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II.A.7 Rice

Economic and Biological Importance of Rice

Rice in Human Life

Among the cereals, rice and wheat share equal importance as leading food sources for humankind. Rice is a staple food for nearly one-half of the world's population. In 1990, the crop was grown on 145.8 million hectares of land, and production amounted to 518.8 million metric tons of grain (paddy, rough rice). Although rice is grown in 112 countries, spanning an area from 53° latitude north to 35° south, about 95 percent of the crop is grown and consumed in Asia. Rice provides fully 60 percent of the food intake in Southeast Asia and about 35 percent in East Asia and South Asia. The highest level of per capita rice consumption (130 to 180 kilograms [kg] per year, 55 to 80 percent of total caloric source) takes place in Bangladesh, Cambodia, Indonesia, Laos, Myanmar (Burma), Thailand, and Vietnam.

Although rice commands a higher price than wheat on the international market, less than five percent of the world's rice enters that market, contrasted with about 16 percent of the wheat. Low-income countries, China and Pakistan, for example, often import wheat at a cheaper price and export their rice.

Biological Value in Human Nutrition

Although rice has a relatively low protein content (about 8 percent in brown rice and 7 percent in milled rice versus 10 percent in wheat), brown rice (caryopsis) ranks higher than wheat in available carbohydrates, digestible energy (kilojoules [kJ] per 100 grams), and net protein utilization. Rice protein is superior in lysine content to wheat, corn, and sorghum. Milled rice has a lower crude fiber content than any other cereal, making rice powder in the boiled form suitable as infant food. For laboring adults, milled rice alone could meet the daily carbohydrate and protein needs for sustenance although it is low in riboflavin and thiamine content. For growing children, rice needs to be supplemented by other protein sources (Hegsted 1969; Juliano 1985b).

The Growing Importance of Rice

On the basis of mean grain yield, rice crops produce more food energy and protein supply per hectare than wheat and maize. Hence, rice can support more people per unit of land than the two other staples (Lu and Chang 1980). It is, therefore, not surprising to find a close relationship in human history between an expansion in rice cultivation and a rapid rise in population growth (Chang 1987).

As a human food, rice continues to gain popularity in many parts of the world where other coarse cereals, such as maize, sorghum and millet, or tubers and roots like potatoes, yams, and cassava have traditionally dominated. For example, of all the world's regions, Africa has had the sharpest rise in rice consumption during the last few decades.

Rice for table use is easy to prepare. Its soft texture pleases the palate and the stomach. The ranking order of food preference in Asia is rice, followed by wheat, maize, and the sweet potato; in Africa it is rice or wheat, followed by maize, yams, and cassava (author's personal observation).

Rice

In industrial usage, rice is also gaining importance in the making of infant foods, snack foods, breakfast cereals, beer, fermented products, and rice bran oil, and rice wine remains a major alcoholic beverage in East Asia. The coarse and silica-rich rice hull is finding new use in construction materials. Rice straw is used less in rope and paper making than before, but except for modern varieties, it still serves as an important cattle feed throughout Asia. Because rice flour is nearly pure starch and free from allergens, it is the main component of face powders and infant formulas. Its low fiber content has led to an increased use of rice powder in polishing camera lenses and expensive jewelry.

Botany, Origin, and Evolution

Botany

Rice is a member of the grass family (Gramineae) and belongs to the genus *Oryza* under tribe Oryzeae. The genus *Oryza* includes 20 wild species and 2 cultivated species (cultigens). The wild species are widely distributed in the humid tropics and subtropics of Africa, Asia, Central and South America, and Australia (Chang 1985). Of the two cultivated species, African rice (*O. glaberrima* Steud.) is confined to West Africa, whereas common or Asian rice (*O. sativa* L.) is now commercially grown in 112 countries, covering all continents (Bertin et al. 1971).

The wild species have both diploid (2n = 2x = 24) and tetraploid (2n = 4x = 48) forms, while the two cultigens are diploid and share a common genome (chromosome group). Incompatibility exists among species having different genomes. Partial sterility also shows up in hybrids when different ecogeographic races of *O. sativa* are hybridized. The cultivated species of *Oryza* may be classified as semiaquatic plants, although extreme variants are grown not only in deep water (up to 5 meters) but also on dry land (Chang 1985).

Among the cereals, rice has the lowest water use efficiency. Therefore, rice cannot compete with dryland cereals in areas of low rainfall unless irrigation water is readily available from reservoirs, bunds, and the like. On the other hand, the highest yields of traditional varieties have been obtained in regions of cloudless skies, such as in Spain, California, and northern Japan (Lu and Chang 1980).

The "wild rice" of North America is *Zizania palustris* (formerly *Z. aquatica* L. [2n = 30]), which belongs to one of the 11 related genera in the same tribe. Traditionally, this species was self-propagating and harvested only by Native Americans in the Great Lakes area. Now it is commercially grown in Minnesota and northern California.

Origin

The origin of rice was long shrouded by disparate postulates because of the pantropical but disjunct distribution of the 20 wild species across four continents, the variations in characterizing and naming plant specimens, and the traditional feud concerning the relative antiquity of rice in India versus China. Among the botanists, R. J. Roschevicz (1931) first postulated that the center of origin of the section *Sativa* Roschev., to which *O. glaberrima* and *O. sativa* belong, was in Africa and that *O. sativa* had originated from multiple species. A divergent array of wild species was proposed by different workers as the putative ancestor of *O. sativa* (Chang 1976b).

Several workers considered "*O. perennis* Moench" (an ambiguous designation of varying applications) as the common progenitor of both cultigens (Chang 1976b). A large number of scholars had argued that Asian rice originated in the Indian subcontinent (South Asia), although A. de Candolle (1884), while conceding that India was more likely the original home, considered China to have had an earlier history of rice cultivation

On the basis of historical records and the existence of wild rices in China, Chinese scholars maintained that rice cultivation was practiced in north China during the mythological Sheng Nung period (c. 2700 B.C.) and that *O. sativa* of China evolved from wild rices (Ting 1961). The finding of rice glume imprints at Yang-shao site in north China (c. 3200–2500 B.C.) during the 1920s reinforced the popular belief that China was one of the centers of its origin (Chinese Academy of Agricultural Sciences 1986).

Since the 1950s, however, rice researchers have generally agreed that each of the two cultigens originated from a single wild species. But disputes concerning the immediate ancestor of *O. sativa* persist to this day (Chang 1976b, 1985; Oka 1988). A multidisciplinary analysis of the geographic distribution of the wild species and their genomic composition in relation to the "Glossopterid Line" (northern boundary) of the Gondwanaland fragments (Melville 1966) strongly indicated the Gondwanaland origin of the genus *Oryza* (Chang 1976a, 1976b, 1985). This postulate of rice having a common progenitor in the humid zones of the supercontinent Pangaea before it fractured and drifted apart can also explain the parallel evolutionary pattern of the two cultigens in Africa and Asia respectively. It also reconciles the presence of closely related wild species having the same genome in Australia and in Central and South America. Thus, the antiquity of the genus dates back to the early Cretaceous period of more than 130 million years ago.

Evolution

The parallel evolutionary pathway of *O. glaberrima* in Africa and of *O. sativa* in Asia was from perennial wild - → annual wild - → annual cultigen, a pattern common to other grasses and many crop plants. The parallel pathways are:

Africa: *O. longistaminata* - → *O. barthii* - → *O. glaberrima.*
Asia: *O. rufipogon* - → *O. nivara* - → *O. sativa.*

This scheme can resolve much that has characterized past disputes on the putative ancestors of the two cultigens. Wild perennial and annual forms having the same A genome are present in Australia and in Central and South America, but the lack of incipient agriculture in Australia and of wetland agronomy in tropical America in prehistoric times disrupted the final step in producing an annual cultigen.

It needs to be pointed out that the putative ancestors, especially those in tropical Asia, are conceptually wild forms of the distant past, because centuries of habitat disturbance, natural hybridization, and dispersal by humans have altered the genetic structure of the truly wild ancestors. Most of the wild rices found in nature today are hybrid derivatives of various kinds (Chang 1976b; 1985). The continuous arrays of variants in natural populations have impaired definitive studies on the wild progenies (Chang 1976b; Oka 1988).

The differentiation and diversification of annual wild forms into the early prototypes of cultigen in South and mainland Southeast Asia were accelerated by marked climatic changes during the Neothermal age of about 10,000 to 15,000 years ago. Initial selection and cultivation could have occurred independently and nearly concurrently at numerous sites within or bordering a broad belt of primary genetic diversity that extends from the Ganges plains below the eastern foothills of Himalaya, through upper Burma, northern Thailand, Laos, and northern Vietnam, to southwest and southern China.

From this belt, geographic dispersal by various agents, particularly water currents and humans, lent impetus to ecogenetic differentiation and diversification under human cultivation. In areas inside China where winter temperatures fell below freezing, the cultivated forms (cultivars) became true domesticates, depending entirely on human care for their perpetuation and propagation. In a parallel manner, the water buffalo was brought from the swamps of the south into the northern areas and coevolved as another domesticate (Chang 1976a).

