 1985, only 866 ha were reported for the entire country.

2.4 Recovery of the triticale area (1986-1990)

Through appropriate investigation, researchers realized that the main limitation to triticale development was cultivar adaptability. Triticale N°2 and N°3 had only limited adaptability and could not be grown in all agro-ecological zones. Breeders thus paid more attention to breeding for specific adaptation to particular environments. In addition, triticale, no longer considered exclusively a food crop, was developed as a forage crop, or as a dual-purpose fodder and grain crop. Besides the normal pedigree selection method, recurrent selection techniques were also implemented. Finally, various types of complete and substituted hexaploid triticales were produced and tested in addition to octoploid types.

The much wider range of materials permitted selection in many different environments. Jingsong N°5 developed from H3908/H3988 with 5 generations of selection, Jingsong N°49 developed from H3797/H3908 with 6 generations of selection, Qianzhong N°1 developed from H1228/H855 with 6 generations of selection, and Qianzhong Nº3 developed from WR3390/H459//Triticale Nº1 with 6 generations of selection were suitable for the Wumen Mountains. Zhongqin Nº1 developed from TB5/T122 with 6 generations of selection and Zhongqin Nº2 developed from H7391/WR877D/H443 with 8 generations of selection, were well adapted to the Qinling Mountain area. Triticale Nº8 developed from WRC/AD20 with 8 generations of selection, 9-14 developed from WR18/AD20 with 8 generations of selection, and Zhongxin Nº1881 developed from H221/Hungary 64 with 9 generations of selection were better adapted to Inner Mongolia. With more genotypes adapted to production conditions and greater marketing opportunities, the triticale area began to expand again, reaching 3,400 ha in 1990.

2.5 The current period (1991 to 2008)

In recent years, the agricultural production structure in China has changed from a food crops/cash crops system to a food crops/cash crops/fodder crops system because fodder is insufficient, whereas the needs for food and cash crops are being met. Because of its high biological yield, both in terms of quick vegetative growth and good nutritional value, triticale has emerged as a valuable food and fodder crop, planted either in winter or spring.

After re-focusing the breeding objectives, new cultivars were released to address the new market needs. These included fodder cultivars Zhongsi Nº1048 developed from NTH324/WOH8-461F_7 with 5 generations of selection after 5 rounds of recurrent selection, Zhongsi Nº828 developed from H4372/WOH90 with 13 generations of selection, Zhongsi Nº237 developed from MS101/XIN14//WOH45/WOH18 with 4 generations of selection after 3 rounds of recurrent selection, and Zhongsi Nº1890 developed from H179/Hungary 64 with 11 generations of selection. Dual-purpose cultivars were also developed, including Zhongxin Nº830 developed from MSH4372//FH12/H435 with 4 generations of selection after 3 rounds of recurrent selection, and Zhongxin Nº1881 developed from H221/Hungary 64 with 9 generations of selection.

Food cultivars included Jinsong Nº49 developed from H3797/H3908 with 6 generations of selection, Qianzhong Nº3 developed from WR3390/H459//Triticale Nº1 with 6 generations of selection, and Xinjiang Triticale Nº1 developed from Zhongxin Nº1881. The new fodder cultivars were able to produce 37-50 t/ha of green fodder, and about 10 t/ha of total dry matter. The food type cultivars have typical grain yields of 3-4 t/ha. With these new cultivars, the national triticale area increased to 10,066 ha in 1991, 108,000 ha in 2000, and 303,333 ha in 2002, However, the area sown to triticale again decreased in recent years, with the total area in 2008 reaching only 73,333 ha.

3. Geographical distribution of cropping systems involving triticale

In its early stages of development, triticale was mainly planted in the cold mountain areas of southwest and northwest China, where the environment and production conditions for cereal crops are marginal due to low temperatures, infertile soils, and poor economic conditions. However, as farmers became aware of its potential as a forage crop, triticale cultivation began to expand into the Yellow and Huai Valleys, south of the lower reaches of the Yangtze River, and into northeastern China from the 1990s.

3.1 Southwestern and northwestern China

The topography and climate prevailing at high altitudes in the cold mountain areas of southwestern and northeastern China are very complex, resulting in highly specific crop distributions and diversified cropping systems. To promote triticale development, it is very important to include it in a technically and environmentally feasible, economically viable cropping system based on local conditions.

Areas with a single crop each year. These are high-altitude mountain areas characterized by generally inclement weather, with low temperatures (2-8ºC average annual temperature), a frost-free period of approximately 150 days, and a very long growing cycle (270-320 days). They include areas in the Yin Mountains (800-1,000 m), the Liupan Mountains (more than 1,000 m), the Funiu Mountains (800-1,000 m), the Qinling Mountains (1000-2,500 m), the Daba Mountains (more than 1,000 m), the Liang Mountains (2,000-2,300 m), and the Wumeng Mountains (2,400-3,000 m). In these environments, crops are often affected by drought and late frosts. Poor and often acidic soils are other yield-limiting factors. Because triticale has better drought tolerance, good performance in poor or acidic soils, ability to avoid late-frost damage, and better resistance to Fusarium head scab than wheat or barley, it has proven to be substantially higher yielding (1.5-2 t/ha) than other crops under these harsh conditions. Triticale yields also tend to be more stable over years in these areas.

Areas with two crops per year. Located at altitudes ranging from 800 to 2,000 m, these areas are characterized by average annual temperatures of 12-16°C (decreasing with increasing altitude) and frost-free periods of 200 to 250 days. They can be divided into succession-cropping areas with annual average temperatures above 14°C and intercropping areas with annual average temperatures below 14°C. Although triticale matures later than wheat, average annual temperatures above 14°C and high solar radiation allow for succession-cropping systems, as enough time is available to plant high yielding crops such as corn and sweet potato after triticale is harvested. Intercropping is practiced in the transitional zones between the single cropping and double cropping areas. Transitional areas are characterized by cooler weather with average annual temperatures of 10-14°C. Triticale is intercropped with high yielding crops, predominantly potato or corn.

Areas with three crops in two years. This cropping system is implemented in the high altitude (2,000-2,400 m) transitional zones between areas using single cropping and those using double cropping systems. Because in transitional areas triticale cannot be sown early enough due to cold weather, harvest of the second crop is delayed. The predominant cropping patterns are triticale/fall buckwheat/potato, triticale/fall potato/early buckwheat and triticale/soybean/potato.

3.2 Triticale cultivation in the Yellow and Huai Valleys and southern lowlands

Two successive crops per year in the Yellow and Huai Valleys. The Yellow and Huai Valleys, currently the largest production area for winter triticale, are characterized by average annual temperatures of 11-15°C and 3,600-4,800°C of cumulative temperatures above 10°C. This region experiences 2,000-2,800 hours of sunshine and 170-240 frost-free days per year. Farmers in both upland and lowland areas produce high yielding crops because irrigation is available (Wang and Guo, 1993). The region also includes areas north of the Yellow River that receive little rainfall. In fact, these conditions make the Yellow and Huai Valleys the main food and cotton production area in China. The major cropping systems involve two successive crops per year, and triticale is planted in rotation with corn, rice, or cotton.

Multiple cropping in the southern lowlands. This region, which receives much more solar radiation than the Yellow and Huai Valleys, experiences 4,600-5,600°C of cumulative temperature above 10°C and about 230 frost-free days. The multiple cropping systems usually involve wheat, rape, corn, rice, peanut, and soybean. The southern lowlands, consistently high yielding because of adequate rainfall and availability of irrigation, represent another major food and oil crop production area in China. Fodder triticale has become a major crop in this area due to its high yield, good quality, and Fusarium head scab resistance (if triticale is harvested for grain), and the possibility of planting in winter.

In fall-sowing areas, triticale is generally sown between late September and October and harvested between June and July. In spring-sowing areas, triticale is generally sown between March and April and harvested between July and August. Distribution of spring and winter triticales is shown in Figure 1.

4. Main triticale cultivars in China

Triticale cultivars in China include winter and spring types; food, fodder and dual-purpose types; and octoploid and hexaploid types. The triticale area in China in 2002 was about 273,000 ha and 30,000 ha, respectively, for winter and spring types, 263,000 ha and 40,000 ha, respectively, for hexaploid and octoploid types, and 250,000 ha and 53,000 ha, respectively, for fodder and food types. However, in recent years, the triticale area in China was reduced with the purpose of ensuring national food goals were met. The triticale area in China in 2008

Figure 1. Distribution of spring and winter triticales in China.

was 73,333 ha, including 70,546 ha for fodder and 2,787 ha for food, with less than 2,000 ha sown to octoploid types. In fact, China is the only country where octoploid triticale is grown commercially to a significant extent. Brief descriptions of the main cultivars released for commercial production in China are provided below.

Triticale N°2, developed from AD20/WR32 (Russian line AD20) in 1976 by the Institute of Crop Breeding and Cultivation (ICBC), CAAS. Ploidy level: octoploid. Growth habit: winter/intermediate. End-use: food. Reaction to prevailing diseases: highly resistant to rusts, immune to powdery mildew, and intermediate response to Fusarium head scab. Agronomic characteristics: intermediate tillering ability, and spike fertility of 80%. Grain characteristics: 1000-kernel weight: 40 g; semi-vitreous grain with grade 3 plumpness (1-5 classification; 1 = best and 5 = worst), and grain protein content of 16.1%. Main areas of adaptation: high altitude, cold areas as well as warmer areas. It is the most widely grown variety in China.

Triticale N°3, developed from WR18/AD20 (Russian line AD20) in 1976 by ICBC, CAAS. Ploidy level: octoploid. Growth habit: winter/intermediate. End-use: food. Reaction to prevailing diseases: highly resistant to rusts, immune to powdery mildew, intermediate response to Fusarium head scab. Agronomic characteristics: intermediate tillering ability, plant height of 140 cm, semi-early maturity, spike fertility of 80%. Grain characteristics: 1000-kernel weight of 45 g, semi-vitreous grain with grade 3 plumpness, grain protein content of 16.3%. Main areas of adaptation: mostly high altitude cold areas, but also adapted to warmer areas.

Zhongla N°1, developed from WA//AD20/WRC (AD20 from Russia) in 1985 by Labudalin Farm and ICBC, CAAS. Ploidy level: octoploid. Growth habit: spring. End-use: food. Reaction to prevailing diseases: highly resistant to rusts, immune to powdery mildew, resistant to viral diseases. Agronomic characteristics: intermediate tillering ability, plant height of 125 cm, early maturity, high spike fertility. Grain characteristics: 1000-kernel weight of 30 g, starchy grain with grade 3 plumpness, grain protein content of 16.9%. Main areas of adaptation: high altitude, cold areas of northern China.

Zhongxin N°1881, developed from H221/Hungary 64 in 1988 by ICBC, CAAS. Ploidy level: hexaploid. Growth habit: spring. End-use(s): food/fodder. Reaction to prevailing diseases: highly resistant to rusts, and immune to powdery mildew. Agronomic characteristics: vigorous tillering ability and vegetative growth, "stay-green" leaves, high leaf/stem ratio, plant height of 140 cm, good lodging resistance due to stiff straw, spike fertility of 80%, grain yield potential of 3-4 t/ha, good stress tolerance, including drought, and performs well in poor soils. Grain characteristics: 1000-kernel weight: 35 g. Forage yield and quality: several cuts possible, green fodder yield of 34-39 t/ha (cut at early flowering) with 16.9% protein and 0.45% lysine contents, dry fodder yield of 7.5-9.7 t/ha (cut at early flowering) with 8-10% protein and 0.3% lysine contents; grass powdery yield of 2.7-3.3 t/ha (cut at tillering), with 20-24% protein and 0.5-0.6% lysine contents. Main areas of adaptation: north central plains (winter), northern China, and south of the Yangtze River.

Zhongqin N°1, from TB5/T122-2 (T122-2 from CIMMYT), and Zhongqin N°2 were developed in 1991 by the Shangluo Seed Station and ICBC, CAAS. Ploidy level: hexaploid. Growth habit: winter. End-use: food. Reaction to prevailing diseases: highly resistant to rusts, immune to powdery mildew, and resistant to viral diseases. Agronomic characteristics: intermediate tillering ability, plant height of 130 cm, early maturity, and spike fertility of 86-88%. Grain characteristics: 1000-kernel weight above 45 g, semi-vitreous grain with grade 3 plumpness, and grain protein content of 16.3%. Main areas of adaptation: areas with a single crop per year.

Zhongsi N°1890, developed from H179/Hungary 64 in 1992 by ICBC, CAAS. Ploidy level: hexaploid. Growth habit: winter. End-use: fodder. Reaction to prevailing diseases: highly resistant to rusts and immune to powdery mildew. Agronomic characteristics: vigorous tillering ability and vegetative growth, "stay-green" leaves, high leaf/stem ratio, plant height of 150-170 cm, good lodging resistance due to stiff straw, spike fertility of 88%, grain yield potential of 3-4.5 t/ha, and good cold and drought tolerance. Grain characteristics: 1000-kernel weight: 38 g. Forage yield and quality: several cuts possible, green fodder yield of 45-53 t/ha (cut at early flowering) with 15.8% protein and 0.44% lysine contents, dry fodder yield of 9-11.3 t/ha (cut at early flowering) with 8-10% protein and 0.3% lysine contents, grass powdery yield of 3-3.7 t/ha (cut at tillering), with 20-24% protein and 0.5-0.6% lysine contents. Main areas of adaptation: north central plains (winter) and northwestern China.

Zhongxin N°830, developed from MSH4372//FH12/H435 (FH12 from CIMMYT) in 1993 by ICBC, CAAS. Ploidy level: hexaploid. Growth habit:

winter. End-use(s): dual-purpose food/fodder. Reaction to prevailing diseases: highly resistant to rusts and immune to powdery mildew. Agronomic characteristics: vigorous tillering ability and vegetative growth, “stay-green” leaves, high leaf/stem ratio, plant height of 140-150 cm, good lodging resistance due to stiff straw, spike fertility of 89%, grain yield potential of 3.5-5.2 t/ha, good stress tolerance and performance in poor soils. Grain characteristics: 1000-kernel weight: 45 g. Forage yield and quality: several cuts possible, green fodder yield of 37-42 t/ha (cut at early flowering) with 15.4% protein and 0.45% lysine contents, dry fodder yield of 8.2-9.7 t/ha (cut at early flowering) with 8-10% protein and 0.3% lysine contents, grass powder yield of 2.7-3.3 t/ha (cut at tillering) with 20-24% protein and 0.5-0.6% lysine contents. Main areas of adaptation: north central plains (winter), northwestern China, and south of the Yangtze River.

Jinsong Nº49, developed in 1995 by ICBC, CAAS. Ploidy level: octoploid. Growth habit: winter/intermediate. End-use: food. Reaction to prevailing diseases: highly resistant to rusts, immune to powdery mildew, and intermediate response to Fusarium head scab. Agronomic characteristics: intermediate tillering ability, plant height of 122 cm, semi-early maturity, and spike fertility of 85%. Grain characteristics: 1000-kernel weight of 42 g, and semi-vitreous grain with grade 3 plumpness. Main areas of adaptation: areas with a single crop per year in northwestern and southwestern China, and areas with two crops per year.

Qianzhong N°3, developed in 1998 by the Guizhou Academy of Agricultural Sciences in Guiyang and ICBC, CAAS. Ploidy level: octoploid. Growth habit: winter/intermediate. End-use: food. Reaction to prevailing diseases: highly resistant to rusts, immune to powdery mildew, and intermediate response to Fusarium head scab. Agronomic characteristics: intermediate tillering ability, plant height of 105 cm, semi-early maturity, and spike fertility of 80%. Grain characteristics: 1000-kernel weight of 41 g, and semi-vitreous grain with grade 3 plumpness. Main areas of adaptation: mountain areas of Guizhou Province.

New Triticale Nº1, developed from Zhongxin Nº1881 in 1995 by Shihezi University, Shihezi, Xinjiang. Ploidy level: hexaploid. Growth habit: spring. End-use: food. Reaction to prevailing diseases: highly resistant to rusts, immune to powdery mildew, and intermediate response to Fusarium head scab. Agronomic characteristics: intermediate tillering ability, plant height of 100 cm, early maturity, spike fertility of 80%. Grain characteristics: 1000-kernel weight of 40 g; semi-vitreous grain with grade 3 plumpness. Main areas of adaptation: Xinjiang Uygur Autonomous Region.

Zhongsi Nº237, developed from MSH101/XIN14//WOH45/WOH18 (WOH18 originally from CIMMYT) in 1998 by ICBC, CAAS. Ploidy level: hexaploid. Growth habit: winter. End-use: fodder. Reaction to prevailing diseases: highly resistant to rusts and immune to powdery mildew. Agronomic characteristics: vigorous tillering ability and vegetative growth, “stay-green” leaves, high leaf/stem ratio, plant height of 150-170 cm, good lodging resistance due to stiff straw, spike fertility of 89%, grain yield potential of 3-4.5 t/ha, and good stress tolerance and performance in poor soils. Grain characteristics: 1000-kernel weight: 45 g. Forage yield and quality: several cuts possible, green fodder yield of 45-52 t/ha (cut at early flowering) with 15.9% protein and 0.44% lysine contents, dry fodder yield of 9-11 t/ha (cut at early flowering) with 8-10% protein and 0.3% lysine contents, grass powder yield of 3-3.7 t/ha (cut at tillering) with 20-24% protein and 0.5-0.6% lysine contents. Main areas of adaptation: northern China and south of the Yangtze River.

Zhongsi Nº828**,** developed from H4372/WOH90 (WOH90 from CIMMYT) in 2002 by ICBC, CAAS. Ploidy level: hexaploid. Growth habit: winter. End-use: fodder. Reaction to prevailing diseases: highly resistant to rusts and immune to powdery mildew. Agronomic characteristics: vigorous tillering ability and vegetative growth, “stay-green” leaves, high leaf/stem ratio, plant height of 150-180 cm, good lodging resistance due to stiff straw, spike fertility of 87%, grain yield potential of 3-4.0 t/ha, and good stress tolerance and performance in poor soils. Grain characteristics: 1000-kernel weight: 36 g. Forage yield and quality: several cuts possible, green fodder yield of 45-52 t/ha (cut at early flowering) with 16.5% protein and 0.6% lysine contents, dry fodder yield of 9-12 t/ha (cut at early flowering) with 9-11% protein and 0.35% lysine contents, grass powder yield of 3.2-3.6 t/ha (cut at tillering) with 22-24% protein and 0.6-0.65% lysine contents. Main areas of adaptation: northern China and south of the Yangtze River.

