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Plant Resources of South-East Asia

No 10

Cereals

G.J.H. Grubben and Soetjipto Partohardjono (Editors)

PROSEA

Bogor Indonesia 1996

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Foreword

Cereals are the mainstay of human nutrition. Their direct consumption provides about 60% of the world food energy on average. Moreover, a large part of the feed needed for livestock also stems from cereals.

Cereal breeding and research have been very successful. High-yielding cultivars of rice, maize, wheat and sorghum, developed by international research institutes, have become widely cultivated in the tropics and subtropics since the 1960s. In most countries, cereal farmers have succeeded in meeting national needs. In recent years, however, population growth has outstripped the increase in grain production, and hence per capita production has declined. This trend is caused by the scarcity of new land for cropping, and the levelling off in increase of yield per ha. As research has concentrated on a few major crops (in South-East Asia, mainly on rice), breeding and agronomic research on several secondary cereals and pseudo-cereals with economic potential have been neglected.

With increasing wealth, consumers in the coming years will tend to vary their diet with more vegetables and animal products, and will also increase their consumption of cereal products other than rice, such as bread and pasta. Nevertheless, rice will remain the most important cereal for South-East Asia. Rising labour costs will force rice farmers to strive to mechanize their production, and more will switch to direct seeding and weed control with herbicides. Research institutes will have a major task in optimizing the yield of rice and other cereals in sustainable cropping systems, and in narrowing the wide gap between actual and potential yield. Moreover, more research will be devoted to crop diversification away from rice, so that marginal soils will become useful for energy-food production, food security will be strengthened and the diet improved. It is of the utmost importance for global food security and thus for economic and political stability in the world, that sufficient reserves of cereals are maintained.

This book on cereals, volume 10 of the Prosea series, gives a comprehensive state-of-the-art overview of cereal production and potential in South-East Asia. It is a rich source of information on cereal cropping under South-East Asian conditions. In addition to rice and maize, ten other true cereals are treated as major species although they are grown very locally and in rather small amounts. They are usually grown as secondary food crops or used for feed or industrial purposes. Three non-graminaceous crops, the so-called pseudo-cereals, have been added because of their potential to attain some economic importance in South-East Asia.

This Prosea volume is the result of the collective effort of an international group of scientists. I hope that the information presented will be an inspiration to all those concerned with the improvement of this important group of food and feed crops in the region. Finally, I wish to express my appreciation to the Board and personnel of the Prosea Foundation for making this very useful book a reality.

Los Baños, April 1996

G. Rothschild
Director General
International Rice Research Institute (IRRI)

1 Introduction

1.1 Definition and species diversity

1.1.1 Choice of species

Strictly speaking the definition of cereals is limited to *Gramineae* species with edible starchy grains. In this volume the definition is widened to include those grain crops cultivated for their starchy seed which is used as a basic food for humans, as a fodder for domesticated livestock or as a raw material for industrial purposes. Most starchy grain crops are 'true' cereals belonging to the *Gramineae* family. By far the most important one for South-East Asia is rice (*Oryza sativa* L.), followed at some distance by maize (*Zea mays* L.). The other true cereals described in full articles in this volume are grown very locally and in much smaller quantities compared with rice or maize. Cereals like sorghum (*Sorghum bicolor* (L.) Moench), proso millet (*Panicum miliaceum* L. cv. group Proso Millet) and wheat (*Triticum* spp.) have some economic importance in South-East Asia, whereas the others like pearl millet (*Pennisetum glaucum* (L.) R. Br.), finger millet (*Eleusine coracana* (L.) Gaertner cv. group Finger Millet), foxtail millet (*Setaria italica* (L.) P. Beauvois cv. group Foxtail Millet), barnyard millet (*Echinochloa* spp.), Job's tears (*Coix lacryma-jobi* L.), rye (*Secale cereale* L.), and barley (*Hordeum vulgare* L.) have been included because they are produced locally on a minor scale, or are being investigated at research institutes as potential new crops. Three non-graminaceous crops, the so-called 'pseudo-cereals', have been added to this group of major species, namely grain amaranth (*Amaranthus* spp.), grain chenopod (*Chenopodium* spp.) and buckwheat (*Fagopyrum esculentum* Moench), because they have the potential to become economically important in South-East Asia. These pseudo-cereals are dicotyledons, which differ from the *Gramineae* in many aspects. They are mentioned only occasionally in this introductory chapter, but are briefly described in general terms in section 1.10.