In West Africa, *O. glaberrima* was domesticated from the wild annual *O. barthii* (Chevalier 1932); the latter was adapted primarily to water holes in the savanna and secondarily to the forest zone (Harlan 1973). The cultigen has its most important center of diversity in the central Niger delta. Two secondary centers existed near the Guinean coast (Porteres 1956).

Cultivation of the wild prototypes preceded domestication. Rice grains were initially gathered and consumed by prehistoric people of the humid regions where the perennial plants grew on poorly drained sites. These people also hunted, fished, and gathered other edible plant parts as food. Eventually, however, they developed a liking for the easily cooked and tasty rice and searched for plants that bore larger panicles and heavier grains.

The gathering-and-selection process was more imperative for peoples who lived in areas where seasonal variations in temperature and rainfall were more marked. The earlier maturing rices, which also tend to be drought escaping, would have been selected to suit the increasingly arid weather of the belt of primary diversity during the Neothermal period. By contrast, the more primitive rices of longer maturation, and those, thus, more adapted to vegetative propagation, would have survived better in the humid regions to the south (Chang 1976b; 1985). In some areas of tropical Asia, such as the Jeypore tract of Orissa State (India), the Batticoloa district (Sri Lanka), and the forested areas of north Thailand, the gathering of free-shattering grains from wild rice can still be witnessed today (Chang 1976b; Higham 1989).

Antiquity of Rice Cultivation

Although the differentiation of the progenitors of *Oryza* species dates back to the early Cretaceous period, the beginning of rice cultivation was viewed by Western scholars as a relatively recent event until extensive excavations were made after the 1950s in China and to a lesser extent in India. Earlier, R. J. Roschevicz (1931) estimated 2800 B.C. as the beginning of rice cultivation in China, whereas the dawn of agriculture in India was attributed to the Harappan civilization, which began about 2500 B.C. (Hutchinson 1976).

Thus far, the oldest evidence from India comes from Koldihwa, U.P., where rice grains were embedded in earthen potsherds and rice husks discovered in ancient cow dung. The age of the Chalcolithic levels was estimated between 6570 and 4530 B.C. (Vishnu-Mittre 1976; Sharma et al. 1980), but the actual age of the rice remains may be as recent as 1500 B.C. (Chang 1987). Another old grain sample came from Mohenjodaro of Pakistan and dates from about 2500 B.C. (Andrus and Mohammed 1958). Rice cultivation probably began in the upper and middle Ganges between 2000 and 1500 B.C. (Candolle 1884; Watabe 1973). It expanded quickly after irrigation works spread from Orissa State to the adjoining areas of Andhra Pradesh and Tamil Nadu in the Iron Age around 300 B.C. (Randhawa 1980).

In Southeast Asia, recent excavations have yielded a number of rice remains dating from 3500 B.C. at Ban Chiang (Thailand); 1400 B.C. at Solana (Philippines); and A.D. 500 at Ban Na Di (Thailand) and at Ulu Leang (Indonesia). Dates between 4000 and 2000 B.C. have been reported from North Vietnam (Dao 1985) but have not yet been authenticated.

These various reports have been summarized by T. T. Chang (1988, 1989a). The widely scattered findings are insufficient to provide a coherent picture of agricultural development in the region, but rice cultivation in mainland Southeast Asia undoubtedly preceded that in insular Southeast Asia (Chang 1988). The paucity of rice-related remains that were confined to upland sites in northern Thailand could be attributed to the sharp rise in sea level around the Gulf of Thailand during the four millennia between 8000 and 4000 B.C. Floods inundated vast tracts of low-lying land amid which rice chaffs and shell knives for cutting rice stalks were recently found at Khok Phanom Di near the Gulf and dated from 6000 to 4000 B.C. (Higham 1989).

For the Southeast Asian region, several geographers and ethnobotanists had earlier postulated that the cultivation of root crops predated rice culture (Sauer 1952; Spencer 1963; Yen 1977). Yet, this hypothesis falters in view of the apparently rather recent domestication (c. 2000 B.C.) of yams in the region (Alexander and Coursey 1969). In many hilly regions, vegeculture probably preceded dryland rice cultivation, but not in wetland areas. In the cooler regions, rice grains were crucial to early cultivators who could store and consume the harvest during the winter months.

Prior to the 1950s, the belief in the antiquity of rice cultivation in China was based on mythical writings in which "Emperor Shen Nung" (c. 2700 B.C.) was supposed to have taught his people to plant five cereals, with rice among them (Candolle 1884; Roschevicz 1931; Ting 1949; Chatterjee 1951). This view, however, was questioned by many non-Chinese botanists and historians because of the paucity of wild rices in China (or rather the paucity of information on the wild rices) and the semiarid environment in north China (Chang 1979b, 1983). Yet in the 1920s, the discovery of rice glume imprints on broken pottery at the Yang-shao site in Henan (Honan) by J. G. Andersson and co-workers (Andersson 1934) was important in linking Chinese archaeology with agriculture. The excavated materials were considered Neolithic in origin and the precise age was not available, though K. C. Chang later gave this author an estimated age of between 3200 and 2500 B.C.

Extensive diggings in the Yangtze basin after the 1950s yielded many rice remains that pushed back rice culture in China even further into antiquity (Chang 1983). The most exciting event was the finding in 1973–4 of carbonized rice kernels, rice straw, bone spades, hoe blades *(ssu),* and cooking utensils that demonstrated a well-developed culture supported by rice cultivation at the He-mu-du (Ho-mu-tu) site in Zhejiang (Chekiang) Province dated at 5005 B.C. (Chekiang Provincial Cultural Management Commission and Chekiang Provincial Museum 1976; Hsia 1977).

The grains were mostly of the *hsien* (Indica) type but included some *keng* (Sinica or Japonica) and intermediate kernels. The discovery also indicated the existence of an advanced rice-based culture in east China that vied in antiquity and sophistication with the millet-based culture in north China as represented by the Pan-po site in Shenxi (Shensi). Another site at Luo-jia-jiao in Zhejiang Province also yielded carbonized rice of both ecogeographic races of a similar age estimated at 7000 B.P. (Chang 1989a). In a 1988 excavation at Peng-tou-shan site in Hunan Province, abundant rice husks on pottery or red burnt clay as well as skeletal remains of water buffalo were found. The pottery was dated at between 7150 and 6250 B.C. (uncorrected carbon dating). Diggings in neighboring Hubei (Hupei) Province yielded artifacts of similar age, but the grain type could not be ascertained (Pei 1989). Excavations in Shenxi also produced rice glume imprints on red burnt clay dated between 6000 and 5000 B.C. (Yan 1989).

In contrast to all this scholarly effort on the antiquity of rice cultivation in Asia, our understanding of the matter in West Africa rests solely on the writing of R. Porteres (1956), who dates it from 1500 B.C. in the primary Niger center, and from A.D. 1000 to A.D. 1200 in the two Guinean secondary centers.

Chinese history also recorded that rice culture was well established in Honan and Shenxi Provinces of north China during the Chou Dynasty (1122 to 255 B.C.) by Lungshanoid farmers (Ho 1956; Chang 1968). During the Eastern Chou Dynasty (255 to 249 B.C.), rice was already the staple food crop in the middle and lower basins of the Yangtze River (Ting 1961). Wild rices were amply recorded in historical accounts; their northern limit of distribution reached 38° north latitude (Chang 1983).

Based on the above developments, it appears plausible to place the beginning of rice cultivation in India, China, and other tropical Asian countries at nearly 10,000 years ago or even earlier. Since rice was already cultivated in central and east China at 6000 to 5000 B.C., it would have taken a few millennia for rice to move in from the belt to the south of these regions. The missing links in the history of rice culture in China can be attributed to the dearth of archaeological findings from south China and the relatively recent age of rice remains in southwest China (1820 B.C. at Bei-yan in Yunnan) and south China (2000 B.C. at Shih Hsiah in Kwangtung). These areas represent important regions of ecogenetic differentiation or routes of dispersal (Chang 1983).

Linguistic Evidence

A number of scholars have attempted to use etymology as a tool in tracing the origin and dispersal of rice in Asia. The Chinese word for rice in the north, *tao* or *dao* or *dau,* finds its variants in south China and Indochina as *k'au* (for grain), *hao, ho, heu, deu,* and *khaw* (Ting 1961; Chinese Academy of Agricultural Sciences 1986). Indian scholars claimed that the word for rice in Western languages had a Dravidian root and that *ris, riz, arroz,* rice, *oruza,* and *arrazz* all came from *arisi* (Pankar and Gowda 1976). In insular Southeast Asia, the Austronesian terms *padi* and *paray* for rice and *bras* or *beras* for milled rice predominate (Chinese Academy of Agricultural Sciences 1986; Revel 1988).

On the other hand, Japanese scholars have also emphasized the spread of the Chinese words *ni* or *ne* (for wild rice) and *nu* (for glutinous rice) to Southeast Asia (Yanagita et al. 1969). N. Revel and coworkers (1988) have provided a comprehensive compilation of terms related to the rice plant and its parts derived from the linguistic data of China, Indochina, insular Southeast Asia, and Madagascar. Yet among the different disciplinary approaches, linguistic analyses have not been particularly effective in revealing facts about the dispersal of rice by humans. In part, this is because the ethnological aspects of human migration in the Southeast Asian region remain in a state of flux. (For various viewpoints see *Asian Perspectives* 1988: 26, no. 1.)