Zhongsi Nº1048**,** developed from NTH324/WOH8-461F7, with 5 generations of selection after 5 rounds of recurrent selection, in 2007 by the Institute of Crop Sciences, CAAS. Ploidy level: hexaploid. Growth habit: winter. End-use: fodder. Reaction to prevailing diseases: highly resistant to rusts and immune to powdery mildew. Agronomic traits: vigorous tillering ability and vegetative growth, “stay-green” leaves, high leaf/stem ratio, plant height of 170-190 cm, good lodging resistance due to stiff straw, spike fertility of 89%, grain yield potential of 3.3-4.5 t/ha, and good stress tolerance, and good performance in poor soils. Grain characteristics: 1000-kernel weight: 40-43 g. Forage yield and quality: several cuts possible, green fodder yield of 45-60 t/ha (cut at early flowering) with 15.7% protein and 0.52% lysine contents, dry fodder yield of 10-13 t/ha (cut at early flowering) with 9-11% protein and 0.35% lysine contents, grass powder yield of 3.5-3.9 t/ha (cut at tillering) with 22-24% protein and 0.5-0.6% lysine contents. Main areas of adaptation: northern China and south of the Yangtze River.

5. Triticale research institutions in China

Chinese institutes involved in triticale research include the Institute of Crop Breeding and Cultivation (ICBC), CAAS, Beijing; the Crop Research Institute, Guizhou Academy of Agricultural Sciences, Guiyang; the Agricultural College of Shihezi University, Shihezi, Xinjiang; and Northeast Agricultural University, Harbin, Heilongjiang. To improve the efficiency of triticale breeding, shorten the time for variety development, and disseminate triticale more effectively, a National Triticale Research Network (NTRN) was created in the 1970s, coordinated by the ICBC, CAAS. The major tasks of this network are described below.

5.1 Cultivar development

Triticale is a relatively new man-made crop, and there is limited genetic diversity within the pool of cultivars developed so far. Therefore, the first objective of the NTRN was to breed new cultivars representing a wider range of genetic variability. Because of its extensive experience in breeding triticale and its more diverse germplasm, ICBC CAAS took a leadership role in this task. To improve breeding efficiency and shorten cultivar development time nationwide, ICBC provided germplasm and breeding expertise to other network members.

Large populations of primary triticale lines were generated for selection and testing in different agro-ecological conditions by network members, resulting in the rapid development and release of cultivars with specific adaptation to diverse environments. Cultivars with specific adaptation included Zhongla N°1 released in eastern Inner Mongolia, Zhongqin N°1 and N°2 released in the Qinling Mountains, Qianzhong N°2 and N°3 released in Guizhou Province, and Xinjiang N°1 released in the Xinjiang Uygur Autonomous Region. On the other hand, several cultivars were characterized by country-wide adaptation: Zhongxin N°830, Zhongxin N°1881, Zhongsi N°1890, and Zhongsi N°237. Release of these cultivars was instrumental in the rapid increase in the area sown to triticale in China.

5.2 Breeding methods for triticale improvement

The complexity of the triticale genome, which combines those of wheat (AB or ABD) and rye (R), slows genetic improvement through breeding. In addition to enhancing breeding efficiency through collaborative research within the NTRN, further gains in efficiency were realized through the use of male sterility-assisted recurrent selection. After 10 years of effort, ICBC transferred the dominant Taigu male-sterile gene (*Ms2*) from wheat to triticale, thereby allowing implementation of recurrent selection breeding schemes for this crop (Liu and Deng, 1997; Sun and Wang, 1997; Sun et al., 1998a, 1998b).

5.3 Multi-location variety testing

Since its inception in 1970, the NTRN has organized four rounds of variety trials, including both winter and spring types. More than 20 cultivars adapted to various agro-ecological zones were approved by provincial committees for release for commercial production. As noted earlier, these new cultivars led to significant expansion of triticale in China. The sites of multi-location cultivar testing are listed in Table 2.

5.4 Development of new end-uses for triticale

Traditionally, triticale was used by farmers in mountain areas to make steamed bread, pancakes, and noodles. In recent years, with the development of forage types, triticale has been used extensively as fresh fodder, silage, and hay in the Yellow and Huai Valleys. Triticale promotion by the NTRN also resulted in the development of new end-uses, including beer, alcohol, and health drinks. Triticale straw is being used in weaving and to make dry flower arrangements.

6. Conclusion

Triticale development in China occurred in three phases: (1) diverse variety types were developed over the last 60 years. Commercial cultivars grown to a significant extent included winter and spring types; food, fodder and dual-purpose types; octoploid

Table 2. Institutes and locations involved in triticale multi-location cultivar testing.

Institute	Location
Institute of Crop Sciences, CAAS	Beijing
Beijing Agriculture Bureau	Beijing
Beijing State Farm Bureau	Beijing
China Agricultural University	Beijing
Institute of Upland Crop Sciences, Hebei AAS	Hengshui, Hebei
Wuqiao Agricultural Bureau	Wuqiao, Hebei
Luoyang Academy of Agricultural Sciences	Luoyang, Henan
Institute of Agricultural Sciences	Binzhou, Shandong
Anhui Agricultural University	Hefei, Anhui
Institute of Crop Sciences, Jiangsu AAS	Nanjing, Jiangsu
Yangzhou University	Yangzhou, Jiangsu
Jiangxi Forage Grass Research Station	Nanchang, Jiangxi
Institute of Soil and Fertilizer Sciences, Hunan AAS	Changsha, Hunan
Institute of Maize Sciences, Shanxi AAS	Xinzhou, Shanxi
Baoji Agricultural Sciences Institute	Baoji, Shaanxi
Qinghai Academy of Agricultural Sciences	Xining, Qingai
Shihezi University	Shihezi, Xinjiang
Xinjiang Production and Construction Corps	Shihezi, Xinjiang
Lanzhou Institute of Agricultural Sciences	Lanzhou, Gansu
Agricultural Technology research Center of Tongwei	Tongwei, Gansu
Institute of Crop Sciences, Ningxia AAS	Yinchuan, Ninxia
Institute of Food Crop Sciences, Guizhou AAS	Guiyang, Guizhou
Northeast Agricultural University	Harbin, Heilongjiang
Yanji Forage Grass Research Station	Yanji, Jinlin
Liaoning Hongtuo Dairy Farm	Shenyang, Liaoning
Hailar Agricultural Bureau	Hailar, Inner Mongolia
Chifeng Agricultural Science Institute	Chifeng, Inner Mongolia

CAAS = Chinese Academy of Agricultural Science;
AAS = Academy of Agricultural Sciences.

and hexaploid types; (2) the main planting areas shifted from high altitude, cold mountainous areas with poor environments to plain areas with better environments; variety types changed from food types to fodder and dual-purpose types; areas sown to hexaploid cultivars greatly increased and those sown to octoploid types decreased; and (3) shifts in planting areas and variety types responded mainly to government food policies aimed at meeting new market needs and adapting to adjustments in agricultural production structure.

References

Bao, W. 1981. Octoploid triticale breeding and its management. Guizhou People's Press, Guiyang, Guizhou Province, China (in Chinese).

Bao, W., and Yan, Y. 1993. Octoploid triticale in China. Advances in Science of China Biology 3: 55-76 (in Chinese).

Blakeslee, A.F. 1937. Methods of inducing doubling of chromosome in plants. Journal of Heredity 28: 392-411.

Gustafson, P., Raskina, O., Ma, X.F., and Nevo, E. 2009. Wheat evolution, domestication, and improvement. In: Carver, B.F. (ed.). Wheat Science and Trade. Wiley-Blackwell, A. John Wiley & Sons, Inc., Iowa, USA. pp. 5-30.

Liu, B., and Deng, J. 1997. A dominant gene for male sterility in wheat. Plant Breeding 3: 204-209.

Meister, G.K. 1921. Natural hybridization of wheat and rye in Russia. Journal of Heredity 12: 467-470.

Muntzing, A. 1979. Triticale: results and problems. In: Advances in Plant Breeding. Berlin and Hamberg, Parey.

Sun, Y. 2002. Triticale: Genetics, Breeding and Utilization in China. Zhejiang Science Press, Hangzhou, Zhejiang Province, China (in Chinese).

Sun, Y., and Wang, C. 1986. Triticale breeding in China. Proceedings of the 1st International Triticale Symposium, Sydney, Australia. Occasional Publications No. 24, pp. 50-59.

Sun, Y., and Wang, C. 1997. Study on utilization of dominant male-sterile triticale in breeding. Wheat Information Service 84: 1-6.

Sun, Y., and Zhang, Y. 1996. The analysis of heritability and combining ability of protein content in triticale. In: H. Guedes-Pinto, N. Darvey, and V.P. Carnide (eds.). Triticale Today and Tomorrow. Kluwer Academic Publishers, Netherlands, pp. 309-314.

Sun, Y., Cui, H., and Chen, X. 1998a. Development of a gene pool for characters of triticale. 4th International Triticale Symposium, July 26-31, Canada, pp. 55-57.

Sun, Y., Cui, H., Wang, Z., and Chen, X. 1998b. Recurrent selection and utilization of triticale. Proceedings of the National Crop Breeding Symposium, China Agritech Press, Beijing, pp. 186-191 (in Chinese).

Sun, Y., Wang, Z., and Cui, H. 2002. Developing new triticale cultivars by chromosome engineering, In: F. Kiichi and X. Zhiyong (eds.). Advances in Chromosome Sciences, Vol. 1, Chromosome Sciences in the New Millennium, Proceedings of the 1st Asia Chromosome Colloquium, Beijing, China, September 27-29, 2001, China Agricultural Science and Technology Press, pp. 477-480.

Sun, Y., Xie, Y., and Wang, Z. 1996. Triticale as forage in China, In: H. Guedes-Pinto, N. Darvey, V.P. Carnide (eds.). Triticale today and tomorrow. Kluwer Academic Publishers, The Netherlands, pp. 879-886.

Wang, Z., and Guo, Y. 1993. Study on the integrated "rice-silage triticale-dairy" farming system. In: Guo, Y. (ed.). Report on Rice Cropping/Farming Systems Project in China. Knowledge Press, Beijing, pp. 302-316 (in Chinese).

Wang, Z., and Sun, Y. 2002. High quality forage crop – triticale. Crops 4: 44-45 (in Chinese).

Wang, Z., and Sun, Y. 2003a. Breeding and utilization of Zhongsi No. 828 triticale. Crops 6: 49 (in Chinese).

Wang, Z., and Sun, Y. 2003b. High quality forage triticale and its superiority in production. Proceedings of the National Crop Breeding Symposium, Beijing, China Agritech Press, pp. 169-171 (in Chinese).

Wilson, A.S. 1876. On wheat and rye hybrids. Proceedings of the Botanical Society of Edinburgh 12: 286-288.

Zillinsky, E.J., and Borlaug, N.E. 1971. Progress in Developing Triticale as an Economic Crop. CIMMYT Research Bulletin 17. Mexico, D.F.: CIMMYT. pp. 27.

Breeding and production of foxtail millet in China

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1. Importance of foxtail millet in China

Also known as Italian, German, Hungarian, or Siberian millet, foxtail millet (*Setaria italica* (L.) Beauv.) is a traditional dryland crop with a long history (more than 8,700 years) of cultivation in China. The crop has played an important role in Chinese culture and was considered the leading crop in ancient times. In 1949, foxtail millet was one of the leading crops in many provinces of northern China. With a planted area of nearly 10 million ha, it was the third most important food crop (after rice and wheat). In recent years, the area sown to foxtail millet has declined due to the expansion of other crops such as high yielding, early maturing hybrid maize. With a current area of around 800,000 ha, foxtail millet remains a leading crop in many arid and semi-arid regions of northern China.

Because of its drought resistance, foxtail millet was described as the "Oasis of Arid Agriculture." Seed germination requires a water content of only 26% by weight, whereas sorghum, wheat, and maize need 40%, 45%, and 48%, respectively. In addition, it tolerates low soil fertility conditions and can achieve satisfactory yields in soils with mineral levels as low as 0.04-0.07% nitrogen, 8 ppm of organic phosphorus, and 0.04% carbon. China has one of the highest water deficits in the world, and over-extraction of groundwater in northern China is becoming a serious problem. Consequently, it seems inevitable that cultivation of water-consuming crops will decrease, while planting of drought tolerant alternative crops such as foxtail millet will increase.

The nutritional value of foxtail millet, called *guzi* in Chinese, is higher than that of rice or wheat flour. Its crude protein content of 11.42% is higher than that of rice, wheat, and maize flour. The amino acid content is appropriate for human health, but, like most cereals, it has low lysine content. In fact, the amount of essential amino acids necessary for human health that is present in foxtail millet is 41% higher than in rice, 65% higher than in wheat flour, and 51.5% higher than in maize. Its average raw fat content (4.28%) is higher than that of rice or wheat flour and similar to that of maize, and unsaturated fatty acids account for 85% of total lipids. With a carbohydrate content of 72.8%, which is lower than that of rice, wheat flour, and maize, foxtail millet is considered an ideal food for diabetics. Its vitamin A and B1 contents are 0.19mg/100g and 0.63mg/100g, respectively, surpassing those of rice, wheat flour, and maize; its mineral (Fe, Zn, Cu, and Mg) contents are also higher than in rice, wheat flour, and maize, while Ca content is similar to that of rice and wheat. Foxtail millet is also rich in selenium (average of 71 ppb), and its edible raw fiber content is four times higher than that of rice. Clearly, this crop has many benefits that justify its role as an indispensable traditional food for northern China.

Foxtail millet can also be used as fodder. Its straw is ideal for livestock because of its high nutritional value (protein content: 6.0%; pentosans: 26.0%; xylogen: 24.2%; fibrin: 42.2%), which is much higher than that of many other crops. In addition, millet straw is relatively soft and easily digested by livestock.

China produces 80% of the world's foxtail millet production. Production of the crop is labor-intensive, and China has the advantage of relatively low labor costs. Given the current international health-food fashion of eating coarse cereals, there should be opportunities for increasing foxtail millet consumption. Foxtail millet is also well known for its strong drought tolerance and resistance to diseases and pests. Consequently, it has relatively low fertilizer and chemical input requirements, which not only reduces production costs, but also makes this grain more attractive as a health food. China currently exports about 2,000 tonnes of foxtail millet annually, mainly to Japan, Korea, Singapore, and Malaysia. It is also an ideal food for birds, and there is a significant and increasing demand for foxtail millet grain and panicles for feeding native birds throughout the world, and especially in developed countries.

2. Geographical distribution and production constraints

Foxtail millet is widely distributed in China, from Heilongjiang Province in the north to Hainan Province in the south, and from Xinjiang and Tibet in the west to Taiwan in the east. However, it is planted mainly in the area bounded by the Huai and Han Rivers and the Qinling Mountains in the south, the Hexi Corridor in the west, the Yinshan Mountains and Heilongjiang in the north, and the Bo Sea in the east; this area lies at N32°~ 48° and E108°~ 130°. In 2008, the foxtail millet cultivated area, average yield, and production in China were 814,000 ha, 1,578 kg/ha, and 1.3 million tonnes, respectively. The main foxtail millet producing provinces are Hebei, Shanxi, Inner Mongolia, Shaanxi, Liaoning, Henan, and Heilongjiang, which account for 90% of all production as presented in Table 1.

Foxtail millet can be classified into spring and summer types, depending upon the sowing season. The spring type is grown in northwestern China with one crop per year. It is planted mostly from mid-April to early May and harvested in late September.

Table 1. Foxtail millet area, yield, and production in China, 2008.

Province	Area (000 ha)	Yield (kg/ha)	Production (000 t)
Hebei	173.5	1871	325
Shanxi	225.1	294	66
Inner Mongolia	143.6	2108	303
Liaoning	76.1	2679	204
Jilin	11.5	2583	30
Heilongjiang	30.4	1645	50
Shandong	15.2	2986	45
Henan	34.5	3014	104
Shaanxi	75.0	1478	111
Gansu	19.8	1604	32
Others	14.0	1143	16
Total	814.7	1578	1286

Source: 2008 China Agriculture Statistical Report, Ministry of Agriculture.

The summer type is planted in the Yellow and Huai Valleys in mid-June, after the wheat harvest, and harvested in late September before wheat planting. The distribution of foxtail millet production areas in China has changed in two ways. First, it has spread increasingly to more arid areas. The cropping areas in Hebei, Shanxi, and Inner Mongolia, located in the arid center of northern China, accounted for 36.1% of the total area in 1949, 42.4% in 1981, and up to 58.2% in 2001, whereas the area in the three northeastern provinces shrank from 29.0% in 1949 to 19.6% in 2001. Second, the proportion of summer millet has increased significantly in certain regions. With the availability of early maturing, high yielding cultivars, spring millet was largely replaced by summer millet, which benefits from the predominant, although limited, summer rainfall. For example, in Shandong, Henan, and middle and southern Hebei, the area of summer millet was previously 10.0%, but is now 85.0%.

Although originally five ecological regions of foxtail millet production were recognized in China, the main production area has been regrouped into three regions: the Northern China Plain Summer Millet Region, the Northeastern China Plain Spring Millet Region, and the Northwestern Loess Soil Plateau Spring Millet Region (Li, 1997).

The Northern China Plain Summer Millet Region includes Shandong, Henan, and middle and southern Hebei. The frost-free period is about 200 days with a mean temperature of 10°C and cumulative temperature of 4,000-4,500°C (above 0°C). Annual rainfall is around 500 mm, and altitude is mainly less than 400 m, with much of it lower than 100 m. Foxtail millet in this area is mainly planted in June after the wheat harvest, and harvested in September before wheat planting. The growth period is about 90 days.

The Northeastern China Plain Spring Millet Region includes Heilongjiang, Liaoning, and Jilin. The frost-free period is 100-180 days with a temperature of 10°C and cumulative temperature lower than 3,000°C. Annual rainfall is 400-700 mm, and altitude is less than 200 m. Except for the southern part of Liaoning, where farmers produce three harvests in two years, most of the region harvests one crop per year. The growth period is 100-135 days; the crop is planted from late April to early May and harvested in late September.

The Northwestern Loess Soil Plateau Spring Millet Region includes Shanxi, Shaanxi, Inner Mongolia, Gansu, northern Hebei, and western Liaoning. The landforms are mainly highland and mountainous with altitudes of 500-1500 m. The frost-free period is 150-180 days with a mean temperature of 10 °C and cumulative temperature of 2,000-4,000°C. Annual rainfall in this area is 300-600 mm. The growth period is 110-125 days; the crop is planted from late April to mid-May and harvested in late September.