In addition to the major species, Chapter 3 briefly describes 9 minor species (8 graminaceous and 1 non-graminaceous), which could be or are actually used as emergency food in times of scarcity. Chapter 4 lists those cereals whose primary use is not as a grain crop, and gives the appropriate references to other volumes of the Prosea handbook.

1.1.2 Domestication

There is archaeological evidence that in the Palaeolithic, 30 000 years ago, primitive people were already collecting dry seeds of grasses. Barley and wheat have been found in the delta of the Nile and the Euphrates, in the Fertile Crescent, in excavations of settlements dating from around 8000–7000 BC. During the Neolithic period (7000–3000 BC) wild types of wheat, millets, barley, sorghum, maize and rice were collected and used as energy food in many places. Domestication and cultivation started gradually at several locations in the world. In the fourth millennium BC, cereal cultivation was already widespread in the Mediterranean area, Western Asia and Western Europe (Evans, 1993; Leakey & Lewin, 1977).

How domestication started can be deduced from the gathering and cropping practices of traditional people in remote areas. Grains of certain grass types with big kernels of good eating quality, the ancestors of modern cereals, would have been collected by sweeping a basket through the dry grass vegetation. Small-seeded types such as millets and amaranths were also harvested, because of their ability to yield large quantities of seed from a dense vegetation. Harvesting in this way, one person could collect over 10 kg of wild cereal seed per day, and the surplus could easily be stored to bridge the period to the next harvest. The next logical step was to protect this grass vegetation and to weed selectively by removing competing broad-leaved plants. Spilled seed will have germinated in compounds or on land near dwellings where the vegetation was burned to stimulate grass growth for livestock.

The distinctive step marking the beginning of agriculture was the intentional saving and actual sowing of part of the collected grain. Aboriginals in Australia, while harvesting wild millet, sometimes scatter some seed to stimulate regrowth. Only the haulms of plants with non-shedding seed will have been picked, and therefore this characteristic plant type will have been selected unconsciously for all cereals and pseudo-cereals. Deliberate roguing and the discarding of plants or seed with undesirable characters marked the beginning of plant breeding. This went hand-in-hand with the refinement of cultural practices. However, this made the incipient landraces more vulnerable to predators and more dependent on the farmer's protection (Brown & Eckholm, 1975; Evans, 1993). Over hundreds of generations humans learned how to grow a good grain crop and that it was possible to improve yield and quality by keeping the most productive plants with desirable traits for the next sowing. In this way, wild grass species were gradually developed into new crop species. They differed from their wild ancestors in aspects such as the size of the grains, the non-shattering seed, the free-threshing glumes, reduced dormancy and other desired traits (de Wet, 1986; Riley, 1975).

1.1.3 Geographic distribution

Irrigated rice cultivation probably developed in China during the Neolithic period 5000 years BC. Already in antiquity it spread from South China to all over South and South-East Asia, and in recent centuries it has spread westwards to central Asia, tropical and subtropical Africa, the Mediterranean area, and to South, Central and North America. Maize originated in Central America, spread to the north and the south, and went eastwards all over the world up to the east coast of Asia.