Geographic Dispersal and Ecogenetic Diversification

Early Dispersal

The early dissemination of rice seeds (grains) could have involved a variety of agents: flowing water, wind, large animals, birds, and humans. The latter have undoubtedly been most effective in directed dispersal: Humans carried rice grains from one place to another as food, seed, merchandise, and gifts. The continuous and varied movements of peoples in Asia since prehistoric times have led to a broad distribution of early *O. sativa* forms, which proliferated in ecogenetic diversification after undergoing the mutation-hybridization-recombination-differentiation cycles and being subjected to both natural and human selection forces at the new sites of cultivation. In contrast, *O. glaberrima* cultivars exhibit markedly less diversity than their Asian counterparts, owing to a shorter history of cultivation and narrower dispersal. The contrast is amplified by other factors as shown in Table II.A.7.1.

Initial dispersal of *O. sativa* from numerous sites in its primary belt of diversity involved a combination of early forms of cultivars and associated wild relatives, often grown in a mixture. Biological findings and historical records point to five generalized routes from the Assam-Meghalaya-Burma region. Rice moved: (1) southward to the southern Bengal Bay area and the southern states of India and eventually to Sri Lanka; (2) westward to Pakistan and the west coast of India; (3) eastward to mainland Southeast Asia (Indochina); (4) southeastward to Malaysia and the Indonesian islands; and (5) northeastward to southwest China, mainly the Yunnan-Kweichow area, and further into east, central, and south China. The early routes of travel most likely followed the major rivers, namely, Brahmaputra, Ganges, Indus, Mekong, and Yangtze. Routes of sea travel, which came later, were from Thailand and Vietnam to the southern coastal areas of China, from Indonesia to the Philippines and Taiwan, and from China to Japan, as well as from China to Korea to Japan. These routes are summarized in Map II.A.7.1.

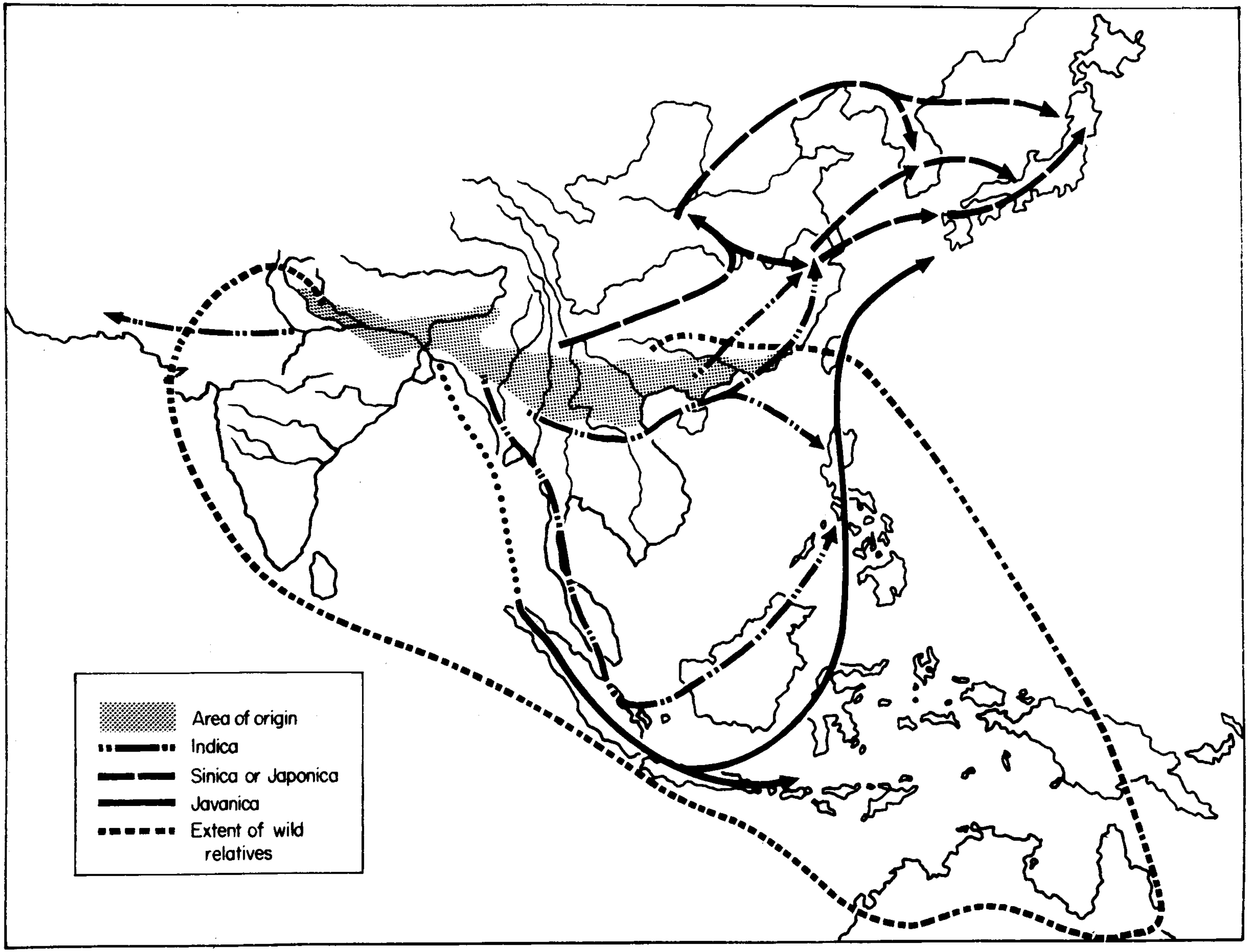
Table II.A.7.1 *Contrast in diversification:* Oryza sativa *vs.* glaberrima

Factor	Asia	W. Africa
Latitudinal spread	10° C–53° N	5° N–17° N
Topography	Hilly	Flat
Population density	High	Low
Movement of people	Continuous	Little
Iron tools	Many	None or few
Draft animals	Water buffalo and oxen	?

On the basis of ancient samples of rice hulls collected from India and Indochina, covering a span of 10 centuries up to around A.D. 1500, three main groups of cultivars (the Brahmaputra-Gangetic strain, the Bengal strain, and the Mekong strain) have been proposed by T. Watabe (1985). The Mekong strain originating in Yunnan was postulated to have given rise to the Indochina series and the Yangtze River series of cultivars; the latter consisted mainly of the *keng* rices of China. It should be pointed out, however, that the ecogenetic diversification processes following dispersal and the cultivators' preferences could have added complications to the varietal distribution pattern of the present, as later discussions will reveal.

Ecogenetic Differentiation and Diversification

During the early phase of human cultivation and selection, a number of morphological and physiological changes began to emerge. Selection for taller and larger plants resulted in larger leaves, longer and thicker stems, and longer panicles. Subsequent selection for more productive plants and for ease in growing and harvesting led to larger grains. It also resulted in increases in: (1) the rate of seedling growth; (2) tillering capacity; (3) the number of leaves per tiller and the rate of leaf development; (4) the synchronization of tiller development and panicle formation (for uniform maturation); (5) the number of secondary branches on a panicle; and (6) panicle weight (a product of spikelet number and grain weight). Concurrently, there were decreases or losses of the primitive features, such as: (1) rhizome formation; (2) pigmentation of plant parts; (3) awn length; (4) shattering of grains from the panicle; (5) growth duration; (6) intensity of grain dormancy; (7) response to short day length; (8) sensitivity to low temperatures; and (9) ability to survive in flood waters. The frequency of cross pollination also decreased so that the plants became more inbred and increasingly dependent on the cultivators for their propagation (by seed) and perpetuation (by short planting cycles) (Chang 1976b).



Map II.A.7.1. Extent of wild relatives and spread of ecogeographic races of *O. sativa* in Asia and Oceania. (Adapted from Chang 1976b.)

When rice cultivars were carried up and down along the latitudinal or altitudinal clines or both, the enormous genetic variability in the plants was released, and the resulting variants expressed their new genetic makeup while reacting to changing environmental factors. The major environmental forces are soil properties, water supply, solar radiation intensity, day length, and temperature range, especially the minimum night temperatures. Those plants that could thrive or survive in a new environment would become fixed to form an adapted population – the beginning of a new ecostrain – while the unadapted plants would perish and the poorly adapted plants would dwindle in number and be reduced to a small population in a less adverse ecological niche in the area.

Such a process of differentiation and selection was aided by spontaneous mutations in a population or by chance outcrossing between adjacent plants or both. The process could independently occur at many new sites of cultivation and recur when environmental conditions or cultivation practices changed. Therefore, rich genetic diversity of a secondary nature could be found in areas of undulating terrain where the environmental conditions significantly differed within a small area. The Assam and Madhya Pradesh states and Jeypore tract of India, the island of Sri Lanka, and Yunnan Province of China represent such areas of remarkable varietal diversity (Chang 1985).