The main constraints for foxtail millet production are weeds, crop establishment problems, and use of the grain. Foxtail millet is very sensitive to nearly all the herbicides currently available on the market. Traditionally, foxtail millet is hand-weeded, a labor-intensive operation. Too many rainy days, or dry days, during germination and seedling establishment can result in reduced yields, or even total crop failure. These are the main reasons for the decline in the foxtail millet area in recent years.

Foxtail millet has very small grains and must be densely planted. One thousand grains weigh only about 3.0 g, and 1 kg of seeds include as many as 670,000 grains. The most appropriate number of seedlings in one mu (15 mu = one hectare) is 25,000-50,000. Because the crop is planted mostly in arid areas with poor seedbeds and uncertain soil moisture conditions, large quantities of seed are traditionally planted to ensure large numbers of seedlings that are later manually thinned to the desired density. The quantity of seeds used is generally around 40 kg/ha, while the actual quantity of seeds required to obtain the target density is only around 6 kg/ha. Thus 40,000 tonnes of millet seeds are wasted each year. In addition, over-crowded seedlings retard early growth, and 4-5 persons per mu are required to thin the seedlings. The combined problem of weeds and crowded seedlings during the early growth stage can seriously reduce yield and sometimes lead to crop failure.

Despite its superior nutritional value, foxtail millet is under-utilized due to a lack of processing technologies. More than 85% of foxtail millet is consumed directly as a raw foodstuff (cooked for gruel), and the amounts used for processed food and fodder account for only about 10% and 5%, respectively. Even the processed products are limited to unrefined products such as crispy millet, millet crispy roll, nutrient powder, fast gruel, and sweet crispy millet. Therefore, improvement of processing technology will be very important for foxtail millet development in China.

3. Origin of Chinese foxtail millet and germplasm collection

Foxtail millet, a self-pollinated crop, is believed to have originated in China. Based on the Catalogue of Chinese Millet Cultivars (Crop Germplasm Resource Institute, CAAS, 1991), and on studies of ancient archaeological sites, agricultural history, idioplasmic resources, and wild relatives, Chinese scholars have pointed out that the Yellow River Valley is the likely center of origin of foxtail millet. Archaeological studies have found evidence that foxtail millet has been cultivated in China for over 8,700 years (Lu et al., 2009). Grains of foxtail millet were unearthed at the Henan Xinzheng Feiligang Site (5,935 BC), representing the Chinese Neolithic Age. Foxtail millet was also found in the Xian Banpo Site representing the middle Neolithic Age, and most cultural sites belonging to the later Neolithic period. Among written records, there are words referring to foxtail millet on 3,000-year-old oracle bones.

The Chinese Academy of Agricultural Science (CAAS) and the Shanxi Academy of Agricultural Science (Shanxi AAS) are responsible for collecting and documenting foxtail millet germplasm. Until 2000, there were 27,059 catalogued accessions, including 26,554 accessions from 29 provinces of China and 505 from 18 foreign countries. Among those accessions, there were 24,225 (89.5%) non-waxy types and 2,834 waxy or glutinous (10.5%) accessions.

4. Genetic improvement of foxtail millet in China

4.1 Early history

Over hundreds of years, local cultivars became well established in different regions under names such as Shishizhun, Golden Black, Maoti Millet, Banyelai, Esiniu, Huang Bianxiao, Xifuxiao, and Qisifeng. Among these landraces, there were many cultivars that had good quality, such as those praised as the Four Tributes: Qinzhouhuang, Taohuami, Jinmi, and Longshanmi. Many ancient millet cultivars are still popular among local farmers. For example, in the Taihang Mountain area in She County, Hebei Province, ancient cultivars such as Laiwugu and Dabaigu are still grown because of their unique adaptation to the local climate.

In China, modern foxtail millet improvement began in the 1920s, when institutions such as the former Jinling University in Nanjing, the Yanjing Crop Improvement Station in Beijing, and the North China Agricultural Research Institute in Beijing started to evaluate and compare genotypes, leading to the release of outstanding cultivars such as Yanjing 811, Kaifeng 48, and Huanong 4.

4.2 Breeding objectives

As for most crops, the major breeding objectives for foxtail millet are yield, quality, and stress resistance/tolerance. Due to food shortages in the early 1950s to the mid-1980s, the main breeding objective was high yield potential. Since the mid-1980s, breeders have paid increasing attention to stress resistance/tolerance and quality, although yield potential is always very important. Because of the widespread use of the susceptible cultivar Yugu 1, millet rust (caused by *Uromyces satariae-italicae*) became a serious disease in the Northern China Summer Millet Region, causing large-scale production losses in some years. Rust resistance became a major breeding objective, and resistant cultivars such as Yugu 2 and Jigu 14 were developed. By 1992, millet rust was under effective control, and average yields increased to 2,360 kg/ha in 1996. As food shortages diminished, consumers began to demand better quality. Breeding emphasis on quality led to good quality cultivars such as Jingumi in Hebei and Jingu 21 in Shanxi. Nevertheless, the breeding focus remained on high yield, and adequate stress resistance/tolerance and quality lagged behind as less important objectives.

Since the end of the 20th century, with adequate food availability and a better standard of living, breeding objectives have changed to meet the requirements for better quality, build on the dietary advantages of foxtail millet as a health-food, and capitalize on other specialized uses of the crop such as birdseed. Agronomic objectives for very early maturing cultivars with herbicide tolerance are continuing challenges.

4.3 Recent history of foxtail millet improvement

Significant progress was made in foxtail millet improvement after the establishment of the new China in 1949. It can be divided into three phases: the reselection phase, the cross-breeding phase, and the integrated breeding phase. The leading cultivars developed during the last 60 years are presented in Table 2.

During the 1950s and 1960s, comparisons of local landraces and other germplasm permitted the selection and promotion of better performing lines. Cultivar Moligu, released by the former North China Agricultural Research Institute in 1955, was a reselection of Jianhuijinmiaohuang, a local landrace from Moli village in Ci county, Hebei Province. Following widespread promotion, this cultivar covered 150,000 ha at its peak and is still grown in some mountainous areas of Hebei Province. By the early 1960s, cultivars developed from reselection of local landraces dominated production; widely grown cultivars, besides Moligu, included Jingu 1, Hualian 1, Angu 18, and Xinnong 724.

Table 2. Leading cultivars of foxtail millet in China, from the 1950s to the present.

Cultivar	Cross	Year of release	Areas of adaptation
Xinnong 724	Mihuanggu reselection	1955	Henan, Hebei, Shandong
Moligu	Jiansuijinmiaohuang reselection	1958	Hebei, Beijing, Shanxi
Hualian 1	Huaidehualiangu reselection	1959	Jilin
Angu 18	Daqingmiao reselection	1965	Heilongjiang
Lugu 2	60 Days Huancang reselection	1971	Shandong
Jingu 1	Baimujizui reselection	1973	Shanxi
Zhaogu 1	Shuangguayin reselection	1977	Inner Mongolia, Liaoning
Baisha 971	Baishagu reselection	1978	Jilin
Jigu 6	Japan 60 Days × Xinnong 724	1982	Hebei, Henan, Shandong
Yugu 1	Japan 60 Days × Tulong	1983	Henan, Hebei, Shandong
Longgu 25	Harbin 5 × Longgu 23	1986	Heilongjiang
Yugu 2	An 30 × Xiaoliugen	1989	Henan, Hebei, Shandong
Jingu 21	Jinfen 52 mutation	1991	Shanxi, Shannxi, Inner Mongolia
Lugu 10	Yugu 1 × 5019-5	1995	Shandong , Hebei
Jigu 14	Lusuigu mutation	1996	Hebei, Henan, Shandong
Gufeng 2	95307 × 8337	2002	Hebei, Henan, Shandong
Jigu19	Ai88 × Qingfenggu	2004	Hebei, Henan, Shandong

The period between the mid-1960s and the late 1970s can be described as the cross-breeding phase. The Xinxiang Agricultural Research Institute in Henan Province initiated cross-breeding and produced the cultivar Xinnongdong 2 in 1959. Cross-breeding became popular throughout the country. Since the 1980s, cross-breeding has continued to make the predominant contributions to millet improvement in China. Leading cultivars developed during this period include Yaojin 1, Zhaogu 1, and Yugu 1. Yugu 1, developed by the Anyang Agricultural Research Institute in Henan in 1981, had a yield potential of more than 8,000 kg/ha and became a landmark cultivar contributing to national production. With strong resistance to lodging and a high level of drought tolerance, the area sown to Yugu 1 reached 400,000 ha, more than 70% of the cropping area.

Mutation breeding began in 1963 at the Zhangjiakou Baxia Agricultural Research Institute in Hebei Province. Cultivar Zhangnong 1 was developed by the use of $^{60}\mathrm{Co}\gamma$-ray mutagenesis. Beginning in the 1970s, mutation breeding was widely applied in China, and for nearly 20 years, cultivars developed by mutation breeding accounted for 30% of all cultivars developed during that period (Li, 1997). However, the actual contribution of mutation breeding to cultivar development needs further investigation.

4.4 Development of herbicide resistant cultivars and hybrids

Because foxtail millet is very sensitive to currently available herbicides, herbicide application is not a practical option for producers (Dhanapal, 1987; Norman and Rachie, 1971). A few low-dosage herbicides, such as Atrazine, have been recommended, but further research is required to develop an effective means of controlling weeds in this crop. In 1998, Nankai University in Tianjin developed a chemical agent called Guyou. The recommendation is to apply Guyou as a pre-emergent herbicide after seeding. Under good moisture conditions, it can reduce both monocot and dicot weeds by 90%, effectively controlling weeds at the seedling stage. This agent, however, can delay the early growth of foxtail millet under conditions of continuous rain or under very dry conditions. These disadvantages have somewhat limited the use of Guyou.

Breeding herbicide resistant cultivars is a very important breeding objective, as this will allow the use of herbicides to control weeds. Darmency and Pernes (1985) reported the genetics of resistance to Atrazine in green foxtail (*Setaria viridis*, 2n=2X=18), which is a wild ancestor of foxtail millet. Inheritance of resistance to Sethoxydim and Trifuraline in green foxtail was reported by Beckie and Juras (1998), Wang and Darmency (1997), and Jasieniuk et al. (1994). Since green foxtail is a wild type of foxtail millet, fertile hybrids between them can be easily obtained, and the anti-herbicide genes readily transferred from green foxtail to foxtail millet. In 1993, lines with herbicide resistance genes were introduced into China by the Millet Research Institute of the Hebei Academy of Agricultural and Forestry Science (Hebei AAFS) in Shijiazhuang, and resistant germplasm and cultivars were later developed by several institutes. For example, line DSB98-625SR with Atrazine resistance was developed by the Tieling Agricultural Research Institute in Liaoning Province, and cultivar Bagu 214 with Sethoxydim resistance was released by the Zhangjiakou Baxia Agricultural Research Institute in Hebei Province.

However, new cultivars with herbicide resistance were not widely used in production until 2003. There were four major reasons for the slow adoption of new cultivars: (1) cultivars with resistance to one type of herbicide could not solve all the major weed problems; (2) genotypes with Trifuraline resistance provided only a low level of resistance, and optimal herbicide use was difficult to achieve; (3) although Sethoxydim resistance was effective, it did not control dicot weeds; (4) herbicide resistance controlled by genes in the cytoplasm was associated with poor agronomic performance because the mutation has negative effects on photosynthesis (Wang and Darmency, 1997).

In 2004, the Millet Research Institute, Hebei AAFS, proposed a multi-line approach in combination with the use of selective herbicides to control weeds in millet production. The approach was to utilize the dominant anti-herbicide genes to develop isogenic lines with resistance to both Sethoxydim and Atrazine, with resistance to Sethoxydim or Atrazine, and without any resistance. Two or three isogenic lines could then be mixed for planting. Low dosages of Guyou (1.5 kg/ha) and Sethoxydim were then used for weed control so as to compensate for the disadvantage of Sethoxydim. When there is good seedling establishment, the combined use of Guyou and Sethoxydim achieves both seedling thinning and effective weed control. With average seedling establishment, only Guyou is employed to control weeds. Thus, the problems of seedling thinning and weeds can be solved together. Since 2006, three herbicide resistant cultivars, viz., Jigu 25, Jigu 29, and Jigu 31, were released by the Millet Research Institute. Jigu 25 covered 50,000 ha by 2009, becoming a leading cultivar in Hebei Province.

Studies on hybrid vigor in foxtail millet were initiated by the Yanan Agricultural Research Institute in Shaanxi Province. In 1967, male-sterile plants were found in cultivar Xuanhua Zhuyeqing. Male sterility in this source was controlled by a single recessive nuclear gene, but because of various breeding difficulties, it could not be utilized to produce commercial hybrids (Cui et al., 1979). In 1973, the Zhangjiakou Baxia Agricultural Research Institute in Hebei Province successfully produced the male-sterile line Suanxi 28 that did have a practical application, and a hybrid of Suanxi 28×Zhangnong 15 with significant hybrid vigor was released to farmers in 1980. Unfortunately, the common problem of insufficient seed production by male-sterile parents could not be overcome and hybrids were not widely used.

Wang et al. (1996) proposed the use of anti-herbicide genes in hybrid millet production, with application of Sethoxydim as a pre-emergent herbicide to kill the non-hybrid plants. The two-line hybrid production approach, including both a highly male-sterile line (95% sterile and 5% normal) and the restoration line, was put into use recently. Using this system, the Zhangjiakou Baxia Agricultural Research Institute in Hebei Province developed several hybrid cultivars: Zhangzagu 2, Zhangzagu 3, Zhangzagu 5, and Zhangzagu 8. Zhangzagu 3, currently covering 40,000 ha in northern China, achieved a new grain yield record of 12,150 kg/ha.

To summarize, cultivars and hybrids with herbicide resistance have been successfully developed and used in China. Detailed information on these cultivars and hybrids is given in Table 3.

5. Diseases and insect pests of foxtail millet

Under intensive cultural practices, several significant constraints have emerged for this relatively disease resistant crop. Currently important diseases include white head caused by *Sclerospora graminicola*, foxtail millet rust caused by *Uromyces satariae-italicae*, and sheath blight caused by *Rhizoctonia solani*. Others include foxtail millet smut, caused by *Ustilago crameri* Korn, foxtail millet blast caused by *Piricularia setariae* Nishik., and foxtail millet nematode caused by *Aphelenchoides oryzae* Yokoo. Before the 1970s, foxtail millet blast and foxtail millet red leaf virus (caused by *Luteoviridae luteovirus*) were very severe, but they declined with the use of resistant cultivars and the large-scale shift from spring to summer cultivars. Nematodes, sometimes a problem in the summer cropping areas, and smut have largely been controlled by seed dressings. Details of white head, rust, sheath blight, and two important insects presented below, were obtained from Chinese books (Yu, 1978; Ge, 1996).

5.1 White head

White head, caused by the oomycete *Sclerospora graminicola*, is a common disease of foxtail millet worldwide. In China, the disease is always serious in the spring millet areas, but in recent years it has been increasing in the summer planting areas, where incidence can be as high as 30%. Control can be achieved by resistant cultivars and seed dressings with oomycete-specific chemicals such as metalaxyl. Removal and destruction or deep burying of diseased plants is also recommended. Crop rotation also helps control the disease.

Table 3. Cultivars and hybrids with herbicide resistance.

Name	Cross	Type	Year of release	Area of adaptation
Zhangzagu 2	A2×1526-4	Hybrid, Sethoxydim resistant	2004	Hebei, Shanxi, Gansu, Inner Mongolia
Zhangzagu 3	A2×1484-5	Hybrid, Sethoxydim resistant	2005	Hebei, Shanxi, Gansu, Inner Mongolia
Zhangzagu 5	A2×Improved Jingu 21	Hybrid, Sethoxydim resistant	2005	Hebei, Shanxi, Gansu, Inner Mongolia
Jigu 24	R219Mutant	Cultivar, Atrazine resistant	2006	Hebei, Henan, Shanxi Shandong, Shanxi
Jigu 25	WR1×Jigu 14	Cultivar, Sethoxydim resistant	2006	Hebei, Henan, Shandong, Shanxi
Jigu 29	WR1×Yugu 1	Cultivar, Sethoxydim resistant	2008	Hebei, Henan, Shandong, Shanxi
Jigu 31	Jigu19×1302-9	Cultivar, Sethoxydim resistant	2009	Hebei, Henan, Shandong, Shanxi

5.2 Rust

Millet rust, caused by the autoecious macrocyclic basidiomycete *Uromyces satariae-italicae*, is also a worldwide problem of foxtail millet. In China, this disease is severe in Henan, Shandong, Hebei, and Liaoning Provinces. In epidemic years, yields can be reduced by more than 30%, with complete losses in some instances. Infection in northern China is predominantly by urediospores, and as for most rusts, infection and spread are favored by moist conditions. Control is achieved by using resistant cultivars and applying chemicals early and regularly.

5.3 Sheath blight

Sheath blight, caused by the imperfect fungus *Rhizoctonia solani*, has increased in recent years with the use of shorter cultivars that retain moisture within the canopy. In 1998, a sheath blight epidemic affected a large part of the Chinese foxtail millet production area, causing severe lodging and yield losses of more than 40%. Sheath blight in foxtail millet usually first appears when the stem begins to extend. It starts as gray diseased spots in irregular shapes on the emerging leaf sheaths. These spots expand rapidly, eventually leading to necrosis. During rainy and humid weather, the disease spreads to surrounding plants. Sheath blight can also be caused by *Pellicularia sasakii*, which causes the same disease in rice.

Although genotypes highly resistant to sheath blight are not available, among cultivars there are significant differences in the disease development rate. Integrated control based on partial resistance and management procedures include the removal of crop residues containing roots and stems, late seeding to shorten the infection phase, and reduced plant densities and timely weed control to minimize humidity levels. Application of chemicals such as Triadimenol and Triadimefon to control pathogen infections has also provided some benefit.

5.4 Insect pests

More than 30 species of insects belonging to over 20 families have been reported in foxtail millet, but only two, the lepidopteran snout moth and the dipteran millet stalk fly, are regarded as regular serious pests.