Although rice, maize, sorghum and millets are thermophile crops and wheat and barley are more at home in cooler climates, the overall adaptation to other environments is noteworthy (Figure 1). Rice is grown from the equator to

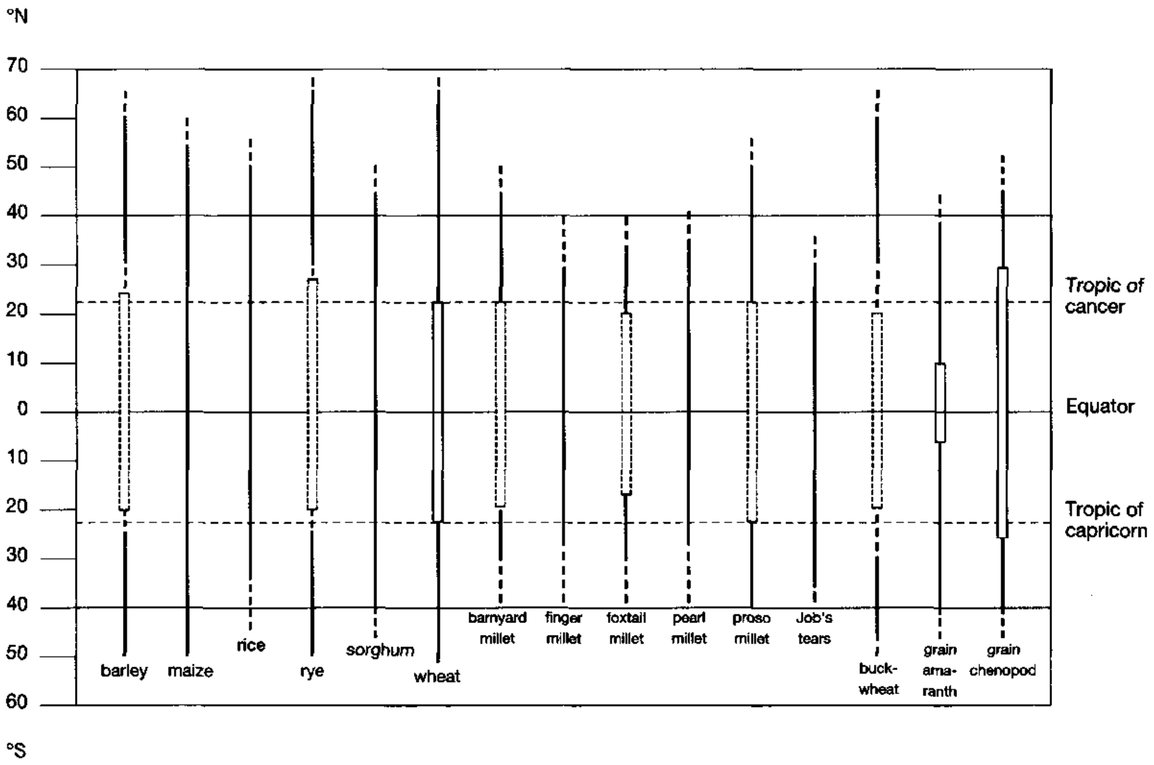


Figure 1. Barchart of the global distribution of the main cereals. ——— suitable; ▭ suitable at high elevations; ------marginal; ⬚ marginal even at high elevations.

northern China at 50°N. Wheat is produced from Alaska, Norway and Siberia at 65°N, almost at the Arctic Circle, to the tropical areas of 20°N in Asia, while in the highlands of Africa and Latin America it touches the equator.

1.2 Role of cereals

1.2.1 Social and cultural aspects

Cereals, food crops of eminent importance for humanity and the backbone of human nutrition derive their English name from Ceres, the Roman goddess of the most basic human need: daily bread. They are interwoven with all aspects of human civilization. When around 2600 years BC pharaoh Zoser in ancient Egypt engaged thousands of workers to build his tomb, the Step Pyramid of Saqqara, he was only able to do so because he had a well-organized supply of emmer wheat (*Triticum turgidum* L.) from the farms in the Nile delta.