Proliferation into Ecogeographic Races and Ecotypes

Continuous cultivation and intense selection in areas outside the conventional wetlands of shallow water depth (the paddies) have resulted in a range of extreme ecotypes: deepwater or floating rices that can cope with gradually rising waters up to 5 meters (m) deep; flood-tolerant rices that can survive days of total submergence under water; and upland or hill rices that are grown under dryland conditions like corn and sorghum. The varying soil-water-temperature regimes in the Bengal Bay states of India and in Bangladesh resulted in four seasonal ecotypes in that area: *boro* (winter), *aus* (summer), transplanted *aman* (fall, shallow water), and broadcast *aman* (fall, deep water). In many double-cropping areas, two main ecotypes follow the respective cropping season: dry (or off) and wet (or main) (Chang 1985).

In broader terms, the wide dispersal of *O. sativa* and subsequent isolation or selection in Asia has led to the formation of three ecogeographic races that differ in morphological and physiological characteristics and are partially incompatible in genetic affinity: Indica race in the tropics and subtropics; javanica race in the tropics; and sinica (or japonica) race in the temperate zone. Of the three races, indica is the oldest and the prototype of the other two races as it retains most of the primitive features: tallness, weak stems, lateness, dormant grains, and shattering panicles.

The sinica race became differentiated in China and has been rigorously selected for tolerance to cool temperatures, high productivity, and adaptiveness to modern cultivation technology: short plant stature, nitrogen responsiveness, earliness, stiff stems, and high grain yield. The javanica race is of more recent origin and appears intermediate between the other two races in genetic affinity, meaning it is more cross-fertile with either indica or sinica. Javanica cultivars are marked by gigas features in plant panicle and grain characters. They include a wetland group of cultivars (*bulu* and *gundil* of Indonesia) and a dryland group (hill rices of Southeast Asia).

The picture of race-forming processes is yet incomplete (Chang 1985). Many studies have relied heavily on grain size and shape as empirical criteria for race classification. Some studies employed crossing experiments and hybrid fertility ratings. Other workers recently used isozyme patterns to indicate origin and affinity. Controversies in past studies stemmed largely from limited samples, oversimplified empirical tests, and reliance on presently grown cultivars to retrace the distant past. The latter involved a lack of appreciation for the relatively short period (approximately 5 to 6 centuries) that it takes for a predominant grain type to be replaced by another (Watabe 1973), which was probably affected by the cultivator's preference. Most of the studies have also overlooked the usefulness of including amylose content and low temperature tolerance in revealing race identity (Chang 1976b, 1985). It should also be recognized that early human contacts greatly predated those given in historical records (Chang 1983), and maximum varietal diversity often showed up in places outside the area of primary genetic diversity (Chang 1976b, 1985).

Parallel to the expansion in production area and dispersal of the cultivars to new lands during the last two centuries was the growth of varietal diversity. In the first half of the twentieth century, before scientifically bred cultivars appeared in large numbers, the total number of unimproved varieties grown by Asian farmers probably exceeded 100,000, though many duplicates of similar or altered names were included in this tally (Chang 1984 and 1992).

The Spread of Asian Rice

Historical records are quite revealing of the spread of Asian rice from South Asia, Southeast Asia, and China to other regions or countries, though exact dates may be lacking. In the northward direction, the Sinica race was introduced from China into the Korean peninsula before 1030 B.C. (Chen 1989). Rice cultivation in Japan began in the late Jomon period (about 1000 B.C., [Akazawa 1983]), while earlier estimates placed the introduction of rice to Japan from China in the third century B.C. (Ando 1951; Morinaga 1968). Several routes could have been involved: (1) from the lower Yangtze basin to Kyushu island, (2) from north China to Honshu Island, or (3) via Korea to northern Kyushu; *hsien* (Indica) may have arrived from China, and the Javanica race traveled from Southeast Asia (Isao 1976; Lu and Chang 1980). The areas that comprised the former Soviet Union obtained rice seeds from China, Korea, Japan, and Persia, and rice was grown around the Caspian Sea beginning in the early 1770s (Lu and Chang 1980).

From the Indian subcontinent and mainland Southeast Asia, the Indica race spread southward into Sri Lanka (before 543 B.C.), the Malay Archipelago (date unknown), the Indonesian islands (between 2000 and 1400 B.C.), and central and coastal China south of the Yangtze River. *Hsien* or Indica-type grains were found at both He-mu-du and Luo-jia-jiao sites in east China around 5000 B.C. (Lu and Chang 1980; Chang 1988). The *keng* or sinica rices were likely to have differentiated in the Yunnan-Kweichow region, and they became fixed in the cooler northern areas (Chang 1976b). On the other hand, several Chinese scholars maintain that *hsien* and *keng* rices were differentiated from wild rices inside China (Ting 1961; Yan 1989). The large-scale introduction and planting of the Champa rices (initially from Vietnam) greatly altered the varietal composition of *hsien* rices in south China and the central Yangtze basin after the eleventh century (Ho 1956; Chang 1987).

The javanica race had its origin on the Asian mainland before it differentiated into the dryland ecotype (related to the aus type of the Bengal Bay area and the hill rices of Southeast Asia) and the wetland ecotype *(bulu* and *gundil)* of Indonesia. From Indonesia, the wetland ecotype spread to the Philippines (mainly in the Ifugao region at about 1000 B.C.), Taiwan (at 2000 B.C. or later), and probably Ryukyus and Japan (Chang 1976b, 1988).

The Middle East acquired rice from South Asia probably as early as 1000 B.C. Persia loomed large as the principal stepping stone from tropical Asia toward points west of the Persian Empire. The Romans learned about rice during the expedition of Alexander the Great to India (c. 327–4 B.C.) but imported rice wine instead of growing the crop. The introduction of rice into Europe could have taken different routes: (1) from Persia to Egypt between the fourth and the first centuries B.C., (2) from Greece or Egypt to Spain and Sicily in the eighth century A.D., and (3) from Persia to Spain in the eighth century and later to Italy between the thirteenth and sixteenth centuries. The Turks brought rice from Southwest Asia into the Balkan Peninsula, and Italy could also have served as a stepping stone for rice growing in that region. Direct imports from various parts of Asia into Europe are also probable (Lu and Chang 1980).

In the spread of rice to Africa, Madagascar received Asian rices probably as early as 1000 B.C. when the early settlers arrived in the southwest region. Indonesian settlers who reached the island after the beginning of the Christian era brought in some Javanica rices. Madagascar also served as the intermediary for the countries in East Africa, although direct imports from South Asia would have been another source. Countries in West Africa obtained Asian rice through European colonizers between the fifteenth and seventeenth centuries. Rice was also brought into Congo from Mozambique in the nineteenth century (Lu and Chang 1980).

The Caribbean islands obtained their rices from Europe in the late fifteenth and early sixteenth centuries. Central and South America received rice seeds from European countries, particularly Spain, during the sixteenth through the eighteenth centuries. In addition, there was much exchange of cultivars among countries of Central, South, and North America (Lu and Chang 1980).

Rice cultivation in the United States began around 1609 as a trial planting in Virginia. Other plantings soon followed along the south Atlantic coast. Rice production was well established in South Carolina by about 1690. It then spread to the areas comprising Mississippi and southwest Louisiana, to adjoining areas in Texas, and to central Arkansas, which are now the main rice-producing states in the South. California began rice growing in 1909–12 with the predominant cultivar the sinica type, which can tolerate cold water at the seedling stage. Rice was introduced into Hawaii by Chinese immigrants between 1853 and 1862, but it did not thrive as an agro-industry in competition with sugarcane and pineapple (Adair, Miller, and Beachell 1962; Lu and Chang 1980).

Experimental planting of rice in Australia took place in New South Wales in 1892, although other introductions into the warmer areas of Queensland and the Northern Territories could have come earlier. Commercial planting in New South Wales began in 1923 (Grist 1975). The island of New Guinea began growing rice in the nineteenth century (Bertin et al. 1971).

The dissemination of Asian rice from one place to another doubtless also took place for serendipitous reasons. Mexico, for example, received its first lot of rice seed around 1522 in a cargo mixed with wheat. South Carolina's early plantings of rice around 1685–94 allegedly used rice salvaged from a wrecked ship whose last voyage began in Madagascar (Grist 1975; Lu and Chang 1980).

In addition, the deliberate introduction of rice has produced other unexpected benefits. This occurred when the Champa rices of central Vietnam were initially brought to the coastal areas of South China. In 1011–12 the Emperor Chen-Tsung of the Sung Dynasty decreed the shipment of 30,000 bushels of seed from Fukien Province into the lower Yangtze basin because of the grain's early maturing and drought-escaping characteristics. But its subsequent widespread use in China paved the way for the double cropping of rice and the multiple cropping of rice and other crops (Ho 1956; Chang 1987).

As for African rice *(O. glaberrima),* its cultivation remains confined to West Africa under a variety of soil-water regimes: deep water basins, water holes in the savannas, hydromorphic soils in the forest zone, and dryland conditions in hilly areas (Porteres 1956; Harlan 1973). In areas favorable for irrigated rice production, African rice has been rapidly displaced by the Asian introductions, and in such fields the native cultigen has become a weed in commercial plantings.

It is interesting to note that the African cultigen has been found as far afield as Central America, most likely as a result of introduction during the time of the transatlantic slave trade (Bertin et al. 1971).