Snout moth, *Chilo infuscatellus*, also known as the two-spotted snout moth or millet borer, occurs mainly in northern China, including Gansu, Shaanxi, Ningxia, Henan, and Shandong, but also in southern China, where it is a common pest of sugarcane. Other hosts include various millets, maize, sorghum, and the weed known as Job's tears (*Semem coicis*). The larvae enter the millet stem and damage either the developing leaves of seedlings before they emerge or the stem itself in older plants, leading to lodging. *Chilo infuscatellus* can produce 1-3 generations per year north of the Yangtze River. Larvae can survive the winter in millet stubble and a few can even survive in millet straw and corn stalks. Potential damage can be predicted by a combination of the frequency of first generation larvae and the level of rainfall in May. For example, in Xinxiang, Henan Province, if rainfall in May exceeds 40 mm or there are more than eight rainfall events, a disaster is likely. The main control measure is the use of omethoate or pyrethroid chemicals. Other recommended control measures include removing all stubble and straw by the end of April to destroy larvae that survived the winter; adjusting the seeding date to avoid the first egg-laying cycle; using early maturing cultivars; and removing obviously affected seedlings to minimize the number of first generation moths.

The foxtail millet stalk fly, *Atherigona besita*, mainly occurs in millet in northern China. Other hosts include golden foxtail (*Setaria glauca*) and green foxtail (*Setaria viridis*). The larvae damage millet crops prior to heading. Stem surfaces show no evidence of infestation, but traces of maggot activity are apparent if the outside leaves are peeled away from the stem. Maggot feeding activity induces inner distortion and rotting, leading to death. *Atherigona besita* usually produces two generations per year in the spring millet areas. The first generation larvae mainly damage spring millet and the second generation larvae cause damage on late-seeded spring millet and summer millet. Most of the aged larvae of the second generation can survive the winter in the soil. This insect can produce three generations in the summer millet areas, where the first generation larvae mainly damage spring millet, and the second and the third generations cause damage on late-seeded spring and summer millet. The larvae overwinter in the soil. Control of stalk fly can be achieved by crop rotation to avoid contact with overwintered larvae, resistant cultivars, seed dressings and chemical sprays, early seeding to avoid the main infestation period, and control of plant densities to maximize aeration of the crop. High rainfall in June leads to higher levels of infestation.

6. Agronomic management

Timely seeding is important to guarantee high, stable yields. Seeding times vary with location, cultivars, and the potential threat of diseases and pests. Spring millet should generally be seeded in the first half of May. Seeding time of summer millet depends on the harvest of the previous crop, but optimally it should be the first half of June and no later than early July. In the temperate zone, the crop performs best on level fields, whereas in cooler regions, hill culture is more suitable.

The optimum density of millet seedlings varies with cultivar and local environmental conditions. Thinning should be done at the 5-7 leaf stage. It can be as single plants or as clumps of 3-5 seedlings. The density of spring millet is generally 30,000-45,000 clumps/ha, whereas that of summer millet is 60,000-75,000 clumps/ha.

Weeding, essential to growing this crop, is usually done 3-4 times with emphasis on the removal of grass competitors. During weeding, usually done by hoe, the earth is molded around the bases of plants to prevent crop lodging.

Foxtail millet is a drought resistant crop mainly grown under dryland conditions; it can produce yields of 3,000-6,000 kg/ha under conditions where the maize cannot survive. It also responds well to water and fertilizer, producing much higher yields.

7. Future prospects

7.1 Yield potential improvement

Grown as a drought resistant dryland crop in poorer agricultural areas, foxtail millet yield levels in China remain comparatively low at around 2,000 kg/ha. However, it has great potential for increased production if cultivated under better conditions. In Shandong Province, the average yield is already 4,000 kg/ha. It is noteworthy that experimental yields of foxtail millet have exceeded 9,000 kg/ha, indicating the very large gap between yield potential and farmers' yields. Thus improvement of yield potential and yield stability across environments are important considerations for breeding programs.

7.2 Improvement of cultivation technologies

The cultivation technologies of foxtail millet in China also require improvement. Foxtail millet is often planted on arid land with rough seedbeds and poor soil conditions. Under such conditions, establishment of seedlings produced from very small seeds is a major problem. Consequently, farmers sow excessive quantities of seed to ensure adequate emergence, followed by thinning to desired levels. This approach is wasteful of seed, labor intensive for seedling thinning, and prone to failure if the weather is wet at thinning.

In the 1980s, the Millet Research Institute, Hebei AAFS, developed a mechanical planting method using a mixture of live and dead seeds. This permitted the seeding rate to be reduced from 40 kg/ha to 15-23 kg/ha, but further reductions are still required. During 1999-2001, the Millet Research Institute of the Shanxi AAS also developed a method in which mixtures of seeds with and without herbicide dressing are planted to reduce the population density.

7.3 Use of foxtail millet as a health food

It is well known that foxtail millet grain is highly nutritious and that millet straw is a good fodder for animals. Currently, over 85% of millet is used for making congee, and that used for processed food and fodder accounts for only 10% and 5%, respectively. The Millet Research Institute, Hebei AAFS, is attempting to better define the special attributes of millet and to develop and promote it as a health food for affluent Chinese and foreign consumers.

7.4 Biotechnology application

During the 1990s, studies on somaclonal variation in foxtail millet led to the development and release of summer millet cultivars Jizhanggu 6 in 1996 and Zheng 407 in 1999 (Diao et al., 1999a).

The Millet Research Institute, Hebei AAFS, initially used trisomic analysis to locate genes in foxtail millet to individual chromosomes, and 19 genes at 12 loci were located (Wang et al., 1994). The Institute has collaborated with the John Innes Center, Norwich, UK, to construct an RFLP map of 180 loci and to locate a gene for tolerance to Trifluralin herbicide (Wang et al., 1998). QTL mapping for kernel weight and threshing ability is currently in progress.

Very recently, an *Agrobacterium* transformation protocol was developed for foxtail millet, and significant progress has also been made in gene cloning and associated work (Diao et al., 1999b, 2006). It is expected that genetically modified organisms (GMOs) and molecular markers will play significant roles in the future development of this crop.

References

Beckie, H.J., and Juras, L.T. 1998. Saskatchewan grain elevator weed survey, herbicide resistance wild oat and green foxtail millet in 1997. Weed Survey Series Publication, Agriculture and Agri Food Canada, 98, Saskatoon, 22 pp.

Crop Germplasm Resource Institute, Chinese Academy of Agricultural Science. 1991. Catalogue of Chinese Millet Cultivars (1986-1990), Volumes I and II, China Agriculture Press, Beijing (in Chinese).

Cui, W., Ma, H., and Zhang, D. 1979. Development and utilization of foxtail millet sterile line Suanxi 28. Journal of Chinese Agricultural Science 12(1): 43-46 (in Chinese).

Darmency, H., and Pernes, J. 1985. Use of wild *Setaria viridis* (L.) Beav. to improve triazine resistance in cultivated *S. italica* (L.) by hybridization. Weed Research 25: 175-179.

Dhanapal, D.N. 1987. Field study on selection of herbicides for dryland crops. Mysore Journal of Agricultural Science 21(1): 87-88.

Diao, X.M., Duan, S., and Chen, Z. 1999a. Millet somatic cell clone variation analysis. Chinese Agricultural Science 32(3): 21-26 (in Chinese).

Diao, X.M., Chen, Z., and Duan, S. 1999b. Factors influencing the transformation of millet callus genes. North China Agricultural Journal 14(3): 31-36 (in Chinese).

Diao, X.M., Freeling, M., and Lisch, D. 2006. Horizontal transfer of a plant transposon. Public Library of Science Biology (PLOS Biology) 4(1): 119-128.

Ge, Z.S. 1996. Control of Diseases, Pest Insects, Weeds, and Rats in Plants. Anhui Science and Technology Press, Hefei, Anhui Province (in Chinese).

Jasieniuk, M., Brule–Babel, A.L., and Morrison, I.N. 1994. Inheritance of trifluralin resistance in green foxtail (*Setaria viridis*). Weed Science 42: 123-127.

Li, Y. 1997. Millet Breeding Science. China Agricultural Press, Beijing (in Chinese).

Lu, H., Zhang, J., Liu, K., Wu, N., Li, Y., Zhou, K., Ye, M., Zhang, T., Zhang, H., Yang, X., Shen, L., Xu, D., and Li, Q. 2009. Earliest domestication of common millet (*Panicum miliaceum*) in East Asia extended to 10,000 years ago. Proceedings of the National Academy of Sciences, USA, 106, 7367-7372.

Ministry of Agriculture. 2008. China Agriculture Statistical Report, China Agriculture Press, Beijing (in Chinese).

Norman, R.M., and Rachie, K.O. 1971. The *Setaria* millet, a review of the world literature. Experiment Station, University of Nebraska College of Agriculture, Nebraska, U.S.A.

Wang, T., and Darmency, H. 1997. Inheritance of Sethoxydim resistance in foxtail millet, *Setaria italica* (L.) Beav. Euphytica 94: 69-73.

Wang, R., Gao, J., Wang, Z., and Wang, Z. 1994. Construction of a millet trisome series. The Plant Journal 36: 690-695.

Wang, T., Du, R., and Chen, H. 1996. New approach to use millet with anti-weed-killer gene to practice two-system crossbreeding advantage utilization. Chinese Agricultural Science 29(4): 96-98 (in Chinese).

Wang, Z.M., Devos, K.M., Liu, C.J., Xiang, J.Y., Wang, R.Q., and Gale, M.D. 1998. Construction of RFLP-based maps of foxtail millet, *Setaria italica*. Theoretical and Applied Genetics 96: 31-33.

Yu, D.F. 1978. Millet Diseases. Science Press, Beijing, China (in Chinese).

Sorghum breeding and production in China

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1. Overview of sorghum in China

1.1 Sorghum production

China has a long history of sorghum (*Sorghum bicolor*) cultivation. Archaeological evidence shows that sorghum has been cultivated in China for at least 40-50 centuries. Sorghum has played an important role in promoting crop production and guaranteeing food security, especially in arid, semi-arid, and waterlogged regions.

Modern sorghum cultivation in China goes back to the early 20th century. In 1914, the sorghum area was 7.4 million ha, with an average yield of 1,117 kg/ha. The peak year for sorghum production was 1918, when the sown area reached 14.7 million ha, production was 16 million tonnes, and average yield was 1,095 kg/ha. In the mid-1920s, the area sown to sorghum began to decline, and by 1929, the area was 9.4 million ha, production was 13.9 million tonnes, and average yield was 1,400 kg/ha. In 1952, the sorghum area reached 9.4 million ha, representing 7.5% of China's total cultivated area, and production was 11.1 million tonnes. In the mid-1950s, agricultural production conditions gradually improved, and the areas sown to paddy rice and maize increased, leading to a significant decrease in the sorghum area. The national sorghum area was 4.3, 2.5, 2.4 and 1.9 million ha in 1976, 1984, 1989 and 1996, respectively. The decline continued, and the total area was only 489,800 ha by 2008. The area, production, and average yield of sorghum in China are shown in Figure 1, and the main sorghum producing provinces are listed in Table 1.

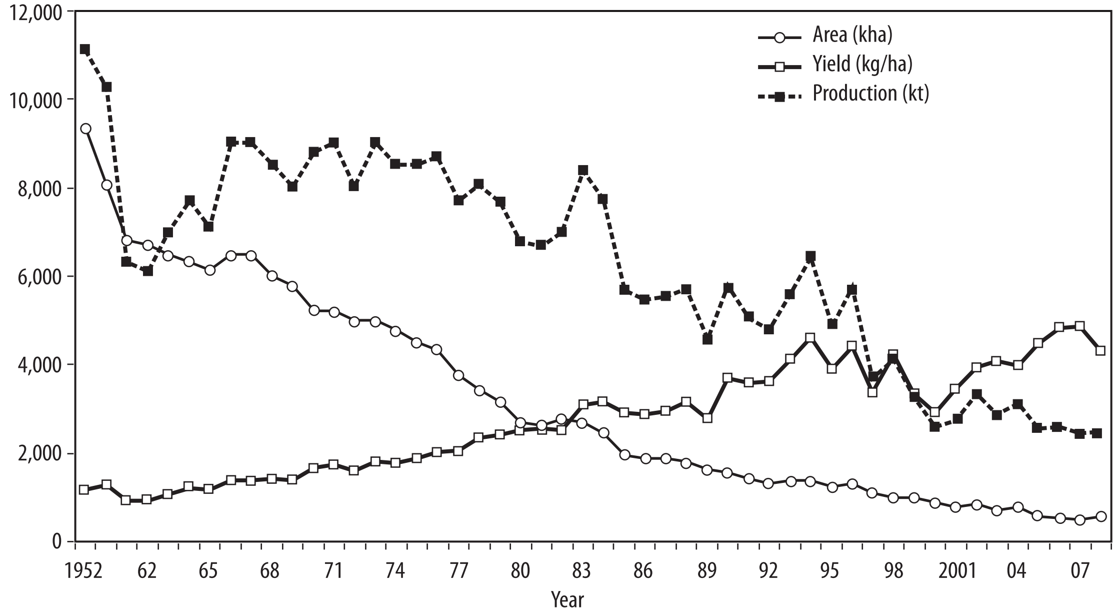

Figure 1. Cultivated area, yield, and production of sorghum in China, 1952-2008.
Source: FAO Statistics Database.

Table 1. Sorghum area, production, and yield by province, 2008.

Province	Area (1000 ha)	Production (000 t)	Yield (kg/ha)
Inner Mongolia	112.6	49.7	4,414
Liaoning	72.7	31.9	4,388
Jilin	69.9	35.9	5,136
Heilongjiang	48.9	17.0	3,476
Sichuan	35.5	14.5	4,085
Shanxi	33.7	1.6	475
Guizhou	25.0	5.4	2,160
Hebei	23.1	4.3	1,861
Gansu	14.7	6.7	4,558
Shaanxi	12.7	3.5	2,756
Chongqing	10.4	3.7	3,558
Others	30.6	9.5	3,702
Total	489.6	183.7	3,751

Source: Chinese Agricultural Data 2008. http://www.agri.gov.cn/sjzl/nongyety.htm.

1.2 Production zones

Sorghum (*Sorghum bicolor*) is an important dryland cereal crop in China, distributed from Taiwan in the east, Xinjiang in the west, north to Aihui county in Heilongjiang, and south to the Sisha Islands. Although distribution is very wide, the major production areas are concentrated in the northern and northeastern parts of the country. Four major production zones are recognized based on cultivars planted and climatic conditions, soil types, and cultivation systems (Qiao, 1988).

The spring-sown early maturing zone covers most of northern China, including Heilongjiang, Jilin, and Inner Mongolia, northern parts of Shanxi and Shaanxi, Chengde and Zhangjiakou Baxia prefectures in Hebei, dryland areas of Ningxia, most of Gansu, and the northern Xinjiang Plain. This zone occupies around 45% of the total sorghum area in China. Altitude ranges from 70 to 3,000 m, and the average temperature range is 2.5-7.0°C, with the total effective daily average temperatures ≥10°C accumulating to 2,000-3,000°C. Annual rainfall in this area generally varies from 100 mm to 700 mm, decreasing from east to west and falling mainly in July and August. The frost-free period is 120-150 days. Because the growing season is short, only one crop can be harvested in a single year. Generally, sorghum is planted in late April or early May and harvested in late September. It is usually grown in rotation with early maize and soybean (growth periods: 100-130 days). Major hybrids include Aoza 1 (*za* is hybrid in Chinese), Neiza 5, Jiza 76, Jiza 80, Jiza 83, and Siza 25. The major constraints to sorghum production are spring drought and low temperature.

The spring-sown late maturing zone covers Liaoning and major parts of Hebei, Shaanxi, and Shanxi; it also includes the eastern and southern parts of Gansu, the Yellow River Irrigated Area in Ningxia, and the oasis in the southern and eastern Xinjiang Basin. It occupies around 40% of China's total sorghum area, with altitudes of 3-2,000 m, annual average temperatures of 8-14.2°C, and total effective daily average temperature of ≥10°C accumulating to 3,000-4,000°C. Annual rainfall across the region is 16.2-900 mm. The frost-free period is 160-250 days. One crop is planted in most locations, and late cultivars are preferred. However, in some areas, early cultivars are planted after the winter wheat harvest, using transplantation to shorten the field growth period. Representative cultivars include Liaoza 10, Jinza 12, Jinza 93, Tieza 10, and Xiongza 4. The main constraint to production is spring drought.

The spring-sown and summer-sown zone covers Shandong, Henan, Anhui, Jiangsu, Hubei, Sichuan, Chongqing, and part of Hebei. The altitude range is 20-3,000 m, and the average annual temperature is 14-17°C. The region is characterized by complex geography and weather that features both continental and plateau climates with four well defined seasons. Due to the influence of the southeastern monsoon, the area has high rainfall (600-1,300 mm), mostly in summer and autumn, and there is abundant sunlight. Such good natural conditions make it China's main agricultural area, where two or even three crops can be grown within a single year. The sowing area is 13% of the total sorghum area in China. The crop can be sown in spring and in summer. Spring-sown sorghum is usually planted in waterlogged lowlands or in barren or alkaline areas, whereas summer-sown sorghum is often rotated with winter wheat. The main soil types are yellow cinnamon soil and yellow-brown soil, and some are paddy soils. Representative cultivars include Qingkeyang, Luza 5 and Lunuo 2. The major constraints to production are insect pests.

The southern zone covers the southern part of central China and the entire area of southern China, including Sichuan, Guizhou, and Hunan Provinces. Although the geographical area is vast, the actual cultivation area is limited, comprising only 2% of the total sorghum area in China. Average altitude is 400-1,500 m, average temperature is 16-22°C, and average rainfall ranges from 1,000 to 2,000 mm. Sorghum can be sown in spring, summer, or autumn in this zone, where transplantation commonly practiced. Throughout the region, sorghum tends to be grown on hillsides or in waysides adjacent to cropping fields and roads. Because of the devastation caused by snout moth (*Mampava bipunctella* Regonat) larvae, cultivars with spreading panicles, such as Xiangnuoliang 1, Xiangxiyounuoliang 1, and Xingxiangliang 2 are preferred. The major constraints to production are insect pests.

1.3 Uses of sorghum

Sorghum grain can be used as food or feed, and as a raw material for the distilling and construction industries. Many kinds of food are made by blending sorghum flour with rice and wheat flours (Zhao, 1987). Depending on the ingredients, sorghum food products can be classified into rice types, wheat types, and puffed types. Sorghum is also used to feed pigs, cattle, and poultry.