In ancient times, the most advanced civilizations could arise only in those areas where suitable growing conditions, paired with inventive cropping practices, guaranteed a high and sustainable cereal production. Examples are the wheat-based civilizations of Ancient Egypt, Mesopotamia and the Roman Empire, and the rice-based civilizations of South-East and East Asia. For thousands of years the Incas and Aztecs in Latin America cultivated maize as a sta-

ple food together with the pseudo-cereals amaranth and quinoa (*Chenopodium quinoa* Willdenow), using them in religious ceremonies too.
Even today the planting and harvesting of cereals is accompanied by feasts and ceremonies. Everywhere in South-East Asia the rice harvest is a happy occasion and the people are thankful to the gods because in the coming period their staple food is guaranteed (White, 1994). The Javanese rice goddess Dewi Sri who guards life and fertility has much in common with the Roman goddess Ceres. And every year citizens of the United States celebrate Thanksgiving Day, a tradition started by a group of European settlers in gratitude for their first wheat harvest.
Why are cereals so popular as a staple food? They have attractive traits: they are compact, energy-rich, easy to grow, store, prepare, carry, trade and ship. Most governments attach great importance to being self-sufficient in cereals, because dependence on imports is considered politically and economically undesirable. Not surprisingly, cereals have always been a trump card in international politics.

1.2.2 Uses

The many uses of cereal grains and by-products can be grouped into four major categories: human consumption, livestock feed, raw material, and subsidiary uses.

Human consumption

Cereals are consumed after the husked kernels have been processed in some way. The whole grain of rice, maize, sorghum, millets and sometimes also of wheat is boiled or steamed and eaten as such or used in soups or to make porridge. The flour obtained by grinding or milling the kernels is used to prepare bread, porridge, pancakes, pasta (macaroni, spaghetti, noodles, couscous) or pastries. Wheat flour, the main ingredient for baking bread, is often mixed with other cereals for economic reasons. Maize, sorghum and millet flours are usually boiled when used as a main dish. Amaranth and quinoa grains are toasted or ground into flour. Various kinds of fermented dishes are prepared from whole kernels or flour.

Livestock feed

Grain and derivatives of grain from all major cereals (called concentrates) are widely used as feed for livestock. Not only the whole kernel but also the waste from the grain-processing industry is widely used as feed. Waste products from rice-polishing or wheat-grinding (bran or meal) are rich sources of protein and macro-nutrients. The straw of many cereals is a popular feed for ruminants. It is used for hay and fodder. In temperate regions it is common to cultivate cereals (mainly maize) and harvest them when immature for use as forage or silage, but this practice is scarcely known in the tropics. There are special forage cultivars of maize and sorghum with a high protein content (2–3%) and excellent digestibility (70%).
The conversion rate of cereal protein into animal protein is about 23% for eggs

or milk, 18% for chicken, 12% for pork and 4% for beef. Under conditions of scarcity, animal products from animals fed with cereals are considered a luxury food, and direct consumption of cereals as human food should be encouraged.

Raw material

Cereal grain is an important raw material for many products. It is used to prepare beer and liquors and for diverse industrial products: starch, alcohol, glue, dextrin. In the United States, maize starch is used for the large-scale production of a sugar substitute called 'High Fructose Corn Syrup', obtained by enzymatic transformation. The introduction of this technology in the beverage industry (aerated drinks, fruit juices) was a major cause of the collapse of sugar cane production in the Philippines in the 1980s. Oil extracted from maize and sometimes also from rice bran is used for cooking or industrial purposes. Rice husk is a raw material for the preparation of building board. Straw of all cereals is used for making cardboard, for weaving mats and for decorative items. Pulp from straw is becoming increasingly important as a substitute for wood pulp in paper manufacture. The manufacture of degradable bioplastics is a new and promising use of starch.

Subsidiary uses

Cereal straw is commonly used for bedding and mulching in vegetable production. Maize and sorghum plants are used as living supports for climbing beans. Straw is used to make compost, which in turn is used as a substrate for mushroom cultivation. Straw is also applied as litter or bedding in livestock sheds. The straw of wheat and rice is a popular material for thatching. Maize and sorghum stalks are harvested for fuel, as are rice husks. As wood becomes scarcer, the use of straw for fuel will increase. Rice straw rope is used in religious ceremonies. Cereals are sown as green manure and as cover crop. Green inflorescences are mixed in bouquets with cut flowers, and dry inflorescences are popular in dry bouquets.