Cultivation Practices and Cultural Exchanges

Evolution of Cultivation Practices

Rice grains were initially gathered and consumed by prehistoric peoples in the humid tropics and subtropics from self-propagating wild stands. Cultivation began when men or, more likely, women, deliberately dropped rice grains on the soil in low-lying spots near their homesteads, kept out the weeds and animals, and manipulated the water supply. The association between rice and human community was clearly indicated in the exciting excavations at He-mu-du, Luo-jia-jiao, and Pen-tou-shan in China where rice was a principal food plant in the developing human settlements there more than 7,000 years ago.

Rice first entered the diet as a supplement to other food plants as well as to game, fish, and shellfish. As rice cultivation expanded and became more efficient, it replaced other cereals (millets, sorghums, Job's tears, and even wheat), root crops, and forage plants. The continuous expansion of rice cultivation owed much to its unique features as a self-supporting semiaquatic plant. These features include the ability of seed to germinate under both aerobic and anaerobic conditions and the series of air-conducting aerenchymatous tissues in the leafsheaths, stems, and roots that supply air to roots under continuous flooding. Also important are soil microbes in the root zone that fix nitrogen to feed rice growth, and the wide adaptability of rice to both wetland and dryland soil-water regimes. It is for these reasons that rice is the only subsistence crop whose soil is poorly drained and needs no nitrogen fertilizer applied. And these factors, in turn, account for the broad rice-growing belt from the Sino-Russian border along the Amur River (53°N latitude) to central Argentina (35°S).

Forces crucial to the expansion and improvement of rice cultivation were water control, farm implements, draft animals, planting methods, weed and pest control, manuring, seed selection, postharvest facilities, and above all, human innovation. A number of significant events selected from the voluminous historical records on rice are summarized below to illustrate the concurrent progression in its cultivation techniques and the socio-politico-economic changes that accompanied this progression.

Rice was initially grown as a rain-fed crop in low-lying areas where rain water could be retained. Such areas were located in marshy, but flood-free, sites around river bends, as found in Honan and Shenxi Provinces of north China (Ho 1956), and at larger sites between small rivers, as represented by the He-mu-du site in east China (Chang 1968; You 1976). Early community efforts led to irrigation or drainage projects. The earliest of such activities in the historical record were flood-control efforts in the Yellow River area under Emperor Yu at about 2000 B.C. Irrigation works, including dams, canals, conduits, sluices, and ponds, were in operation during the Yin period (c. 1400 B.C.).

A system of irrigation and drainage projects of various sizes were set up during the Chou Dynasty. Large-scale irrigation works were built during the Warring States period (770–21 B.C.). By 400 B.C., "rice *[tao]* men" were appointed to supervise the planting and water management operations. The famous Tu-Cheng-Yen Dam was constructed near Chendu in Sichuan (Szechuan) Province about 250 B.C., which made western Sichuan the new rice granary of China.

Further developments during the Tang and Sung dynasties led to extensive construction of ponds as water reservoirs and of dams in a serial order to impound fresh water in rivers during high tides. Dykes were built around lake shores to make use of the rich alluvial soil (Chou 1986), and the importance of water quality was recognized (Amano 1979).

Among farm implements, tools made from stone (spade, hoe, axe, knife, grinder, pestle, and mortar) preceded those made from wood and large animal bones (hoe, spade); these were followed by bronze and iron tools. Bone spades along with wooden handles were found at the He-mu-du site. Bronze knives and sickles appeared during Shang and Western Chou. Between 770 and 211 B.C. iron tools appeared in many forms. The iron plow pulled by oxen was perfected during the Western Han period. Deep plowing was advocated from the third century B.C. onward. The spike-tooth harrow *(pa)* appeared around the Tang Dynasty (sixth century), and it markedly improved the puddling of wet soil and facilitated the transplanting process. This implement later spread to Southeast Asia to become an essential component in facilitating transplanted rice culture there (Chang 1976a). Other implements, such as the roller and a spiked board, were also developed to improve further the puddling and leveling operations.

Broadcasting rice grains into a low-lying site was the earliest method of planting and can still be seen in the Jeypore tract of India and many parts of Africa. In dry soils, the next development was to break through the soil with implements, mainly the plow, whereas in wetland culture, it was to build levees (short dikes or bunds) around a field in order to impound the water. In the latter case, such an operation also facilitated land leveling and soil preparation by puddling the wet soil in repeated rounds.

The next giant step came in the transplanting (insertion) of young rice seedlings into a well-puddled and leveled wet field. Transplanting requires the raising of seedlings in nursery beds, then pulling them from those beds, bundling them, and transporting them to the field where the seedlings are thrust by hand into the softened wet soil. A well-performed transplanting operation also requires seed selection, the soaking of seeds prior to their initial sowing, careful management of the nursery beds, and proper control of water in the nursery and in the field. The transplanting practice began in the late Han period (A.D. 23–270) and subsequently spread to neighboring countries in Southeast Asia as a package comprised of the water buffalo, plow, and the spike-tooth harrow.

Transplanting is a labor-consuming operation. Depending on the circumstances, between 12 and close to 50 days of an individual's labor is required to transplant one hectare of rice land (Barker, Herdt, and Rose 1985). On the other hand, transplanting provides definite advantages in terms of a fuller use of the available water, especially during dry years, better weed control, more uniform maturation of the plants, higher grain yield under intensive management, and more efficient use of the land for rice and other crops in cropping sequence.

Despite these advantages, however, in South Asia the transplanting method remains second in popularity to direct seeding (broadcasting or drilling) due to operational difficulties having to do with farm implements, water control, and labor supply (Chang 1976a).

Variations of the one-step transplanting method were (1) to interplant an early maturing variety and a late one in alternating rows in two steps (once practiced in central China) and (2) to pull two-week-old seedlings as clumps and set them in a second nursery until they were about one meter tall. At this point, they were divided into smaller bunches and once more transplanted into the main field. This method, called double transplanting, is still practiced in Indochina in anticipation of quickly rising flood waters and a long rain season (Grist 1975).

Weeds in rice fields have undoubtedly been a serious production constraint since ancient times. The importance of removing weeds and wild rice plants was emphasized as early as the Han Dynasty. Widely practiced methods of controlling unwanted plants in the southern regions involved burning weeds prior to plowing and pulling them afterward, complemented by maintaining proper water depth in the field. Fallowing was mentioned as another means of weed control, and midseason drainage and tillage has been practiced since Eastern Chou as an effective means of weed control and of the suppression of late tiller formation by the rice plant.

Different tools, mainly of the hoe and harrow types, were developed for tillage and weed destruction. Otherwise, manual scratching of the soil surface and removal of weeds by hand were practiced by weeders who crawled forward among rows of growing rice plants. Short bamboo tubes tipped with iron claws were placed on the finger tips to help in the tedious operation. More efficient tools, one of which was a canoe-shaped wooden frame with a long handle and rows of spikes beneath it, appeared later (Amano 1979: 403). This was surpassed only by the rotary weeder of the twentieth century (Grist 1975: 157).

Insect pests were mentioned in Chinese documents before plant diseases were recognized. The *Odes* (c. sixth century B.C.) mentioned stemborers and the granary moth. During the Sung Dynasty, giant bamboo combs were used to remove leaf rollers that infest the upper portions of rice leaves. A mixture of lime and tung oil was used as an insect spray. Kernel smut, blast disease, and cold injury during flowering were recognized at the time of the Ming Dynasty. Seedling rot was mentioned in the *Agricultural Manual* of Chen Fu during South Sung (Chinese Academy of Agricultural Sciences 1986).

The relationship between manuring and increased rice yield was observed and recorded more than two thousand years ago. The use of compost and plant ash was advocated in writings of the first and third centuries. Boiling of animal bones in water as a means to extract phosphorus was practiced in Eastern Han. Growing a green manuring crop in winter was advised in the third century. The sixth century agricultural encyclopedia *Ch'i-Min-Yao-Shu* (Ku undated) distinguished between basal and top dressings of manure, preached the use of human and animal excreta on poor soils, and provided crop rotation schemes (Chang 1979b).

Irrigation practices received much attention in China because of the poor or erratic water supply in many rice areas. Therefore, the labor inputs on water management in Wushih County of Jiangsu Province in the 1920s surpassed those of weeding or transplanting by a factor of two (Amano 1979: 410), whereas in monsoonal Java, the inputs in water management were insignificant (Barker et al. 1985: 126).

Because of the cooler weather in north China, irrigation practices were attuned to suitable weather conditions as early as the Western Han: Water inlets and outlets were positioned directly opposite across the field so as to warm the flowing water by sunlight during the early stages of rice growth. Elsewhere, the inlets and outlets were repositioned at different intervals in order to cool the water during hot summer months (Amano 1979: 182). The encyclopedia *Ch'i-Min-Yao-Shu* devoted much space to irrigation practices: Watering should be attuned to the weather; the fields should be drained after tillage so as to firm the roots and drained again before harvesting.

In order to supplement the unreliable rainfall, many implements were developed to irrigate individual fields. The developments began with the use of urns to carry water from creeks or wells. The urn or bucket was later fastened to the end of a long pole and counterbalanced on the other end by a large chunk of stone. The pole was rested on a stand and could be swung around to facilitate the filling or pouring. A winch was later used to haul a bucket from a well (see Amano 1979 for illustrations).