Many well-known types of liquor, such as Moutai, Wuliangye, Fenjiu, Yanghedaqu, and Gujinggongjiu, are produced from sorghum grain as the main feedstock. High quality northern Chinese vinegar (for example, the famous Shanxi Old Vinegar) is also made from sorghum.

Sorghum stems and other tissues can be used in various ways, in construction and in industries such as paper manufacturing and fuel. Through weaving and knotting, the stems can be processed into delicate crafts and products such as matting, straw items, and hats. Finally, the inflorescence fringe can be used as a broom, the necks of fringes can be used to make lids, and the hulls can be used for extracting food pigments.

2. Origin and evolution of sorghum in China

There are two theories on the origin and evolution of sorghum (*S. bicolor* var. Kaoliang) in China: (1) that it was introduced from Africa, and (2) it has a separate origin in China. It has been suggested that sorghum originated in Africa and was then introduced to India and, subsequently, to the Far East. Hagerty (1941) pointed out that the names of sorghum, millet, and sugarcane are very confusing in Chinese historical records, which lack sufficient evidence to confirm the cultivation of sorghum in central and northern China before the 12th century. He presumed that sorghum was introduced into China by Genghis Khan after an expedition to southern Asia between 1206 and 1228, and that it spread during the Hubilie Khan period (1260-1295). Martin (1970) thought that sorghum was introduced from Africa into India and subsequently spread across southern Asia, reaching China in the 13th century. It then developed into the unique varieties of China and Japan. Some Chinese scholars agree with this, but Qi (1953) believed that in northern and northeastern China, sorghum was an alien crop whose presence became evident after the Jin dynasty (265-420), and it was only after the Song dynasty (960-1279) that cultivation of the crop began to prevail. He thought it might have been grown initially by minority groups in southwestern China, later spreading throughout China.

In support of an independent origin of cultivated sorghum in China, the Russian botanist E. Bretschneider discovered that the characteristics of Chinese sorghum were quite different from those of African sorghum and that sorghum utilization in China was well developed. He believed ancient millet produced in Sichuan was the progenitor. Vavilov (1935) proposed that China was an large, ancient center of origin for cultivated plants. He listed sorghum as one of the most important crops in the grass family and stated that the Chinese pronunciation of sorghum as Kaoliang referred only to the cultivated sorghum that originated in China. Hu (1981) pointed out that the word for sorghum was frequently seen in documents of the Xian Qin period (2,100-221 BC) and suggested the ancient Liang millet was today's sorghum.

Unearthed relics of sorghum are the most important and direct evidence for sorghum's origin and evolution in China. As early as 1935, Japanese scholars identified sorghum in cereal remains unearthed from the Shanxi Wanrong County Jincun New Stone Age Site. In 1955, the Northeastern Museum found a small pile of charred sorghum in the Liaoning Liaoyang Sandaohao Xihancun Site. In the same year, piles of charred sorghum grains were found in the State Zhao Site of the Warring States Period (475-221 BC) unearthed in Zhuangcun, Shijiazhuang City, Hebei Province. In 1957, the Chinese Archaeological Studies Institute found bent frames made with sorghum stems in an earthen wall from the Western-Han dynasty (206 BC-25 AD) Architectural Site in the western suburbs of Xi'an City, Shaanxi Province. In 1959, the Nanjing Museum found charred sorghum stems and leaves in the Cultural Site of the Western Zhou dynasty (1,100-771 BC) near Sanlidun, Xinyi county, Jiangsu.

Based on these reports of unearthed relics, Wan (1962) pointed out that sorghum cultivation must have been common in Liaoning, Hebei, Shanxi, and Jiangsu as early as the period between the Western Zhou dynasty and the Western Han dynasty. In 1976, the Zhengzhou Museum of Henan Province found charred sorghum grains held in gallipots in the Dahecun Yangshao Cultural Site in northeastern Zhengzhou city. Carbon 14 isotope tracing suggested that these grains were over 5,000 years old. Hu (1981) claimed that evidence of sorghum remains in the period from the New Stone Age to the Western Han dynasty was enough to confirm that sorghum was an ancient crop of China, rather than a relatively recent introduction. Li (1984) claimed that wild sorghum existed in northern China and in Henan Province, and that it also occurred along with *S. propinquum* in southern and southwestern China. Today wild sorghums such as *S. propinquum* and *S. nitidum* can be found in provinces along the southeastern coast.

The chromosome number of *S. propinquum* (2n=20), a perennial plant in the tropical and subtropical zones, is the same as that of cultivated sorghum. Some scientists, including Zhu (1972), claimed that 3,000-5,000 years ago, the Yellow River Valley had a warmer climate, similar to current tropical and subtropical climates, and would thus have been suitable for wild sorghum. Moreover, according to the records of the Shaanxi Sorghum Cultivar Resource Catalog of 1983, wild sorghum was even found in southern Shaanxi Province. Thus, based on archaeological records for the Yellow River Valley, the distribution of wild sorghum in the area, and the ancient ecological environment, it can be assumed that the valley might be the area where Chinese sorghum was initially cultivated.

Chinese sorghum (*kaoliang* in Chinese) has many characteristics that distinguish it from African and Indian sorghums. The stems of *kaoliang* are filled with medulla and lack water when mature; the main veins of the leaves are white; the plant has a strong aerial root system, weak tillering, and high productivity; the internodal lengths are relatively long, and the good quality stalk is suitable for weaving. The hull of the grain is soft and easy to thresh, and the panicles are not prone to shattering. Chinese sorghum has strong cold resistance and good seedling vigor, allowing rapid emergence and early growth. However, it has poor disease and pest resistance, but shows high tolerance to both. The practice of using hybrids of Chinese sorghum proves that Chinese sorghum is very different from African and Indian sorghums. The high level of hybrid vigor between Chinese and foreign sorghum types (such as kafir, milo, and hegari) supports a very wide genetic gap between them. *Kaoliang* has traits that are different from those of other sorghums.

3. History of sorghum breeding in China

Modern sorghum breeding in China started in the 1920s, when cultivar trials managed by Jinling University in Nanjing were conducted at experimental stations in Beijing, Taigu in Shanxi Province, Dingxian in Hebei Province, and Kaifeng in Henan Province. Other northern agricultural institutes began to perform similar studies, and in 1933, cultivars Longnan 330 and Longnan 403 were selected at the Longnan Research Station in Gansu Province; 26-12 at the Kaifeng Experiment Station; 26-24 at Suzhou in Jiangsu Province; and 6-1 in Beijing. During the Japanese occupation in the 1930s and 1940s, Japanese scientists established experiment stations for yield trials in Gongzhuling and Xiongyuecheng in northeastern China. Reselection and cross-breeding, initiated in 1939 and 1941, respectively, focused on improving cultivars such as Nixinbang and Heikesheyanhong.

Since the founding of the People's Republic of China in 1949, sorghum improvement progressed in four phases: germplasm collection, landrace reselection, cross-breeding, and hybrid breeding. Germplasm collection began in 1951, when the government called on people to collect and evaluate good landraces. Scientists cooperated with farmers and selected many superior genotypes, such as Daluobang and Guandongqing in Liaoning Province, Hongbangzi and Huboxiang in Jilin, Dabaye in Heilongjiang, Pingdingguan in Hebei, Zhuyeqing in Shandong, Luyiwaitou in Henan, Sanchisan in Shanxi, Xiheliu in Anhui, Dahongpao in Jiangsu, and Jinghehong in Xinjiang.

Some cultivars were also bred through reselection, including Xiongyue 334 and 360 by the Xiongyue Agricultural Sciences Institute of Liaoning Province; Hejianghong 1 by the Hejiang Agricultural Science Institute in Heilonjiang Province; and Zhaonong 303 by the Chifeng Agricultural Experiment Station in Inner Mongolia. Through reselection, the Xiongyue Agricultural Sciences Institute bred the high yielding cultivar Xiongyue 253 in 1957. In 1966, other cultivars were released, such as Jinliang 9-2, Yuejin 4 and Xiongyue 191, by the Xiongyue Agricultural Sciences Institute and Jinzhou Agricultural Science Institute in Shanxi; Fenxiaodahongsui by Shenyang Agricultural College; Kangya 2 by the Agricultural Institute of Shandong; Hu 2, Hu 4, and Hu 22 by the Agricultural Institute of Jilin; Pingyuanhong by the Agricultural Science Institute of Heilongjiang; and Zhaonong 300 by Chifeng Agricultural Experiment Station in Inner Mongolia.

Cross-breeding of sorghum started quite late in China. In the late 1950s and early 1960s, Liaoliang 119 was bred by Agricultural Science Institute of Liaoning Province, Jinliang 5 by Jinzhou Agricultural Science Institute, and Jiuliang 5 by Jilin Agricultural Science Institute.

Hybrid breeding started in 1956 when CMS line TX3197A and its maintainer TX3197B were introduced into China by Dr. Xu Guanren. Hybrid breeding in China has gone through three phases: direct use of introduced CMS lines, development of new CMS lines by introducing the male-sterility trait into local cultivars, and development of maintainer and restorer lines.

With regard to fertility restoration of TX3197A cytoplasmic sterility, most local cultivars were classified as half-fertile or fertile, and only a few could achieve sterility. Therefore, sterile hybrids were used to breed new sterile lines, and the fertile ones were used to select the best maintainer lines. In 1958, the Chinese Academy of Sciences and the Chinese Academy of Agricultural Sciences, both located in Beijing, released two series of hybrids, the Yiza series and the Yuanza series, based on TX3197A cytoplasm and using local cultivars as maintainer and restorer lines. They were the first generation of Chinese hybrid sorghums. These hybrids had many advantages and yielded 20-60% more than the parents. Their growth period lasted from 110 to 120 days, and average height was more than 200 cm, and as much as 295 cm. Excessive height and weak straw limited their planting over large areas.

Due to the short frost-free periods and the long vegetative growth stage of male-sterile sorghums, they could not be grown in northern China. For that reason, new hybrids were bred using local genotypes as maintainer lines. For example, the Agricultural Science Institute of Jilin Province produced Hongbangzi A, Hu 2A, and Cuo 1A using Hongbangzi, Hu 2, and Cuobazi as parents. Because the advantages of hybrids derived from *kaoliang* sterile and maintainer lines were not significant, they were not planted over large areas. Breeding short hybrid cultivars started in the early 1970s. The first breakthrough was achieved by using the local cultivar Sanchisan as the restorer line, and crossing it with TX3197A. The resulting hybrid, Jinza 5, yielded 6,000 kg/ha and was widely accepted by farmers.

Later, when the Jinza and Xinza hybrids were released, sorghum production in China entered a new stage. In 1975, the area sown to hybrid sorghum rose to 2.7 million ha or 50% of the total sorghum area. Although their yields were very high, hybrids contained very high tannic acid levels, low protein content, and a disagreeable taste. As a result, the hybrid sorghum area rapidly declined. In 1976, the Ministry of Agriculture formulated specific criteria for selecting and breeding sorghum, emphasizing the development of hybrids with high yields, high quality, and resistance to diseases and insects. Subsequently, many hybrids such as Jinza 1, Tieza 1, Shenza 3, and Jiza 1 were developed that met the specified criteria for high yield and good quality (including low tannic acid).

The Agricultural Science Institute of Liaoning Province introduced more male-sterile lines from the USA in 1979, including TX622A, TX623A, and TX624A. Subsequent evaluations showed that these strains performed much better than TX3197A in terms of hybrid vigor, stable fertility, and immunity from smut. These lines were distributed to breeding units, which subsequently produced many high yielding, good quality hybrids, such as Liaoza 1, Shenza 5, Tieza 7, Jinza 83, and Qiaoza 2.

After adopting more open policies, China introduced thousands of sorghum cultivars from India (ICRISAT), USA, and Australia. This provided a greatly expanded range of germplasm for breeding throughout the country. Some hybrids based on these materials were released directly, whereas others were developed through breeding. By the 1990s, cross-breeding of local sterile and maintainer strains had become routine, with increasing numbers of local hybrids being produced, including Liaoza 10, Shenza 5, and Xiongza 4. Others, such as Jinza 12 from the Agricultural Science Institute in Shanxi Province, Jiza 80 and Jiza 83 from the Agricultural Science Institute of Jilin, and Siza 25 from Siping Agricultural Science Institute in Jilin, combined the Texas male-sterile A_2TAM428 with local maintainer lines; these hybrids have become leading cultivars.

Before the 1990s, almost all sorghum hybrid varieties developed had Milo cytoplasm, which endangered sorghum production due to its susceptibility to some diseases (Lu et al., 1997). New CMS lines with different cytoplasms were developed in the USA and India. Schertz et al. (1997) defined Milo cytoplasm as A1, and the others were named A2-A6, and 9E. Of these, A1 and A2 are widely used in grain sorghum hybrid production, and A3 cytoplasm is used in forage sorghum breeding. In the 1990s, varieties with A2 cytoplasm, viz., Jinza 12 (in Shanxi), Liaoza 10 (in Liaoning), and Jiza 80, Jiza 83, and Siza 25 (in Jilin), were developed and released.

The A3 CMS line, described in 1980 (Worstell et al., 1984), was derived from a cross with the cytoplasm of IS1112C (belonging to the Durra-Subglabrescens group of the Durra-bicolor race native to India). Only a very few Chinese kaoliang genotypes can restore their fertility, but can retain their sterility; hence they cannot be used directly in hybrid breeding. However, their use in forage sorghum breeding shows great potential. Several A3 cytoplasm hybrid varieties have been developed and released in more than 20 provinces. The new forage sorghum variety Jincao No. 1 was the first one with A3 cytoplasm in the world.

4. Breeding objectives

Kaoliang is a distinct crop with unique characteristics such as white vein, dry stem, and a strong aerial root system. For it to remain an important crop, kaoliang has to be improved to meet special needs such as adaptation to lower rainfall and poorer soils, and suitability for increased mechanization; genotypes should also be developed that tolerate grass herbicides while retaining their special quality traits and high yield potential.

4.1 Special needs to be met by sorghum improvement

High yield potential. High yields can be achieved in two ways: (1) through further improvement of hybrids, and (2) by modifying the plant to enable it to better utilize the physical environment; for example, morphological changes will lead to greater light interception and higher photosynthetic efficiency.

Quality. Quality must be targeted to the intended uses of the crop. For food and feed, the objectives must include protein content, improved protein digestibility, and reduced tannic acid content. For brewing, the objectives are to maximize carbohydrate content and minimize fat content. However, starch component requirements are different for each brand (Song et al., 1996). For Moutai and Luzhou flavors, higher amylopetine contents are required.

Resistance to diseases and pests. Sorghum must be resistant to the main diseases, including smut (*Sphacelotheca reiliana*), blotch (*Exserohilum turcicum*), anthracnose (*Colletotrichum* spp.), and purple blotch (*Cercospora* spp.), as well as to the main pests: European corn borer (*Ostrinia furnacalis* (Guence)), sorghum aphid (*Melanaphis sacchari* (Zehntner)), and armyworm (*Mythimna separata* (Walker)). Some introduced sorghums have good resistance to diseases (e.g., TX626B and NK-133) and pests (e.g., TAM 428 and NK-133), but their agronomic traits need to be improved to suit Chinese conditions. Finding kaoliang cultivars with adequate pest and disease resistance, in combination with good agronomic performance, will be a major challenge in the future.

Tolerance to environmental stress. Sorghum is a drought tolerant crop, but further tolerance will always be sought in order to address climate change, extend the range of the crop to drier areas, and increase production utilizing limited water resources, particularly in locations where the crop is transplanted. Sorghum also has advantages over maize in areas subject to waterlogging, alkaline soils, and low temperatures.

Herbicide resistance. Herbaceous weeds such as barnyardgrass (*Echinochloa crusgalli*) goosefoot (*Chenopodium scrotinum* L.), pigweed (*Acalypha stralis*), and cocklebur (*Xanthium sibiricum*) are major challenges to sorghum production. Unfortunately, kaoliang is highly sensitive to many herbicides, and the choice of available selective herbicides is extremely limited. Genetic engineering to introduce glyphosate resistance would be a worthwhile objective.

Suitability for mechanical harvesting. With the increasing migration of the labor force from rural to urban areas, mechanization of agriculture has become a significant trend in China, especially in areas with low populations. Mechanized harvesting is already a common practice on state-owned farms in Heilongjiang Province. For this, short dense plant types are preferred.

5. Milestone hybrids

The major sorghum breeding programs are located in Shanxi, Liaoning, Jilin, and Inner Mongolia Provinces, although research is also being conducted in Beijing and Shandong. The leading sorghum hybrids released after 1967 are described below.

Yuanza 10, derived from Yuanxin 1/Xinliang 7, was developed by the Institute for Application of Atomic Energy, CAAS, in 1968. It was the first hybrid sorghum variety in China developed using the A-line Yuanxin 1 (developed by introducing CMS from 3197A into a local cultivar). It has a growth period of 105-120 days, plant height of 160 cm, a strong, thick stem, head length of 30 cm, tolerance to drought, waterlogging, and salinity, and yield potential of 5,250-6,000 kg/ha. It was released in 1968 in Hebei, Henan, Shandong, Hubei, and Anhui Provinces, and its total area was over 0.26 million ha until 1977.

Jinza 5, derived from 3197A/Sanchisan, was developed by the Jinzhong and Lvliang Institutes of Agricultural Science in Shanxi Province in 1973. Its height is 180-200 cm; it has a strong stem, the spindly fringe length is 22-25 cm, and fringy grain weight is 140-190 g. It has a red hull and eggy orange grain, with a 75% shelling rate, and 1000-grain weight of around 32.5 g. It has intermediate maturity, with a growth period of around 130 days. It has high yield potential (8,000 kg/ha), is widely adapted, and shows high resistance to drought, waterlogging, lodging, and salinity. The total sowing area reached 1 million ha in the spring-sowing late maturity zone.

Tongza 2, derived from Heilong 11A/unknown line, was developed by the Datong Breeding Farm in Shanxi Province and released in Jilin Province in 1981. It is characterized by early maturity (growth period: around 110 days) and wide adaptation, and has a yield potential of 4,000-4,500 kg/ha. It has a black hull and red-brown elliptical grain. Its average height is 240 cm, and fringe length is 28 cm. The panicle is medium scattering and cup-shaped. Its fringy grain weight is 70-85 g, and 1000-grain weight is around 27g. It is widely planted in Jilin, with a total sowing area of 1 million ha in the early maturity zone.