1.2.3 Nutritional aspects

Relative importance

Cereals constitute the main source of energy in human nutrition. On average, direct consumption of cereals provides 56% of the world food energy (rice 21%, wheat 20%, maize 5%, other cereals 10%), compared with livestock products and fish 11%, vegetables, fruits and nuts 10%, fats and oils 9%, sugar 7%, roots and tubers 7% (Brown & Eckholm, 1975). Moreover, a large part of the feed needed for livestock is derived from cereals. The income elasticity for cereal consumption is negative; direct consumption of cereals decreases with increasing wealth, whereas the consumption of livestock products and other more expensive 'luxury' foodstuffs increases. Most people perceive meat and dairy products as being more palatable than rice or bread. About two-thirds of the cereal production of western countries is used for the production of meat, eggs and dairy products. In South-East Asia, the proportion of cereal used for livestock feed is still rather low – possibly about 10% – but it is increasing rapidly, in line with earlier developments in industrialized countries.

Composition

The chemical composition of cereals and cereal products is presented in Table 1, in which foodstuffs from other commodity groups have been included for comparison. Cereals are an important source of carbohydrates, proteins, B vitamins, minerals and dietary fibre. The low fat content is an advantage for the keeping quality of the flour. The consumption of non-refined cereals (high-extraction flour) is a particularly healthy practice. Yet a cereal-based diet with insufficient other foodstuffs will lead to nutrient deficiencies because of the lack of certain essential amino acids and vitamins. In a well-balanced diet the energy-supplying staple food of cereals is complemented with pulses, livestock products, vegetables, fruits and other foodstuffs which compensate the nutrients deficient in cereals.
On a fresh weight basis, the differences in energy value between the commodity groups are rather large. However, if compared in terms of dry matter, all cereals, pseudo-cereals, pulses, roots and tubers have about the same energy value. The popular method of fine milling, followed by fractionation and removal of coarse parts, or, for rice, the practice of polishing, means that a certain percentage of the grain is lost for human consumption. Moreover, the composition of the flour is less nutritious than the composition of the whole kernel or the remaining coarse part, which is destined for feed. In industrialized countries, many diets are based upon refined cereal products supplemented with much sugar, fat, meat, eggs and dairy products. This type of diet supplies large amounts of energy and protein, but is deficient in micro-nutrients and fibre and contains too much fat. It is associated with a high incidence of constipation, cancer of the bowel, heart attacks and other diseases.

Carbohydrates Cereals contain about the same content of carbohydrates as roots and tubers. Carbohydrates constitute the bulk of the grain, about 80% of the dry weight. They are mainly stored as starch in the endosperm cells, and only a minor part is present as free sugar. Starch is a polysaccharide $(C_6H_{10}O_5)_n$. Cereal starch is roughly composed of 25% amylose (15–30%) and 75% amylopectin (70–85%). Its digestibility is improved by heating. The ratio of amylose to amylopectin strongly affects the palatibility and the industrial use. Amylose is water-soluble, and the industrial separation of amylose and amylopectin is based on this property. Amylopectin gelatinizes in hot water (60–80°C); the higher the amylopectin content, the higher the glutinosity. The endosperm of waxy cultivars of rice, barley, sorghum and maize lacks amylose (Southgate, 1988).
Dietary fibre is mainly present as non-starch polysaccharides from cell-wall structures (indigestible cellulose, hemicellulose and lignine). The highest concentrations are found in the outer bran layers of the grain. The lower the extraction rate, the lower the fibre content of the flour. Dietary fibre stimulates peristalsis.

Protein Protein is mainly present in the endosperm (about 70% of the total) but the highest concentration is found in the aleurone layer and the germ. Even within the same species the protein content of different samples may show large variation, depending on cultivar, growing conditions and cultural practices (mainly on N fertilizer). The variation is largest in maize (6–15%). The biological value of cereal protein is rather low compared with egg protein or meat protein because the content of some essential amino acids (mainly lysine, methionine, cystine; and in maize also tryptophan) is limiting. Lysine is present in high concentrations in the germ. High-extraction flour (for which almost the whole grain is used) has a higher protein content and a better biological value than low-extraction flour. The biological value of protein from the pseudo-cereals amaranth, buckwheat and quinoa is higher than that from the true cereals. Some of the cereal proteins (gliadin, glutenin) are insoluble in water, producing the 'gluten', a swelling, sticky, elastic compound, when the meal is wetted and kneaded. Carbon dioxide bubbles formed in the dough during fermentation are retained by this gluten, thus bringing about the porous crumb structure of bread. Only wheat and, to a lesser degree, rye contain enough gluten to enable this type of bread to be baked.