The square-pallet chain pump came into use during the Eastern Han; it was either manually driven by foot pedaling or driven by a draft animal turning a large wheel and a geared transmission device (Amano 1979: 205, 240). The chain pump was extensively used in China until it was replaced by engine-driven water pumps after the 1930s. The device also spread to Vietnam. During hot and dry summers, the pumping operation required days and nights of continuous input. Other implements, such as the water wheel in various forms, were also used (Amano 1979; Chao 1979).

Although deepwater rice culture in China never approached the scale found in tropical Asia, Chinese farmers used floating rafts made of wooden frames and tied to the shore so as to grow rice in swamps. Such a practice appeared in Late Han, and the rafts were called *feng* (for frames) fields (Amano 1979: 175).

Many rice cultivars are capable of producing new tillers and panicles from the stubble after a harvest. Such regrowth from the cut stalks is called a ratoon crop. Ratooning was practiced in China as early as the Eastern Tsin period (A.D. 317–417), and it is now an important practice in the southern United States. Ratooning gives better returns in the temperate zone than in the tropics because the insects and diseases that persist from crop to crop pose more serious problems in the tropics.

Seed selection has served as a powerful force in cultivar formation and domestication. Continued selection by rice farmers in the field was even more powerful in fixing new forms; they used the desirable gene-combinations showing up in the plantings to suit their farmer's different needs and fancies. The earliest mention of human-directed selection in Chinese records during the first century B.C. was focused on selecting panicles with more grains and fully developed kernels. Soon, varietal differences in awn color and length, maturity, grain size and shape, stickiness of cooked rice, aroma of milled rice, and adaptiveness to dryland farming were recognized. The trend in selection was largely toward an earlier maturity, which reduced cold damage and made multiple cropping more practical in many areas. The encyclopedia *Ch'i-Min-Yao-Shu* advised farmers to grow seeds in a separate plot, rotate the seed plot site in order to eliminate weedy rice, and select pure and uniformly colored panicles. The seeds were to be stored above ground in aerated baskets, not under the ground. Seed selection by winnowing and floatation in water was advised.

Dryland or hill rice was mentioned in writings of the third century B.C. (Ting 1961). During Eastern Tsin, thirteen varieties were mentioned; their names indicated differences in pigmentation of awn, stem and hull, maturity, grain length, and stickiness of cooked rice (Amano 1979). Varieties with outstanding grain quality frequently appeared in later records. Indeed, a total of 3,000 varieties was tallied, and the names were a further indication of the differences in plant stature and morphology, panicle morphology, response to manuring, resistance to pests, tolerance to stress factors (drought, salinity, alkalinity, cool temperatures, and deep water), and ratooning ability (You 1982). The broad genetic spectrum present in the rice varieties of China was clearly indicated.

Harvesting and processing rice is another laborious process. The cutting instruments evolved from knives to sickles to scythe. Community efforts were common in irrigated areas, and such neighborly cooperation can still be seen in China, Indonesia, the Philippines, Thailand, and other countries. Threshing of grains from the panicles had been done in a variety of ways: beating the bundle of cut stalks against a wooden bench or block; trampling by human feet or animal hoofs; beating with a flail; and, more recently, driving the panicles through a spiked drum that is a prototype of the modern grain combine (see Amano 1979: 248–54 for the ancient tools).

Other important postharvest operations are the drying of the grain (mainly by sun drying), winnowing (by natural breeze or a hand-cranked fan inside a drum winnower), dehusking (dehulling), and milling (by pestle and mortar, stone mills, or modern dehulling and milling machines). Grains and milled rice are stored in sacks or in bulk inside bins. In Indonesia and other hilly areas, the long-panicled Javanica rices are tied into bundles prior to storage.

To sum up the evolutionary pathway in wetland rice cultivation on a worldwide scale, cultivation began with broadcasting in rain-fed and unbunded fields under shifting cultivation. As the growers settled down, the cultivation sites became permanent fields. Then, bunds were built to impound the rain water, and the transplanting method followed. As population pressure on the land continued to increase, irrigation and transplanting became more imperative (Chang 1989a).

The entire range of practices can still be seen in the Jeypore Tract and the neighboring areas (author's personal observations). The same process was retraced in Bang Chan (near Bangkok) within a span of one hundred years. In this case, the interrelationships among land availability, types of rice culture, population density, labor inputs, and grain outputs were documented in a fascinating book entitled *Rice and Man* by L. M. Hanks (1972).

In the twentieth century, further advances in agricultural engineering and technology have to do with several variations in seeding practices that have been adopted to replace transplanting. Rice growers in the southern United States drill seed into a dry soil. The field is briefly flushed with water and then drained. The seeds are allowed to germinate, and water is reintroduced when the seedlings are established. In northern California, pregerminated seeds are dropped from airplanes into cool water several inches deep. The locally selected varieties are able to emerge from the harsh environment (Adair et al. 1973).

Recently, many Japanese farmers have turned to drill-plant pregerminated seed on wet mud. An oxidant is applied to the seed before sowing so as to obtain a uniform stand of plants. For the transplanted crop, transplanting machines have been developed not only to facilitate this process but also to make commercial raising of rice seedlings inside seed boxes a profitable venture. As labor costs continue to rise worldwide, direct seeding coupled with chemical weed control will be the main procedures in the future.

For deepwater rice culture, rice seeds are broadcasted on dry soil. The seeds germinate after the monsoon rains arrive. The crop is harvested after the rains stop and the flooding water has receded.

For dryland rice, seeds are either broadcasted, drilled, or dropped (dibbled) into shallow holes dug in the ground. Dibbling is also common in West Africa. Dryland (hill or upland) rice continues to diminish in area because of low and unstable yield. It has receded largely into hilly areas in Asia where tribal minorities and people practicing shifting cultivation grow small patches for subsistence.

Rice Cultivation and Cultural Exchanges

The expansion of rice cultivation in China involved interactions and exchanges in cultural developments, human migration, and progress in agricultural technology. Agricultural technology in north China developed ahead of other regions of China. Areas south of the Yangtze River, especially south China, were generally regarded by Chinese scholars of the north as primitive in agricultural practices. During travel to the far south in the twelfth century, one of these scholars described the local rain-fed rice culture. He regarded it as crude in land preparation: Seed was sown by dibbling, fertilizer was not used, and tillage as a weeding practice was unknown (Ho 1969).

However, the picture has been rather different in the middle and lower Yangtze basins since the Tsin Dynasty (beginning in A.D. 317) when a mass migration of people from the north to southern areas took place. The rapid expansion of rice cultivation in east China was aided by the large-scale production of iron tools used in clearing forests and the widespread adoption of transplanting.

Private land ownership, which began in the Sung (beginning in A.D. 960), followed by reduction of land rent in the eleventh century and reinforced by double cropping and growth in irrigation works, stimulated rice production and technology development. As a result, rice production south of the Yangtze greatly surpassed rice production in the north, and human population growth followed the same trend (Ho 1969; Chang 1987). Thus, the flow of rice germ plasm was from south to north, but much of the cultural and technological developments diffused in the opposite direction.

Culinary Usage and Nutritional Aspects

Rice Foods

Before the rice grain is consumed, the silica-rich husk (hull, chaff) must be removed. The remaining kernel is the caryopsis or brown rice. Rice consumers, however, generally prefer to eat milled rice, which is the product after the bran (embryo and various layers of seed coat) is removed by milling. Milled rice is, invariably, the white, starchy endosperm, despite pigments present in the hull (straw, gold, brown, red, purple or black) and in the seed coat (red or purple).

Parboiled rice is another form of milled rice in which the starch is gelatinized after the grain is precooked by soaking and heating (boiling, steaming, or dry heating), followed by drying and milling. Milled rice may also be ground into a powder (flour), which enters the food industry in the form of cakes, noodles, baked products, pudding, snack foods, infant formula, fermented items, and other industrial products.

Fermentation of milled glutinous rice or overmilled nonglutinous rice produces rice wine *(sake).* Vinegar is made from milled and broken rice and beer from broken rice and malt. Although brown rice, as well as lightly milled rice retaining a portion of the germ (embryo), are recommended by health-food enthusiasts, their consumption remains light. Brown rice is difficult to digest due to its high fiber content, and it tends to become rancid during extended storage. Cooking of all categories of rice is done by applying heat (boiling or steaming) to soaked rice until the kernels are fully gelatinized and excess water is expelled from the cooked product. Cooked rice can be lightly fried in oil to make fried rice. People of the Middle East prefer to fry the rice lightly before boiling. Americans often add salt and butter or margarine to soaked rice prior to boiling. The peoples of Southeast Asia eat boiled rice three times a day, including breakfast, whereas peoples of China, Japan, and Korea prepare their breakfast by boiling rice with excess water, resulting in porridge (thick gruel) or *congee* (thin soup).

Different kinds of cooked rice are distinguished by cohesiveness or dryness, tenderness or hardness, whiteness or other colors, flavor or taste, appearance, and aroma (or its absence). Of these features, cohesiveness or dryness is the most important varietal characteristic: High amylose (25 to 30 percent) of the starchy endosperm results in dry and fluffy kernels; intermediate amylose content (15 to 25 percent) produces tender and slightly cohesive rice; low amylose content (10 to 15 percent) leads to soft cohesive (aggregated) rice; and glutinous or waxy endosperm (0.8 to 1.3 percent amylose) produces highly sticky rice. Amylopectin is the other – and the major – fraction of rice starch in the endosperm.