Jiza 26, from 2731A/7313, was released in 1978 by the Jilin Academy of Agricultural Science located in Gongzhuling. It is characterized by early maturity and wide adaptation, has a yield potential of 4,500-5,000 kg/ha, with a growth period of around 125 days. Its height is 240-260 cm. The tight 21-23 cm fringe is cylindrical and the fringy grain weight is 80-100 g. It has red hulls and brown grain with a 1000-grain weight of around 26 g. It is mostly planted in Jilin, Liaoning, and Inner Mongolia, with a total sowing area of 1.3 million ha.

Liaoza 1, from TX622A/Jinfu 1, was developed in 1983 by Liaoning AAS in Shenyang. It is characterized by high yield potential (around 8,000 kg/ha) and wide adaptation, and has a growth period of about 125 days (intermediate maturity). Its average height is 207 cm, and its fringe length is 29 cm with medium spindly scattering. The weight of fringy grain is 110 g, the hull is black, and it has shallow orange grain and a 1000-grain weight ranging from 27 to 35 g. Its protein content is 8.47%, lysine content 3.3%, tannin content 0.116%, and shelling rate 80%. It has wide adaptation and a total sowing area of 2 million ha.

Aoza 1, from 314/5922, was developed in 1984 by the Aohanqi Farm in Inner Mongolia. It has high yield potential (7,000 kg/ha), a short growing period of around 115 days, a height of 160-170 cm, and a medium tight and spindly fringe 22-24 cm long. The fringy grain weight is 85 g, with yellow-brown hulls, red-white grain, and a 1000-grain weight of around 30 g. Aoza 1 is planted mainly in the early maturity zone and has a total sowing area of 1.3 million ha.

Kang 4, from TX 622A/Jinliang 5, was developed by the Shanxi Academy of Agricultural Sciences in 1987. Its head length is 30.3 cm, grain weight per head is 120.7 g, and 1000-grain weight is 31.2 g. Its average yield is 7,247 kg/ha (5,707-12,900 kg/ha). It has good resistance to head smut, and high tolerance to salinity and drought. Its total planting area has reached more than 1 million ha in Hebei, Shanxi, Shaanxi, and Gansu since its release, and Kang 4 remains a popular variety for saline soils in the Bohai coastal region of Hebei Province.

Jinza 12, from A2V4A/1383-2, was developed in 1992 by the Sorghum Research Institute of Shanxi AAS. It was developed from an A-line (A2V4A) carrying A2 cytoplasm, and has high yield potential (around 8,500 kg/ha), with a growing period of around 123 days. Its height is around 200 cm, and spindly fringe length is 30 cm with medium scattering, and fringy grain weight of 108 g. It is red-hulled with red grain, and has a 1000-grain weight of around 31 g. It contains 70.75% starch, 8.81% protein, 0.52% lysine, 0.39% tannin, and 3.95% fat. Jinza 12 was widely planted in Shanxi, Xinjiang, Henan, and Anhui.

Jinza 93, developed in 1993 from 232 E A/5-27 by the Jinzhou Agricultural Institute in Shanxi Province, has a growth period of around 127 days, plant height 175 cm, inflorescence length 25 cm, single head grain weight 85 g, and 1000-grain weight of 37 g. Its average yield is 8,178 kg/ha, and it has a protein content of 9.6%, lysine content of 0.19%, low tannin content of 0.05%, and good taste. It also shows good resistance to lodging, leaf diseases, aphids, and head smut. Jinza 93 was widely planted in Liaoning, northern Hebei, Jilin, and Shanxi. At present, it is the control variety in provincial and national variety trials.

Xiangliangnuo No. 1, from XiangnuoliangS-1/Xiang10721, was developed by the Hunan Academy of Agricultural Sciences in 1996. It was the first two-line hybrid sorghum in the world. Its average yield is 6,000-7,500 kg/ha, but its yield potential is 9,750 kg/ha. It can be harvested twice a year, with a combined yield as high as 15 t/ha. In Changsha, Hunan Province, its growth period is 110 days when sown in spring and 95-105 days when sown in autumn. Its regeneration ability is very strong, and the ratoon crop matures in 85 days. It has a plant height of 1.5-1.7 m, head length of 23-34 cm, single head grain weight of 56-90 g, and 1000-grain weight of 21.24 g. It has very strong lodging resistance. Its grain is glutinous, with a starch content of 65.85%, fat content 4.64%, protein 10.06% and tannin 0.29%. This is a preferred variety for producing famous Chinese liquors. Its parental line, Xiangnuoliang S-1, is sensitive to temperature and sterile when the average daily temperature is less than 23.8°C. At temperatures higher than 23.8°C, it becomes partially fertile.

Liaoza 10, derived from 7050A/LR9198 with both A1 and A2 cytoplasm, was developed by the Liaoning AAS in 1997. It has a yield potential of 9,000 kg/ha and a growth period of 130 days (intermediate to late maturity). Its average height is 190-200 cm, and the spindly fringe length is 30-35 cm with medium scattering. The fringy grain weight is 115 g, with red hulls, white grain, and a 1000-grain weight of around 30 g. It has high resistance to smut, sorghum aphid, and lodging. Liaoza 10 is planted in Liaoning and parts of Hebei, Shanxi, Shaanxi, and Gansu, with a total sowing area of 400,000 ha.

Siza 25, derived from TAM 428/Nan 133, was developed in 1998 by the Siping Academy of Agricultural Science in Jilin Province. It has a yield of around 7,700 kg/ha, with a growth period of around 124 days. Its height is 160-175 cm, and its spindly fringe is 26-28 cm with medium scattering. The fringy grain weight is 93-100 g, the hulls are red and the 1000-grain weight is 28-31 g. It is widely planted in midwestern Jilin and the most temperate zone of Heilongjiang Province, with a total sowing area of 0.54 million ha.

Jinza 18, from 7501A/R111, was developed by the Sorghum Research Institute, Shanxi AAS. It was the first hybrid sorghum variety developed by using somaclonal breeding techniques. The R111 parent is a new restorer selected from somaclonal variants of Jinliang 5. Jinliang 5 is a key restorer and has served as a parent for many hybrids. However, it is susceptible to head smut, whereas R111 is resistant. Jinza 18 is resistant to lodging and drought, and has high yield potential and good quality, with a starch content of 75.7%, protein content 9.12%, and fat content of 3.48%. The grain is preferred for liquor production.

Liaotian 1, a sweet sorghum hybrid suitable for fuel ethanol production, was released by the Liaoning AAS in 1997. It was bred by crossing the sterile line L0201A with the sweet sorghum fertility restoring line LTR102. Its growth period is 134 days. The average stalk yield is 75-90 t/ha, and grain yield is 4.5-6 t/ha. The juice brix (content of soluble matter measured with refractometer) is 17-20%. Juice extraction is about 65%. The leaves stay green until harvest. It is resistant to head smut, leaf diseases, and lodging. As an energy crop, it can be planted in most areas of China provided the effective accumulated temperature is more than 2850°C.

Jincao 1, from SXIA/Sudan grass, was developed in 2004 by the Sorghum Research Institute, Shanxi AAS. It is the first forage sorghum with A3 cytoplasm. It has strong regeneration ability, high biomass, and is widely adapted. Growth duration is 130 days, plant height is 280 cm, crude protein content is 15.29%, crude fiber 16.87%, and ash content 10.77%. The total fresh yield of two cuts is 131-197 t/ha.

6. Problems and prospects

6.1 The main problems in sorghum breeding

Although significant progress has been achieved in sorghum improvement during the past 60 years and strong contributions made to national food production, breeding gains and production remain far behind other crops, such as maize. The main reasons for this include: (1) sorghum's yield potential is lower than that of maize due to the slower progress in genetic improvement. The overall sorghum research effort is far behind maize, and China does not have a long-term plan for germplasm introgression in sorghum; (2) serious yield losses due to bird damage; and (3) sorghum breeding procedures are more complex than maize procedures.

Genetic resource development, utilization, and enhancement are crucial for improving breeding progress. In recent years, sorghum breeding has experienced a slowing in genetic gains, largely due to the narrow genetic base of parental lines (Gao et al., 2008). The combination of conventional breeding and biotechnology, including molecular marker-assisted selection (MAS) and genetically modified organisms (GMOs), will play important roles in future germplasm enhancement and hybrid development efforts.

Chinese sorghum belongs to the unique kaoliang group that is characterized by outstanding adaptation to Chinese environments. However, the broad adaptation of Chinese sorghum is declining, largely due to the extensive use of foreign germplasm with very poor performance abilities in the northern low-latitude areas. Low temperatures, slow germination and juvenile development, and susceptibility to diseases and insects are major limiting factors. Hybrids of foreign germplasm and Chinese kaoliang appear to combine the advantages of both groups.

6.2 Potential for use in the human diet

Although sorghum is no longer a staple food in China, it nevertheless has potential as a foodstuff for at least part of the population, as well as a raw material for traditional foods (Li et al., 2004a). Three problems need to be solved before it can expand as a foodstuff: (1) national standards need to be developed based on research; (2) quality attributes need to be defined for each of its uses; and (3) evaluation systems and breeding techniques to develop varieties adequate for making food products need to be established.

6.3 Potential use in the liquor industry

All famous Chinese liquors are produced using sorghum as the main feedstock (Lu et al., 2009). It is estimated that the liquor production industry consumes 2.2-2.8 million tonnes of sorghum grain per year. Annual sorghum production in China is about 2.5 million tonnes. Besides being used for making liquor, sorghum is also utilized as feed and as a raw material for making many other products (e.g., vinegar). Consequently, the supply of sorghum is in a state of tight balance, and in some years, sorghum production is inadequate.

Income from liquor production is one of the economic mainstays in some regions, where local governments organize farmers to grow feedstock sorghum for distilleries in order to guarantee constant production and supply. However, a close association between sorghum producers and the liquor industry has not been established.

Many varieties specifically for distilling have been developed in China (Wang et al., 2006; Zhao et al., 2007; Ding and Zhao, 2008), but their adoption has been rather slow, partly because sorghum breeders do not work in close collaboration with liquor manufacturers. Thus the varieties being developed do not always meet the requirements of special brands.

There are many traditional types of Chinese liquor, each with its own special flavor and characteristics that may require a particular sorghum genotype, but there are no standards for specifying the special needs. The yields of varieties used for making liquor need to be improved to levels produced by other varieties, particularly because special quality varieties do not have a price advantage at present.

Standard procedures for growing sorghum destined for making Maotai (one of the two most famous brands; the other one is Wuliangye) have been established. However, there are no recommendations for other brands. In the future, a set of evaluation criteria should be available for breeders. Greater cooperation between breeders and the liquor industry would undoubtedly lead to genotypes with better quality and higher yield, and obvious economic advantages to both farmers and liquor producers.

6.4 Potential for biofuel production

Sorghum has attracted attention all over the world as an energy crop. In the USA, sweet sorghum and high biomass sorghum are both included in biofuel research and development programs. In China, only sweet sorghum has attracted interest to date.

Sweet sorghum differs from grain sorghum in its sweet juicy stems (Li et al., 2004b). The fresh stem yield can reach 75-105 t/ha with Brix values of 15-20%. Alcohol production potential is up to 6,000 L/ha.

Currently, more than 10 research institutions and some large companies are engaged in sweet sorghum research. The main problems for sweet sorghum research and development are: (1) industrialization is lagging due to a short processing season; (2) utilization techniques for other products are not available, thus the market competitiveness of sweet sorghum still needs a lot of improvement; and (3) shortage of high quality sweet sorghum germplasm for use in breeding programs. CMS lines are not available and lodging is a serious problem. Some institutions have started to develop new CMS lines in order to produce hybrids with higher sugar contents. While lines with A3 cytoplasm can be used to produce sweet sorghums without grains, A3-lines with higher sugar content must first be developed (Zhao et al., 2007).

According to government regulations, sweet sorghum for energy use should be planted mainly in the arid and saline/alkaline regions of the country due to the limited availability of arable land. Breeding programs must therefore target resistance to abiotic stresses in the first instance. Obviously achieving adequate biomass yields in stress environments will be a major problem.

6.5 Potential for forage

As living standards in China improve, animal husbandry is developing very rapidly, and the forage supply does not meet market demands (Xu et al., 2006). The forage cropping areas are increasing significantly, and production of forage sorghum in marginal lands is being promoted by the government.

Two types of forage sorghum cultivars and hybrids are produced in China: one for silage and another for hay. Sorghum for silage is usually a sweet sorghum or hybrid grain sorghum with higher stalk and grain yields. Sweet forage sorghums are generally 3-4 m in height, with high sweet juice content, and brix values of 13-15%. The biomass yield is 75-100 t/ha. Forage grain hybrid sorghums grow 2-3 m in height and produce a silage yield similar to that of maize, but with one-third less water than maize.

Forage sorghums for hay or grazing are typically sudan grass cultivars or sorghum-sudan grass hybrids produced by using a male-sterile grain sorghum female hybridized with a sudan grass pollinator. They can be cut two or three times a year.

Although several forage varieties have been developed and released in China, research on breeding forage sorghum is still in its infancy. Many genetic aspects of forage traits need to be investigated. For both types of forage sorghums, yield and quality are complex and quantitatively inherited. In silage sorghum, emphasis needs to be placed on both forage quality and grain yield. For sorghum-sudan grass hybrids, emphasis needs to be placed on developing pollinator lines with good combining ability for leafiness, forage quality, and high tillering capacity (Rooney, 2004). Incorporating photoperiod sensitivity into sorghum-sudan grass hybrids would improve forage quality by expanding the management window, but this work has not started in China.

Sorghum with the brown midrib trait has improved palatability and digestibility. Research on the use of brown midrib in forage variety breeding is ongoing. Brown midrib reduces lignin content, which is critical to maintaining the structural integrity of the plant. However, lines with the lowest lignin contents are prone to lodging. Thus future work on the use of brown midrib sorghums must target improved lodging resistance while maintaining most of the forage quality attributes.

References

Ding, G., and Zhao, G. 2008. Breeding of a new liquor-making sorghum variety Lulo No. 10 with good quality and high yield. Seeds 27(10): 113 (in Chinese).

Gao, S., Liu, X., and Li, J. 2008. Advance in sorghum hybrid breeding in China. China Agricultural Information 12: 15-18 (in Chinese).

Hagerty, M.J. 1941. Comments on writing concerning Chinese sorghums. Harvard Journal of Asiatic Studies 5: 234-260.

Hu, X.W. 1981. Archaian LiangShu is sorghum. China Agricultural History 00: 77-84 (in Chinese).

Li, F. 1984. History of Cultivated Plant Development. Science Press, Beijing (in Chinese).

Li, G., Lu, Q., and Zou, J. 2004a. Alterative uses of sorghum - methods and feasibility: Chinese perspectives. In: Alternative Uses of Sorghum and Pearl Millet in Asia. Proceedings of an expert meeting, ICRISAT, Patancheru, Andhra Pradesh, 1-4 July, 2003.

Li, G.Y., Gu, W.B., and Chapman, K. 2004b. Sweet Sorghum. China Agriculture and Science Press, Beijing.

Lu, Q., Ding, G., Zou, J., and Zhu, K. 2009. On sorghum industry development in China, II. On sorghum liquor brewery. Rainfed Crops 29(3): 174-177 (in Chinese).

Lu, Q., Song, R., and Lu, F. 1997. Research and application of foreign sorghum germplasm. Rainfed Crops 4: 19-23 (in Chinese).

Martin, J.H. 1970. History and classification of sorghum, *Sorghum bicolor* (Linn). Moench. In: Wall J.S. and Ross W.M. (eds.). Sorghum Production and Utilization. The AVI Publishing Company, Westport, CT, USA. pp. 1-27.

Qi, S.H. 1953. Great contribution of minorities to Chinese culture. History Teaching 7: 9-12 (in Chinese).

Qiao, K.D. 1988. China Sorghum Cultivation. China Agriculture Press, Beijing. pp. 11-16 (in Chinese).

Rooney, W. L. 2004. Sorghum improvement—Integrating traditional and new technology to produce improved genotypes. Advances in Agronomy 83: 38-111.

Schertz, K.F., Sivaramakrishnan, S., Hanna, W.W., Mullet, J., Sun, Y., Murty, U.R., Pring, D.R., Rai, K.N., and Reddy, B.V.S. 1997. Alternate cytoplasms and apomixis of sorghum and pearl millet. In: Proceedings of the International Conference on Genetic Improvement of Sorghum and Pearl Millet. Texas A&M University, Lubbock, Texas, USA. pp. 213-223.

Song, G, Su, Y., and Lu, W. 1996. Discussion of sorghum breeding for liquor production. J. Nucl. Agric. Sci. 17(4): 165-168 (in Chinese).

Vavilov, N.I. 1935. Theoretical Basis of Plant Breeding. VIR, St Petersburg, USSR.

Wan, G.D. 1962. History of Food Crops. Zhong Hua Book Company, Beijing (in Chinese).

Wang, Y., Lu, F., Song, R, Li, Z., and Wang, L. 2006. Selection report of a liquor-brewing sorghum hybrid Liaoza No.23. Rainfed Crops 26(5): 330-332 (in Chinese).

Worstell, J.V., Kidd, H.J., and Schertz, K.F. 1984. Relationships among male-sterility inducing cytoplasms in sorghum. Crop Science 24: 186-189.

Xu, Y.,Yang, W., and Li, W. 2006. Perspective of forage sorghum in China. Rain Fed Crops 26(2): 152-153 (in Chinese).

Zhao, G., Ding, G., and Xiong H. 2007. Selection and application of a good-quality, high-yielding, glutinous and wine-making sorghum hybrid Lunuo No. 9. Rainfed Crops 27(1): 10-11.

Zhao, S.K. 1987. China traditional sorghum food. Liaoning Agricultural Science 2: 55-56 (in Chinese).

Zhao, W., Zhang, F., Cheng, Q., Li, M., and Wang, H. 2007. Research and application of sorghum A3 CMS lines. Crops 1: 62-64.

Zhu, K.Z. 1972. Preliminary study of Chinese temperature changes over the past five thousand years. Acta Archaeologica Sinica 1: 168-189 (in Chinese).

Oat improvement in China

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1. Introduction

Oat belongs to the genus Avena of the Gramineae family. Two types of oats are cultivated in China, namely naked oat (*Avena nuda* L.) and hulled oat (*A. sativa* L.). Naked or non-hulled oat is traditionally cultivated in China. Hulled oats were introduced from other countries only in recent decades, and have been successfully cultivated in northwestern China. Naked oats are mainly used as food, whereas hulled oats are used for feed and forage.

Oat has many names in China, for example, *youmai* in the north, *yumai* in the northwest, *lingdangmai* in the northeast, and *yanmai* in the southwest. Oat, recognized as a health food and an important forage and feed crop in China, has received considerable attention from researchers. In general, naked oat is characterized by large grains, more florets and seed set, early maturity, strong resistance to drought, and tolerance to poor soils. It plays a very important role in the dry areas of northern and northwestern China. Naked oats, which account for about 90% of the total oat area, are easier for local consumers to thresh and process into flour or food with simple tools and equipment (Yang, 1989; Tian, 2002).

1.1 Origin of naked oats

It is widely recognized that China is the center of origin of naked oats. Vavilov (1926), for one, wrote in *Centres of Origin of Cultivated Plants*, that naked oats originated in China. Stanton (1955) also indicated that naked oats originated in China or the eastern part of the former USSR. It was also accepted that naked oat was a special geographical form that arose by mutation in the region between China and Mongolia (Dong and Zheng, 2006). In China, oats are mostly grown in the north, particularly in Inner Mongolia, where wild species of oats are also found. Recent studies using molecular markers on Chinese oat landraces and wild species support the idea that naked oat originated in China (Xu et al., 2009).

1.2 Oat production in China

Oat has been cultivated in China for more than 2000 years. According to descriptions in historical records by Si Matsian (145-87 BC), it played an important role in food production. It was widely distributed throughout the country and grown for food in competition with other crops. However, oat cultivation area declined dramatically in recent decades. In 1939, oat covered 1.07 million ha with a production of 0.9 million tonnes. During the 1950s and 1960s, it was grown on about 1.5 million ha annually and distributed over 210 counties across the country. Since the 1970s, the oat area has decreased due to the adoption of high yielding varieties of rice, wheat, and corn. Today the average annual cultivated area is about 0.5 million ha, where about 0.6 million tonnes are produced. Although grown in many parts in the country, oats are mainly concentrated in northern and northwestern China. Inner Mongolia has the largest area of production, with about 37% of the total cultivated area, followed by Hebei with about 21%, Gansu with 18% and Shanxi with 15%. These four provinces thus account for more than 90% of China's total oat cultivated area and production.

Oats are usually grown in poor soils in dryland areas, and higher yielding crops such as wheat, rice, and corn always occupy the better land. In many oat producing areas, few resources are invested in oats, and annual precipitation, especially in the north and northwest, can be meager. Under such conditions, oats yields range from 500 to 2,200 kg/ha, but may reach 3,000-3,750 kg/ha, or even over 4,500 kg/ha, when the crop is grown under well-managed, irrigated conditions.

1.3 Uses of oats in China

Oat is used not only as staple food in some production areas, but also as a health food because of its high level of nutritional components. In northern and northwestern China, oats contribute to the livelihoods of many millions of people. Oats were recently recommended as a priority food for people suffering from high blood pressure, high blood fat levels, and diabetes. The protein and fat contents in oat grain are about 15.0% and 8.5%, respectively. The lysine, phosphorus, iron, and calcium contents are higher than that of any other cereal crops. Oat grain is also rich in vitamins B1 and E. Research carried out in hospitals showed that cholesterol, lipoprotein, and triglyceride levels, and the body weight of patients suffering from hyperlipoidemia diminished with a diet that included eating 100 g per day of oat flakes for three months; there were no side effects (Shi et al., 1988; Lu, 1990).

Oats are considered an important source of feed and forage. Oat stems are characterized by a soft, tender texture and good palatability, and have more juice and more digestible fiber than similar tissues of millet and barley. They are considered one of best forage crops for animals. It has been claimed that cows fed oat grain produce more milk, and that hens fed on oats lay more eggs. Dry oat stalks are also good industrial raw materials for making paper and instant food boxes.

1.4 General oat research in China

Oat improvement research in China focuses on germplasm resources, breeding, and biotechnology applications. Research on germplasm resources involves collection, characterization, evaluation, documentation, and conservation of genetic materials. This research activity is implemented by the national genebank at the Institute of Crop Science (CAAS) in cooperation with relevant research organizations throughout the country. Research on oat breeding aims to develop varieties with high yield potential, disease resistance, and drought tolerance, and to advance oat productivity and use in China.

The organizations engaged in breeding include Zhangjiakou Prefecture Agricultural Research Institute (Zhangjiakou PARI) in Hebei; Inner Mongolia Academy of Agricultural Sciences (Inner Mongolia AAS); Shanxi Academy of Agricultural Sciences (Shanxi AAS); Baicheng Academy of Agricultural Sciences (Baicheng AAS) in Jilin; as well as research teams at different universities. National multilocation testing of oat varieties is coordinated by the National Extension Center of Agricultural Science and Technology. Biotechnology approaches such as molecular markers are widely used for assessing genetic diversity (Wang et al., 2004; Xu et al., 2009) and gene mapping (He et al., 2007). These research activities have gained support from the Ministry of Agriculture, the Ministry of Science and Technology, as well as provincial governments. A new national oat research program involving oat research organizations in major oat producing areas will focus on germplasm enhancement, improved yield potential and quality, improved cultivation technologies, and various food processing aspects.

2. Oat-based production systems in China

2.1 Production zones

Oats are mainly planted in the northern, northwestern, and southwestern agricultural regions. Ecological conditions in oat growing regions vary widely, especially in terms of environmental stresses, cropping systems, variety ecotypes, and productivity levels. In the1970s, the natural ecological division for oat production was based on variety characteristics and their performance in regional tests. Oat production areas were divided into two major agro-ecological zones and four subzones:

Zone I: Northern China Spring Oats Region

- ***Subzone 1:*** Northern Early Spring Oats Region
- ***Subzone 2:*** Northern Mid-late Spring Oats Region

Zone II: Southern China Facultative Oats Region

- ***Subzone 1:*** Late Oats in the Southwestern Mountainous Region
- ***Subzone 2:*** Late Oats in the Southwestern Plains Region

2.2 Ecological conditions and variety types in different zones and sub-zones

2.2.1 Zone I: Northern China Spring Oats Region

Subzone 1: Northern Early Spring Oats Region. This subzone includes the Tumochuan Plain in Inner Mongolia, and the Datong and Xinding Basins in Shanxi. This subzone has an annual planting area of about 66,700 ha, comprising 5-7% of China's total oat area. The region possesses calcareous alluvial and chestnut soils with good fertility. Yearly precipitation is 300-500 mm, of which 50% falls in July and August. The annual average temperature is 4-6°C, and 15-25°C in the growing season from May to August. Oats are sown generally in early or mid-April, and harvested in late July or early August. This region mainly grows naked oat varieties with a strong spring growth habit, good tillering ability, and cold and drought tolerance. Generally, the 1000-grain weight is 20-22 g and the growth period is 90-95 days. Representative varieties include Yong 492 and Hebei 2.

Subzone 2: Northern Mid-late Spring Oats Region. This subzone consists of many areas, including the central and western parts of Xinjiang, Dingxi, and Linxia located in the southern foothills of Helanshan Mountain and Liupanshan Mountain in Gansu; mountainous areas of the Huangshui and Yellow River Valleys in Qinghai; the northern foothills of the Qinling Mountains and Yanan area in Shaanxi; the Guyuan area in Ningxia; the southern and northern parts of Yingshan Mountains in Inner Mongolia; Taihangshan and Lingshan Mountain areas in Shaanxi; Bashang area in Hebei; the Yanshan hilly areas in Beijing; and the southern foothills of the Large and Small Xinganling Mountains in Heilongjiang. The area sown to oats in this region represents about 80% of China's total oat area. The topography in this subzone is complicated, with altitudes ranging from 500 to 1,700 m. Soils vary from chernozem and meadow chestnut soils to light chestnut soils, with large differences in fertility. The climate is characterized by strong winds and drought, and is especially dry in spring. Total annual precipitation is 300-400 mm, of which about 70% falls from June to August. This coincides with the period of high water requirement in oats. The mean annual temperature is 2.5-6°C, and the annual effective accumulated temperature (equal to or higher than 10°C) is 1,500-2,000°C, which meets the needs of oats during the growing season. Three types of varieties are grown in this subzone:

- *Mid to late varieties on hilly dryland.* These varieties cover more than 80,040 ha, and are characterized by slow seedling development, early prostrate growth, strong tillering ability, and rapid elongation after the onset of warm weather in July, when rainfall is more likely. Usually tall, with weak stems, long, narrow leaves, and large grain (1000-grain weight: 22-25 g), they are sown in mid- to late May and harvested in late August or early September. The entire growing period is 95-110 days. Representative varieties are Sanfensan, Huabei 2, and some local large-grained naked genotypes.
- *Early varieties on hilly dryland.* Varieties of this type have shorter plant height, a longer creeping growth period, shorter grain-filling, 1000-grain weight of less than 20 g, and a growth period of 80-85 days. They can be grown as emergency crops following failures of other crops. Examples are local, small-grained, naked oat varieties such as Mengyan 1809 and Beihuang 1.
- *Mid-season varieties in arid sandy areas.* These varieties are planted on a relatively large area (233,300 ha). The Yellow River is used as a source of irrigation water in some areas. Seedlings of these varieties are upright or semi-upright, with short wide leaves, and tall plant height; they are tolerant to waterlogging and fertilizers, as well as resistant to lodging. Planting occurs in early or mid-May and harvesting in mid-August; the growing period is 90-95 days. Representative varieties are Sanfensan, "578" and Yan 1211.

2.2.2 Zone II: Southern China Facultative Oats Region

Subzone 1: Late Oats in the Southwestern Mountainous Region. This region, with altitudes above 2,000 m, and covering about 100,000 ha, is in Yunnan, Guizhou, and Sichuan Provinces, where there are wide temperature variations and inadequate sunlight during the growing period. Yearly rainfall is about 1,000 mm. Oats are planted in autumn and harvested in spring; the total growing period is 220-240 days. Varieties here have strong drought and cold tolerance, but poor lodging resistance, poor seed-holding capacity, and low 1000-grain weight. A representative variety is Tuotuoyanmai.

Subzone 2: Late Oats in the Southwestern Plains Region. The area sown to oat in this region is about 66,700 ha and includes the Large and Small Langshan Mountains of Sichuan, Guizhou, and Yunnan. The area is noted for its rich soil fertility, humid climate, good irrigation, and intensive cultivation practices with planting done with drills. The varieties in this high yielding area are characterized by tallness, strong stems, slow seedling development, large, wide, dark-green leaves, and a long grain-filling period. The 1000-grain weight is about 17 g. Planting occurs in mid-October and harvesting in late May and early June of the following year. The total growing period is 200-220 days. A representative variety is Yunnan Large Naked Oat.

2.3 Major pests and diseases of oats

World surveys of oat diseases have been conducted since the 1920s. All species of oats, including diploids, tetraploids and hexaploids, are attacked by fungi, bacteria, and viruses. The main oat diseases in China are smuts, rusts, red leaf disease (BYDV), and several physiological diseases.

2.3.1 Oat diseases

Oat smut. Two related fungal pathogens cause smut diseases on oats: *Ustilago avenae* (loose smut) and *U. kolleri* (also known as *U. hordei* and *U. levis*) (covered smut). The latter is more common in China. In the case of loose smut, the black chlamydospores blow or wash from the maturing spikes leaving denuded structures, whereas in the case of covered smut the spore mass is enclosed in a pale grayish membrane that remains intact until the plants are mature. Spores of both pathogens are either seed-borne or survive in the soil. Both *Ustilago avenae* and *U. kolleri* infect the coleoptiles of germinating seedlings, and the fungi grow with the growing points and sporulate in the florets of infected tillers. Spores can survive for long periods, especially under low temperatures and dry conditions. Both species occur as distinct races that can be distinguished on sets of differential host genotypes.

Oat smut can cause heavy yield losses. Generally, over 10%, but sometimes up to 46-90%, of spikes can be affected in northern and northwestern China. Control methods are: (1) seed treatment using 1% formalin (HCHO) to achieve 95-100% control; (2) disease resistant varieties to replace local varieties, more than 90% of which are susceptible; a few are resistant, e.g., Yong-492, 73-7, Baxuan 3, and Yong-75; and (3) integrated management, using, for example, resistant varieties, crop rotation to avoid soils with high spore loads, fungicide seed treatment, and soil sterilization.

Barley yellow dwarf virus (BYDV). The disease known as oat red leaf disease in China is commonly called barley yellow dwarf or cereal yellow dwarf in western countries. The disease appears in most oat growing regions of China. Symptoms include thick, hard, red leaves, reduced plant height, premature senescence, floret sterility (blasting), and reduced 1000-grain weight. The aphid vectors of the disease are *Schizaphis graminum* and *Macrosiphum avenae.*

The BYD virus can survive the winter in perennial grass weeds and autumn-sown cereal crops. The non-crop hosts may be symptomless or have varying degrees of the symptoms described above, depending on actual host species (often tending to yellow rather than red color) and genotype, time of infection, and environmental conditions. BYDV occurs as a number of serotypes; those reported in China include GPV, GAV, PAV, and RMV (Zhou et al., 1984). The major methods for combating the disease in China are to control the aphid vectors using SUMILEX (N-(3,5-Dichlorophenyl)-1,2-dimethyl-1,2-Cyclopropanedicarboximide); remove or reduce primary infection points to reduce the likelihood that pathogens will transfer to neighboring plants; and use resistant varieties such as Xiaoluoyanmai, Yong 492, and Jian 19.

Oat stem rust. The pathogen that causes oat stem rust is *Puccinia graminis* f. sp. *avenae*. Stem rust is important only in northern China, mainly in Inner Mongolia, where it attacks the crop in early or mid-July. Red urediniospores (summer spore stage) are produced on leaves and stems. Stem rust can cause yield losses of 25-50%. In 1980-1982, most oat fields in the Wumeng region of Inner Mongolia were infected with stem rust that caused losses exceeding 30%. The uredinial stage of the pathogen overwinters on grasses such as *Bromus* species in the warmer parts of southern China; urediospores migrate to the north with summer winds and infect oats. Stem rust is favored by high temperatures and high humidity. Control can be achieved with resistant varieties and chemical fungicides, provided they are applied sufficiently early. The pathogen occurs as a complex of races, and resistance may be short-lived due to increases in previously rare races or to new mutants with virulence.

2.3.2 Pests

Aphids. Aphids not only transmit BYDV but also cause significant damage by their feeding activities. Control measures were discussed under BYDV.

Armyworm. Armyworm (*Mythimna separate* Walker), one of 10 major pests of oats in China since the 1950s, can seriously damage oats, especially in the north and northwest. The larvae, characterized by a yellow-brown or black body, brown head with black-brown lines, half ring brown crochet, and six instars; they consume leaves and young spikes. Armyworms cannot survive the winter in northern China. They must migrate from the south, permitting 3-4 generations in the oat growing regions of the north and 2-3 generations in the northwest. First-generation larvae are particularly damaging to oats. Control includes trapping the adults with snare nets, and chemically controlling the larvae before the third instar.

Grasshoppers. Six species of grasshoppers can seriously attack oats. They are common in the oat growing areas of Inner Mongolia. They survive for one generation annually in northern China. Monitoring of eggs and nymphs, and using pesticides on the nymphs are the most effective means of control.

Wireworms. These pests undergo one generation in three years, and the larval stage lasts 2-3 years. Both larvae and adults overwinter in the soil and become active when soil temperatures at 10 cm depth are over 10°C (the critical time to control wireworm). Treating seed with 20% phorate and baiting and disinfecting the soil are effective ways to control wireworm.

3. Oat genetic improvement

3.1 History of oat improvement

Before the founding of the People's Republic of China in 1949, there were no special research units for oat improvement. In the 1950s, CAAS, in cooperation with agricultural research institutes in oat producing areas such as Inner Mongolia, Shanxi, and Hebei, initiated special efforts to collect, identify, and conserve oat germplasm from the main oat growing areas of the country. In the early 1980s, the wild oat genetic resources in China were initially investigated. In 1983, the first *Catalogue of Chinese Oat Germplasm Resources* was published by the Institute of Crop Germplasm Resources (ICGR, CAAS). It contains passport and characterization data on 1,492 oat accessions collected throughout the country. Efforts to collect and conserve oat germplasm resources continued in the 1990s, and a national project on oat germplasm resources was implemented by the ICGR (CAAS) in cooperation with relevant research organizations in the main oat producing provinces. In 1995, the second *Catalogue of Chinese Oat Germplasm Resources* was published, in which a further 1,484 accessions collected from China and abroad were documented. Currently, more than 3,200 accessions of oats are conserved in the national genebank. The work on germplasm collection and conservation established the basis for variety improvement of oats in China.

China initiated breeding activities in the 1960s, when regional yield trials of naked oats were conducted in the north, particularly Zhangjiakou in Hebei and Wumeng in Inner Mongolia. As a result of the tests, Huabei l and Huabei 2 were selected and released for production. These varieties produced oat yields that were 10-30% higher than those of local varieties such as Sanfensan. In the mid-1960s, naked varieties of the Yanhonghao series were bred through intervarietal crossing by the Yanbei Prefectual Agricultural Research Institute in Shanxi. Subsequently, hybridization became the main method used for breeding new naked oat varieties.

From the beginning of the 1970s, interspecific crosses between *Avena sativa* and *Avena nuda* were carried out. New strains of naked oats were selected that had shorter, thicker stems and better lodging resistance than older varieties. The improved varieties had a yield potential of over 4,500 kg/ha in rich soils and adequate water conditions. For example, variety Yong 492, with short stature and strong lodging resistance, had a yield increase of 10-20% compared with Huabei 2. Yong 492 was well-suited to irrigated areas. Later interspecific cross derivatives included Jingyan 2, Neiyan 4, Neiyan 5, Jingza 2, Wuyan 2, "578", and Jian 19. The yields of these varieties were over 10% higher than those of the main local varieties.

Of all the cross combinations that were made annually in the 1980s, 70-80% were interspecific crosses between *Avena sativa* and *Avena nuda*. Many varieties with good agronomic traits were developed, such as Tiegandali (7634-10-1) with a 1000-grain weight of 35 g, about 15 g higher than that of landraces. Variety 766-38-2-1 with more florets, more grains set, and BYDV resistance was developed by the Zhanjiakou PARI. Neiyou 1 (suitable for both irrigated and rainfed environments) and Neiyou 2 and early variety 758-38 (growth season: 65-70 days) were bred by the Wumeng Prefectural Agricultural Research Institute in Inner Mongolia. In addition, new breeding materials with special traits were developed, and these in turn contributed to oat improvement. Some progress was also achieved by pedigree selection following irradiation treatments, mainly with gamma rays.