These four classes of amylose content and cooked products largely correspond with the designation of Indica, Javanica, Sinica (Japonica), and glutinous. Other than amylose content, the cooked rice is affected by the rice–water ratio, cooking time, and age of rice. Hardness, flavor, color, aroma, and texture of the cooked rice upon cooling are also varietal characteristics (Chang 1988; Chang and Li 1991).

Consumer preference for cooked rice and other rice products varies greatly from region to region and is largely a matter of personal preference based on upbringing. For instance, most residents of Shanghai prefer the cohesive *keng* (Sinica) rice, whereas people in Nanjing about 270 kilometers away in the same province prefer the drier *hsien* (Indica) type. Tribal people of Burma, Laos, Thailand, and Vietnam eat glutinous rice three times a day – a habit unthinkable to the people on the plains. Indians and Pakistanis pay a higher price for the basmati rices, which elongate markedly upon cooking and have a strong aroma. People of South Asia generally prefer slender-shaped rice, but many Sri Lankans fancy the short, roundish *samba* rices, which also have dark red seed coats. Red rice is also prized by tribal people of Southeast Asia (Eggum et al. 1981; Juliano 1985c) and by numerous Asians during festivities, but its alleged nutritional advantage over ordinary rice remains a myth. It appears that the eye appeal of red or purple rice stems from the symbolic meaning given the color red throughout Asia, which is "good luck."

The pestle and mortar were doubtless the earliest implements used to mill rice grains. The milling machines of more recent origin use rollers that progressed from stone to wood to steel and then to rubber-wrapped steel cylinders. Tubes made of sections of bamboo were most likely an early cooking utensil, especially for travelers. A steamer made of clay was unearthed at the He-mu-du site dating from 5000 B.C., but the ceramic and bronze pots were the main cooking utensils until ironware came into use. Electric rice cookers replaced iron or aluminum pots in Japan and other Asian countries after the 1950s, and today microwave ovens are used to some extent.

Nutritional Considerations

Rice is unquestionably a superior source of energy among the cereals. The protein quality of rice (66 percent) ranks only below that of oats (68 percent) and surpasses that of whole wheat (53 percent) and of corn (49 percent). Milling of brown rice into white rice results in a nearly 50 percent loss of the vitamin B complex and iron, and washing milled rice prior to cooking further reduces the water-soluble vitamin content. However, the amino acids, especially lysine, are less affected by the milling process (Kik 1957; Mickus and Luh 1980; Juliano 1985a; Juliano and Bechtel 1985).

Rice, which is low in sodium and fat and is free of cholesterol, serves as an aid in treating hypertension. It is also free from allergens and now widely used in baby foods (James and McCaskill 1983). Rice starch can also serve as a substitute for glucose in oral rehydration solution for infants suffering from diarrhea (Juliano 1985b).

The development of beriberi by people whose diets have centered too closely on rice led to efforts in the 1950s to enrich polished rice with physiologically active and rinse-free vitamin derivatives. However, widespread application was hampered by increased cost and yellowing of the kernels upon cooking (Mickus and Luh 1980). Certain states in the United States required milled rice to be sold in an enriched form, but the campaign did not gain acceptance in the developing countries. After the 1950s, nutritional intakes of the masses in Asia generally improved and, with dietary diversification, beriberi receded as a serious threat.

Another factor in keeping beriberi at bay has been the technique of parboiling rough rice. This permits the water-soluble vitamins and mineral salts to spread through the endosperm and the proteinaceous material to sink into the compact mass of gelatinized starch. The result is a smaller loss of vitamins, minerals, and amino acids during the milling of parboiled grains (Mickus and Luh 1980), although the mechanism has not been fully understood. Parboiled rice is popular among the low-income people of Bangladesh, India, Nepal, Pakistan, Sri Lanka, and parts of West Africa and amounts to nearly one-fifth of the world's rice consumed (Bhattacharya 1985).

During the 1970s, several institutions attempted to improve brown rice protein content by breeding. Unfortunately, such efforts were not rewarding because the protein content of a variety is highly variable and markedly affected by environment and fertilizers, and protein levels are inversely related to levels of grain yield (Juliano and Bechtel 1985).

Production and Improvement in the Twentieth Century

Production Trends

Prior to the end of World War II, statistical information on global rice production was rather limited in scope. The United States Department of Agriculture (USDA) compiled agricultural statistics in the 1930s, and the Food and Agriculture Organization of the United Nations (FAO) expanded these efforts in the early 1950s (FAO 1965). In recent years, the *World Rice Statistics* published periodically by the International Rice Research Institute (IRRI) provides comprehensive information on production aspects, imports and exports, prices, and other useful information concerning rice (IRRI 1991).

During the first half of the twentieth century, production growth stemmed largely from an increase in wetland rice area and, to a lesser extent, from expansion of irrigated area and from yields increased by the use of nitrogen fertilizer. Then, varietal improvement came in as the vehicle for delivering higher grain yields, especially in the late 1960s when the "Green Revolution" in rice began to gather momentum (Chang 1979a).

Rice production in Asian countries steadily increased from 240 million metric tons during 1964–6 to 474 million tons in 1989–90 (IRRI 1991). Among the factors were expansion in rice area and/or irrigated area; adoption of high-yielding, semidwarf varieties (HYVs); use of nitrogen fertilizers and other chemicals (insecticides, herbicides, and fungicides); improved cultural methods; and intensified land use through multiple cropping (Herdt and Capule 1983; Chang and Luh 1991).

Asian countries produced about 95 percent of the world's rice during the years 1911–40. After 1945, however, Asia's share dropped to about 92 percent by the 1980s, with production growth most notable in North and South America (IRRI 1991; information on changes in grain yield, production, annual growth rates, and prices in different Asian countries is provided in Chang 1993b; Chang and Luh 1991; David 1991; and Chang 1979a).

But despite the phenomenal rise in crop production and (in view of rapidly growing populations) the consequent postponement of massive food shortages in Asia since the middle 1960s, two important problems remain. One of these is food production per capita, which advanced only slightly ahead of population growth (WRI 1986). The other is grain yield, which remained low in adverse rain-fed environments – wetland, dryland, deepwater, and tidal swamps (IRRI 1989). In fact, an apparent plateau has prevailed for two decades in irrigated rice (Chang 1983). Moreover, the cost of fertilizers, other chemicals, labor, and good land continued to rise after the 1970s, whereas the domestic wholesale prices in real terms slumped in most tropical Asian nations and have remained below the 1966–8 level.

This combination of factors brought great concern when adverse weather struck many rice areas in Asia in 1987 and rice stocks became very low. Fortunately, weather conditions improved the following year and rice production rebounded (Chang and Luh 1991; IRRI 1991).

However, the threat to production remains. In East Asia, five years of favorable weather ended in 1994 with a greater-than-usual number of typhoons that brought massive rice shortages to Japan and South Korea. And in view of the "El Niño" phenomenon, a higher incidence of aberrant weather can be expected, which will mean droughts for some and floods for others (Nicholls 1993).

Germ Plasm Loss and the Perils of Varietal Uniformity

Rice is a self-fertilizing plant. Around 1920, however, Japanese and U.S. rice breeders took the lead in using scientific approaches (hybridization selection and testing) to improve rice varieties. Elsewhere, pureline selection among farmers' varieties was the main method of breeding.

After World War II, many Asian countries started to use hybridization as the main breeding approach. Through the sponsorship of the FAO, several countries in South and Southeast Asia joined in the Indica-Japonica Hybridization Project during the 1950s, exchanging rice germ plasm and using diverse parents in hybridization.

These efforts, however, provided very limited improvement in grain yield (Parthasarathy 1972), and the first real breakthrough came during the mid-1950s when Taiwan (first) and mainland China (second) independently succeeded in using their semidwarf rices in developing short-statured, nitrogen-responsive and high-yielding semidwarf varieties (HYVs). These HYVs spread quickly among Chinese rice farmers (Chang 1961; Huang, Chang, and Chang 1972; Shen 1980).

Taiwan's semidwarf "Taichung Native 1" (TN1) was introduced into India through the International Rice Research Institute (IRRI) located in the Philippines. "TNI" and IRRI-bred "IR8" triggered the "Green Revolution" in tropical rices (Chandler 1968; Huang et al. 1972). Subsequent developments in the dramatic spread of the HYVs and an associated rise in area grain yield and production have been documented (Chang 1979a; Dalrymple 1986), and refinements in breeding approaches and international collaboration have been described (Brady 1975; Khush 1984; Chang and Li 1991).

In the early 1970s, China scored another breakthrough in rice yield when a series of hybrid rices (F_1 hybrids) were developed by the use of a cytoplasmic pollen-sterile source found in a self-sterile wild plant ("Wild Abortive") on Hainan Island (Lin and Yuan 1980). The hybrids brought another yield increment (15 to 30 percent) over the widely grown semidwarfs.