In the last two decades, varieties Neicaoyou 1, Neiyan 3, and Neiqingyou 323, characterized by fast growth, tall plant height, and high forage productivity, contributed to the development of animal husbandry. With the development of oat markets, many breeders focused on developing good quality varieties with high protein content and large grain in order to meet the needs of oat-flake processing. A tetraploid oat (*A. magna*) from Morocco, with 32.4% protein content, 36.1 g 1000-grain weight, and stem rust resistance, was used in oat improvement. After overcoming the incompatibility of wide crossing and poor seed-holding capacity, strains with more than 18% protein content were selected. To meet the needs of oat flake processing, breeders developed a number of naked oat varieties with 1000-grain weights of more than 30 g. For example, Mengyan 7306 with a 1000-grain weight of 32 g was developed by the Inner Mongolia AAS. At the same time, varieties with green stems at maturity were developed for forage use. Green stems are more tender than yellow stems and contain more juice, which is preferred by animals. In recent years, increased grain β-glucan content has been a focus in oat breeding, and a number of varieties such as Bayou 1 and Baiyan 2 were released by the Zhangjiakou PARI and the Baicheng AAS, respectively.

3.2 Oat genetic resources

Since the 1950s, China has been collecting oat germplasm throughout the country. As a result, more than 3,200 accessions of oats have been collected and stored in the national genebank in Beijing. Of these, about 1,700 accessions are naked oats and 1,500 are hulled oats, in addition to 50 accessions of wild oat species. After the collection was characterized for major agronomic traits, many accessions with important traits such as drought tolerance and resistance to various diseases were made available to breeding programs. More than 60% of accessions are local varieties collected from farms. Some of these varieties have a short growing period (generally 60-75 days), 50-175 cm plant height, growth habits ranging from erect and semi-prostrate to prostrate, very different panicle types and fertilities, and 1000-grain weights ranging from 11 to 40 g. Protein content ranges from 11.9 to 20.5%, and β-glucan content is 2.5-7.5% (Zheng et al., 2006).

3.3 Naked oat breeding objectives

Breeding objectives for naked oats in the different agro-ecological zones vary depending on their use, major biotic and abiotic stresses, and production conditions. Oats are mostly grown in cool, high mountainous regions under a mixed crop/livestock system. New varieties are thus likely to be used for both grain and fodder.

In rainfed areas, breeding objectives should focus on developing varieties with good tillering ability, high grain and vegetative harvest indices, longer growing period, slow growth at the seedling stage, fast grain-filling rates, taller plant heights (100-124 cm), large spikes, well-developed root systems with stronger and deeper roots, and a good combination of yield components (3 million spikes per hectare, 30-35 kernels per spike, and 1000-grain weights of more than 25 g).

For irrigated conditions, varieties should have a shorter growing period (90 days), short stature (95-100 cm), compact plant type, lodging resistance, uniform tillering with more florets and kernels, tolerance to high water and fertility conditions, and a good combination of yield components (4.8-6.7 million spikes per hectare, 35-50 seeds per spike, and a 1000-grain weight of more than 20 g).

Covered smut, stem rust, and BYDV occur very frequently, and aphid damage can also limit oat production in most oat growing areas. Therefore, improving varieties with resistance to these diseases and aphids should be a priority for oat breeding programs.

Development of high quality oat varieties is a major objective in China. Breeding varieties with high protein content (more than 17%) began in 1990. Forage varieties should have green stems with high protein content at maturity and higher stature (over 120 cm). Today oat breeding programs focus on high quality, yield, drought tolerance, and diversified maturities. Improving the quality of oat varieties, particularly the β-glucan content, became a priority in order to meet processing requirements, particularly for oat flakes. Because oats are grown mostly in dry areas of Inner Mongolia, Gansu, Ningxia, it is important to have strong drought tolerance. Oats are planted as a second crop in a single season in areas such as Baicheng in Jilin Province. Improved varieties with short growing periods and photoperiod insensitivity are important in such areas.

3.4 Major breeding techniques used in oats

Landrace improvement. Initially, Chinese breeders mainly improved landraces. Varieties collected from local farms in the 1950s were very different in terms of agronomic traits. Breeders used population improvement to raise yields of landraces. They usually selected superior individual plants from large populations of particular varieties and formed new populations with improved traits. This resulted in varieties such as Sanfensan and Huabei 1.

Cross-breeding. Cross-breeding was popularly used to develop oat varieties after the 1960s. Varieties, particularly hulled types with useful traits such as high yield potential and lodging and disease resistance, were selected as parents and crossed with Chinese naked genotypes. Pedigree selection was then used to develop new varieties such as Jizhangyou 2, Neiyan 2, and Pin 6.

Irradiation treatment. Varieties Yanhong 3, Fuza 2, and naked oat "1809" were selected following gamma ray treatments of 15,000-25,000 Roentgen units at 100-150 units/min.

3.5 Descriptions of major oat cultivars

Yong 492 (Xiao 46-5) was released in Inner Mongolia under the name Yong 492 and in Shanxi as Xiao 46-5. It has spring habit, lodging resistance, strong tillering ability, and an intermediate response to BYDV. Seedlings are erect with short, erect, wide, dark-green leaves. Plant height is around 100 cm, and plant type is compact. The panicle spike is about 20 cm long, with 25-30 spikelets. Each spike generates 60-70 seeds with pale yellow color, spindle shape, and good quality. Its 1000-seed weight is about 19 g. Seed protein content is 14.4%, fat 4.6%, and lysine 0.57%. The growing period is about 85 days; yield potential is about 3,000 kg/ha under normal growing conditions and 4,500-6,000 kg/ha with irrigation and fertilizers.

***Huabei 2**, a* spring type naked variety, was widely distributed in Inner Mongolia, Hebei, and Shanxi Provinces in the 1960s. It has weak tillering ability and an intermediate response to BYDV. Plant height is about 120 cm, and panicle spike is 20-25 cm long with 21-23 spikelets. Each pale yellow spike contains 40-50 seeds. It has good quality and 1000-grain weight of about 20 g. It is prone to lodging under high fertility and irrigated conditions. Protein, fat, and lysine contents are 15.8, 6.7, and 0.56%, respectively. Its growth period is about 95 days; yield potential is 1,500 kg/ha under normal growing conditions and 3,750 kg/ha under high water and fertilizer levels. Huabei 2 is broadly adapted and well-suited for dryland or wetland soils with intermediate fertility levels.

Baxuan 3 was developed in 1961 by bulk selection from Hungarian variety 1-6-800 by the Zhangjiakou PARI in Hebei. It is characterized by good resistance to lodging and grain shattering. Plant height is about 100 cm. It has a panicle spike and 1000-grain weight of 21-22 g. Baxuan 3 is an intermediate to early naked oat, with a growing period of 85-90 days. It is suitable for irrigated plain conditions.

Jizhangyan 1 was developed in 1971 through intervarietal crossing by the Zhangjiakou PARI in Hebei Province. It is characterized by a semi-prostrate seedling habit, high tillering ability, and a panicle spike. Plant height is 110-130 cm, spike length 20-25 cm, and each spike contains 40-55 seeds. The 1000-seed weight is 26-28 g. The variety shows vigorous, uniform maturity with medium resistance to drought and lodging, but is susceptible to covered smut. The elongated grains contain 16.2% protein, 8.7% fat, and 0.513% lysine. It is intermediate maturing with a growing period of 85-95 days. Its yield potential is 1,800-2,400 kg/ha under normal growing conditions. The area sown to Jizhangyan 1 was 66,700 ha in the early 1980s. It is suitable for high fertility conditions in arid areas.

Pin 1 was bred from the cross Xiao46-5/Yong 118 by the Zhangjiakou PARI. It has a panicle spike and strong, thick stems. Plant height is 80-100 cm. Its 1000-seed weight is about 20 g. It is resistant to lodging and covered smut. Pin 1 is mid-early maturing with a growing period of 85 days. Its yield potential is 3,000-3,750 kg/ha under normal irrigated conditions.

Jinyan 1 was developed in 1973 from Huabei 2/Huabei 1 by the Crop Research Institute for Cool and High Land, Shanxi Academy of Agricultural Sciences (SAAS). Jinyan 1 has large spikes with many spikelets and strong, thick stems. Plant height is about 124 cm, and 1000-seed weight is about 24 g. Jinyan 1 is a late maturing variety with growing period of 104 days. Its yield potential is 2,737-3,247 kg/ha. It is suitable for wet, hilly areas.

Jinyan 3, selected in 1974 from Huabei 1/Sanfensan by the Crop Research Institute for Cool and High Land, SAAS, is characterized by semi-prostrate seedlings and strong stems. Plant height is about 124 cm, and 1000-seed weight about 23 g. It has medium tillering ability with high spiking rate, lodging resistance, drought tolerance, and wide adaptability. Jinyan 3 is a mid maturing variety with a growing period of 95 days. Its yield potential is 1,507-4,000 kg/ha. It is suitable for growing under both irrigated and arid conditions in Inner Mongolia, Ningxia, Shanxi, and Hebei.

Jinyan 4 was developed in 1980 from Huabei 2/Sanfensan by the Crop Research Institute for Cool and High Land, SAAS. It is characterized by semi-prostrate seedlings, relatively low numbers of short leaves, and a gray, waxy stem. It has a 1000-kernel weight of about 22 g and good tillering ability with high spiking rate, strong drought tolerance, and wide adaptability. Jinyan 4 is a mid maturing variety with a growing period of 88 days and yield potential of 3,900 kg/ha. It is suitable for growing in arid areas of northern China, but does not respond to high fertilizer and water conditions.

Neiyou 2 was developed in 1975 from Hebol/Jianzhuang by the Wumeng Agricultural Research Institute in Inner Mongolia. Neiyou 2 is characterized by medium tillering and 100-110 cm in height. The 1000-seed weight is 24-25 g. It has strong resistance to lodging, mid-early maturity, and a growing period of 85-87 days. Its yield potential is 4,185 kg/ha. It is suitable for intermediate to high fertility soils.

Neiyou 1 was developed from Huabei 2/Milfotd in 1974. It has strong stems and is 115 cm high. Its 1000-seed weight is 21-23 g. It has good tillering ability and lodging resistance, but is susceptible to stem rust. Neiyou 1 is a mid maturing variety with a growing period of 88-92 days. Its yield potential is about 4,176 kg/ha. It should be grown under high fertility conditions.

Neiyan 4. Derived from Jianzhuang/Yong 492 by the Inner Mongolia Academy of Agricultural Sciences, Neiyan 4 is characterized by spring habit, panicle spikes, and resistance to lodging and BYDV. Plant height is 100-110 cm, and l000-seed weight is 22-24 g. It is an early maturing variety with a growing period of 85-90 days. Its yield potential is 5,115-5,655 kg/ha, and it is mainly suitable for irrigated conditions.

Neiyan 5 developed from Yong492/Huabei 2 by the Inner Mongolia Academy of Agricultural Sciences, is characterized by spring habit, compact plant type, and panicled spikes. Its height is 115-120 cm, and its spindle-shaped panicles are yellow in color. The 1000-seed weight is about 20 g. It is tolerant to high fertility and irrigation, and resistant to lodging and diseases. This mid to early maturing variety has a growing period of 90 days. It has high yield potential (6,075 kg/ha) under optimal water and fertilizer conditions.

Mengyan 7312. Developed by the Inner Mongolian Academy of Agricultural Sciences, this variety is about 115 cm in height, with a 1000-grain weight about 20 g. It is early to intermediate in maturity with a growing period of 90 days.

Bayou 1 was bred by the Zhangjiakou Bashang Agricultural Research Institute in Hebei. Its plant height is 100-110 cm, and 1000-grain weight about 25 g. Its grain has a distinct elliptical shape and light-yellow color, about 15.6% protein and 5.5% fat. Bayou 1, a medium-term variety (90 days), shows strong resistance to lodging and is suitable for growing in a wide range of environments.

8309-6 was developed by the Dingxi Dry Area Agricultural Research and Extension Centre in Dingxi, Gansu Province. Its plants are 90-120 cm high and are characterized by a one-sided loose spike and yellow glumes. Its 1000-grain weight is 21-22 g, and its grain contains 12.1% protein and 6.7% fat. It has strong tolerance to drought and lodging. It is a medium-term variety, with a growing period of 93-110 days.

4. Applications of biotechnology in oat improvement

Molecular markers such as AFLP, RAPD, RFLP, and SSR have been used to characterize oat genetic resources. Chen et al. (2001) constructed a linkage map with 112 RFLP loci, and three horizontal resistance QTLs (namely, PRQ1, PRQ2, and PRQ3) were identified on oats. Wang et al. (2004) detected genetic diversity in 21 oat genotypes from 8 oat species using RAPD markers and confirmed a classification of these species similar to that achieved using the traditional method. Xu et al. (2009) analyzed the genetic diversity of Chinese naked oats using AFLP markers and found that accessions from Inner Mongolia and Shanxi were the most diverse, which made them potential parent materials for the oat breeding program. Molecular markers are also being used to map useful traits and genes. Research on identifying key genes controlling β-glucan content in oat grain is being conducted at the Institute of Crop Science (CAAS). Using in vitro culture, Zhang et al. (2000) selected calli and oat variants for resistance to high saline conditions and obtained a variant of salt resistant callus. Yang and Wang (2005) developed Huazhong 21, the first oat variety bred using issue culture.

5. Future prospects

In China, oat is not only a traditional food, but also a health food based on its functional components. Its grains and stems also make good feed and fodder. Due to the multiple uses of oats, there is a bright future for research on oat nutritional value, breeding methods, agronomic practices, and processing techniques.

5.1 Improving oats as a health food

Research has shown that the digestible fiber, particularly the β-glucan component, in oats can prevent and cure diabetes by reducing the levels of blood cholesterol, fat, and sugar. The β-glucan content in oat grain may vary from 2 to 7%, but higher levels are desirable. Therefore, breeding varieties with improved grain β-glucan content is a major objective of oat breeding programs.

In China, various traditional oat products are made by hand, including steamed dough roll, steamed dough drop, and several types of noodles. These foods are popular in rural households, and are being introduced to restaurants in the cities. However, manual processing of oat products cannot meet the increased need for oat-based foods in the cities. Thus oat processing has attracted researchers' attention and gained government support. Products such as oat flakes, oat porridge, oat instant noodles, and oat ice cream have become popular and provide more options for people to increase the amounts of oats in their diets.

5.2 Promoting oats for multiple uses

In addition to food, oats can be used for feed and forage, and as a crop for preventing desertification. In western China, particularly Xinjiang, Qinghai, and Tibet, oats are widely cultivated for animal feed. They will continue to play an important role in the development of animal husbandry in those regions. Also, research in western China has shown that oats can grow in very dry soils and thus have a potential use in preventing desertification.

5.3 Developing and adopting new technologies for oat improvement

Currently, many modern technologies such as molecular tools and in vitro culture are playing important roles in improving crops in China, and oats are no exception. Molecular markers will be widely used to identify and map desirable traits and genes in oat germplasm. They also will be useful for MAS in breeding programs. Such applications will be extremely important for selecting genes required to improve quality. Since oats are beneficial to health, research aimed at identifying the causes of those benefits will be a priority. But whether the breeding objectives are food- or feed-related, it is essential to breed varieties with high nutritional content, high yield potential, drought tolerance, and disease and pest resistance. Given the advances in gene cloning and transformation, there will be even greater opportunities to improve oats as a cultivated crop in the future.

References

Chen, G., Rines, H.W., Stuthman, D.D., Leonard, K.J., and Ding S.R. 2001. Identification of QTLs for horizontal resistance to crown rust in oat. Journal of Zhejiang University (Agric. & Life Sci.) 27(2): 151-155 (in Chinese).

Dong, Y., and Zheng, D. 2006. Crops and Their Wild Relatives in China. China Agriculture Press, Beijing (in Chinese).

He, J., Han, B., Guo, H., Zhang, Z., and Zhao, Y. 2007. Cloning and sequence analysis of the B-1, 3-glucanase II gene 3' end cDNA of oat. Biotechnology 17(1): 5-8 (in Chinese).

Lu, D. 1990. The Collection of Research on Reducing Blood Fat by Oats. Sci-Tech Press of China, Beijing (in Chinese).

Shi, J., Yang, Z., Mei, H., Hong, Z., Xuan, Q., and Lu, D. 1988. Study on the effective components in oats for reducing blood fat. Journal of Nutrition 12(4): 348-353 (in Chinese).

Stanton, T.R. 1955. Oat identification and classification. USDA. Tech. Bull. N.1100, 206 p.

Tian, C. 2002. Oats. In: Li, R., Chai, Y., Liao, Q., and Sun, S. (eds.). Minor Grain Crops in China. China Agricultural Sci-Tech Press, Beijing (in Chinese).

Vavilov, N.I. 1926. Centres of origin of cultivated plants. Bull. Appl. Bot. Genet. Plant Breed. 16(2): 139-248.

Wang, M., Fu, X., and Qi, X. 2004. Genetic diversity revealed by RAPD in different species of *Avena*. Journal of North China Agriculture 19(4): 24-28 (in Chinese).

Xu, W., Zhang, Z., Wu, B., and Cui, L. 2009. Genetic diversity in naked oat (*Avena nuda*) germplasm revealed by AFLP markers. Acta Agronomica Sinica 35: 2205-2212 (in Chinese).

Yang, C., and Wang, X. 2005. Development of new variety of *Avena nuda* Huazhong 21 by adopting anther haploid breeding method. Journal of Hebei North University (Natural Science Edition) 21(3): 39-42 (in Chinese).

Yang, H. 1989. Oats in China. Agricultural Press, Beijing (in Chinese).

Zhang, Y., and Zhang, Y. 2000. Variant selection for salt-resistant callus of oat. Journal of Inner Mongolia Normal University (Natural Science Edition) 29: 297-299 (in Chinese).

Zheng, D., Lu, Y., Tian, C., and Zhao, W. 2006. Analysis of beta-glucan content of naked oat (*Avena nuda* L.) in China. Journal of Plant Genetic Resources 7(1):54-58 (in Chinese).

Zhou, G.H., Cheng, Z.M., and Zhang, S.X. 1984. Serological identification of luteo viruses of small grains in China. Plant Disease 68: 710-713.

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