Along with the rapid and large-scale adoption of the HYVs and with deforestation and development projects, innumerable farmers' traditional varieties of all three ecogenetic races and their wild relatives have disappeared from their original habitats – an irreversible process of "genetic erosion." The lowland group of the javanic race *(bulu, gundill)* suffered the heaviest losses on Java and Bali in Indonesia. Sizable plantings of the long-bearded *bulus* can now be found only in the Ifugao rice terraces of the Philippines.

In parallel developments, by the early 1990s the widespread planting of the semidwarf HYVs and hybrid rices in densely planted areas of Asia amounted to about 72 million hectares. These HYVs share a common semidwarf gene (sd_1) and largely the same cytoplasm (either from "Cina" in older HYVs or "Wild Abortive" in the hybrids). This poses a serious threat of production losses due to a much narrowed genetic base if wide-ranging pest epidemics should break out, as was the case with hybrid maize in the United States during 1970–1 (Chang 1984).

Since the early 1970s, poorly educated rice farmers in South and Southeast Asia have planted the same HYV in successive crop seasons and have staggered plantings across two crops. Such a biologically unsound practice has led to the emergence of new and more virulent biotypes of insect pests and disease pathogens that have overcome the resistance genes in the newly bred and widely grown HYVs. The result has been heavy crop losses in several tropical countries in a cyclic pattern (Chang and Li 1991; Chang 1994).

Fortunately for the rice-growing world, the IRRI has, since its inception, assembled a huge germ plasm collection of more than 80,000 varieties and 1,500 wild rices by exchange and field collection. Seeds drawn from the collection not only have sustained the continuation of the "Green Revolution" in rice all over the world but also assure a rich reservoir of genetic material that can reinstate the broad genetic base in Asian rices that in earlier times kept pest damage to manageable levels (Chang 1984, 1989b, 1994).

Outlook for the Future

Since the dawn of civilization, rice has served humans as a life-giving cereal in the humid regions of Asia and, to a lesser extent, in West Africa. Introduction of rice into Europe and the Americas has led to its increased use in human diets. In more recent times, expansion in the rice areas of Asia and Africa has resulted in rice replacing other dryland cereals (including wheat) and root crops as the favorite among the food crops, wherever the masses can afford it. Moreover, a recent overview of food preferences in Africa, Latin America, and north China (Chang 1987, personal observation in China) suggests that it is unlikely that rice eaters will revert to such former staples as coarse grains and root crops. On the other hand, per capita rice consumption has markedly dropped in the affluent societies of Japan and Taiwan.

In the eastern half of Asia, where 90 to 95 percent of the rice produced is locally consumed, the grain is the largest source of total food energy. In the year 2000, about 40 percent of the people on earth, mostly those in the populous, less-developed countries, depended on rice as the major energy source. The question, of course, is whether the rice-producing countries with ongoing technological developments can keep production levels ahead of population growth.

From the preceding section on cultivation practices, it seems obvious that rice will continue to be a labor-intensive crop on numerous small farms. Most of the rice farmers in rain-fed areas (nearly 50 percent of the total planted area) will remain subsistence farmers because of serious ecological and economic constraints and an inability to benefit from the scientific innovations that can upgrade land productivity (Chang 1993b). Production increases will continue to depend on the irrigated areas and the most favorable rain-fed wetlands, which now occupy a little over 50 percent of the harvested rice area but produce more than 70 percent of the crop. The irrigated land area may be expanded somewhat but at a slower rate and higher cost than earlier. Speaking to this point is a recent study that indicates that Southeast Asia and South Asia as well, are rapidly depleting their natural resources (Brookfield 1993).

With rising costs in labor, chemicals, fuel, and water, the farmers in irrigated areas will be squeezed between production costs and market price. The latter, dictated by government pricing policy in most countries, remains lower than the real rice price (David 1991). Meanwhile, urbanization and industrialization will continue to deprive the shrinking farming communities of skilled workers, especially young men. Such changes in rice-farming communities will have serious and widespread socioeconomic implications.

Unless rice farmers receive an equitable return for their efforts, newly developed technology will remain experimental in agricultural stations and colleges. The decision makers in government agencies and the rice-consuming public need to ensure that a decent living will result from the tilling of rice lands. Incentives must also be provided to keep skilled and experienced workers on the farms. Moreover, support for the agricultural research community must be sustained because the challenges of providing still more in productivity-related cultivation innovations for rice are unprecedented in scope.

Although the rice industry faces formidable challenges, there are areas that promise substantial gains in farm productivity with the existing technology of irrigated rice culture. A majority of rice farmers can upgrade their yields if they correctly and efficiently perform the essential cultivation practices of fertilization, weed and pest control, and water management.

On the research front, rewards can be gained by breaking the yield ceiling, making pest resistance more durable, and improving the tolerance to environmental stresses. Biotechnology will serve as a powerful force in broadening the use of exotic germ plasm in *Oryza* and related genera (Chang and Vaughan 1991). We also need the inspired and concerted teamwork of those various sectors of society that, during the 1960s and 1970s, made the "Green Revolution" an unprecedented event in the history of agriculture.

Lastly, control of human population, especially in the less-developed nations, is also crucial to the maintenance of an adequate food supply for all sectors of human society. Scientific breakthroughs alone will not be able to relieve the overwhelming burden placed on the limited resources of the earth by uncontrolled population growth.

Te-Tzu Chang

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II.A.8 Rye

Rye As a Grass

Rye (*Secale cereale* L.) is closely related to the genus *Triticum* (which includes bread wheat, durum wheat, spelt, and the like) and has sometimes been included within that genus (Mansfeld 1986: 1447). In fact, it was possible to breed Triticale, a hybrid of *Triticum* and *Secale,* which is cultivated today (Mansfeld 1986: 1449).

Cultivated rye *(Secale cereale)* is also so closely related genetically to the wild rye *(Secale montanum)* that both species would appear to have had the same ancestors. Yet to say that the cultivated rye plant derived from the wild one is an oversimplification because both plants have been changing their genetic makeup since speciation between the wild and cultivated plants first occurred.

The cultigen *Secale cereale* was brought to many parts of the world, but wild rye still grows in the area where cultivated rye originated, which embraces the mountains of Turkey, northwestern Iran, Caucasia, and Transcaucasia (Zohary and Hopf 1988: 64–5; Behre 1992: 142).

The distribution area of wild rye is slightly different from the area of origin of other Near Eastern crops. Wild rye is indigenous to areas north of the range of the wild *Triticum* and *Hordeum* species; these areas have a more continental climate with dry summers and very cold, dry winters. The environmental requirements of cultivated rye reflect these conditions of coldness and dryness: It has a germination temperature of only 1 to 2 degrees Centigrade, which is lower than that of other crops. Indeed, low temperatures are necessary to trigger sprouting (Behre 1992: 145), and the plant grows even in winter if the temperature exceeds 0 degrees Centigrade, although rye can suffer from a long-lasting snow cover. In spring it grows quickly, so that the green plant with unripe grains reaches full height before the summer drought begins (Hegi 1935: 498–9). Obviously, these characteristics make rye a good winter crop. It is sown in autumn, grows in winter and spring, and ripens and is harvested in summer – a growth cycle that is well adapted to continental and even less favorable climatic conditions. There is also another cultigen of rye – summer rye – which is grown as a summer crop. But because of a low yield and unreliability, it is rather uncommon today (Hegi 1935: 497).

Clearly, then, the constitution of the wild grass ancestor of cultivated rye is reflected in the cultivated crop. Rye is predominantly grown as a winter crop, on less favorable soils, and under less favorable climatic conditions than wheat.

The Question of Early Cultivation

There is evidence for the ancient cultivation of rye in the Near East dating back to the Neolithic. Gordon Hillman (1975: 70–3; 1978: 157–74; see also Behre 1992: 142) found cultivated rye in aceramic early Neolithic layers of Tell Abu Hureyra in northern Syria and also at Can Hasan III in central Anatolia. Hillman reports that there were entire rachis internodes at these sites, proof that the selective pressures of cultivation were operating, because only a plant with a nonbrittle rachis can be harvested efficiently. It is not clear, however, if rye was actually cultivated at these Neolithic sites or whether the plant only underwent such morphological adaptations while being sown and harvested as a weedy contaminant of other crops.

To this day, rye remains a vigorous weed in Near Eastern wheat and barley fields, and its nonbrittle rachis internodes resemble a cultivated plant in spite of the fact that it is not intentionally sown. It is harvested together with the more desirable wheat and barley as a "maslin crop" (a crop mixture), and, in climatically unfavorable years, the rye yield is often better than the yield of barley or wheat in these fields. Even an examination of the harvested crop may give the false impression that the rye has been deliberately cultivated. It is interesting to note that such "volunteer" rye is called "wheat of Allah" by Anatolian peasants (Zohary and Hopf 1988: 64) because it is assumed that God "sent" a crop in spite of the bad weather conditions that were unfavorable to the sown wheat.

Possibly this process of unintentionally cultivating rye, while intentionally cultivating wheat and barley, also took place in the early Neolithic fields of Tell Abu Hureyra and Can Hasan III that Hillman investigated. So we do not know if rye was deliberately grown as a crop in its own right or if it was only "wheat of Allah." It is the case that Hillman's evidence