Vitamins and micro-nutrients Cereals are an important source of B vitamins, mainly thiamine (B_1), riboflavine (B_2) and nicotinic acid or niacin (PP). Polished rice contains considerably less thiamine than home-pounded or parboiled rice. The thiamine is present in the outer layers of the grain. Beri-beri disease, caused by a deficiency of thiamine, claimed many victims in Java in the early 20th Century when the use of polished rice became widespread. The symptoms of this disease are nausea, neuritis, muscular convulsions and cardiac disturbances. The riboflavine concentration is highest in the germ. Riboflavine deficiency causes irritation of the mucocutaneous junctions of eyes and lips and desquamation of the skin. Nicotinic acid is present in wholemeal cereals, but in maize the content is low. It is associated with the amino acid tryptophan. In a normal diet, part of the tryptophan is converted into nicotinic acid. Deficiency of tryptophan, and thus of nicotinic acid, causes pellagra, a dangerous skin disease which occurs in areas with a monotonous maize diet. Vitamin A and vitamin C are generally lacking in cereals. Yellow maize is the only cereal with a significant vitamin A content. Durum wheat and proso millet contain a small quantity of carotenoids.
Cereals contain many inorganic constituents, mostly in the germ and the outer layers of the grain. Only zinc and iron are considered as important contributions to the diet. In low-extraction meal (white wheat flour) a large part of these valuable micro-nutrients has been lost.

1.2.4 Economic aspects

In the South-East Asian countries the first priority is to safeguard food production for the nutrition of the rapidly growing population. Because cereals are the most important staple food, governments follow a strategy to become or to remain self-sufficient – especially in rice.
Tables 2 and 3 present some figures derived from national statistics collected by FAO (1994; 1995). These figures are reasonably accurate for the larger cropping areas of main cereals, but are less reliable for the minor cereals, especially those used for subsistence.

Table 1. Composition of cereals, pseudo-cereals and other food products per 100 g edible portion (dry matter basis) (Wu Leung & Flores, 1961; Wu Leung et al., 1972).

Food	Moisture (%)	Energy (kJ)	Carbohydrates (g)	Protein (g)	Fat (g)	Fibre (g)	Ash (g)
Cereals							
Barley							
whole grain	13.7	1586	83.2	12.2	2.4	2.9	2.2
Barnyard millet							
whole grain	11.1	1611	81.7	11.0	4.4	8.1	2.9
Finger millet							
whole grain	11.7	1573	88.6	7.0	1.6	1.4	2.8
Foxtail millet							
whole grain	11.3	1607	84.2	10.7	3.3	1.4	1.8
milled	12.5	1736	84.8	10.8	2.9	0.6	1.6
Job's tears							
whole grain, hulled	15.0	1506	76.4	14.1	7.9	0.9	1.6
Maize							
whole grain – yellow	13.6	1690	83.0	10.5	4.9	2.7	1.6
Pearl millet							
whole grain	11.0	1573	78.9	12.8	5.6	1.7	2.7
Proso millet							
milled	14.0	1720	84.4	12.3	1.7	0.9	1.4
Rice							
hulled grain	13.5	1711	87.7	8.8	2.1	0.8	1.3
milled, polished	11.8	1736	91.2	7.3	0.9	0.3	0.7
parboiled	12.4	1741	90.5	7.6	1.1	0.7	0.7
Rye							
whole grain	12.5	1598	80.5	14.6	3.0	2.2	1.9
Sorghum							
whole grain	12.0	1628	82.6	11.4	4.2	2.5	1.7
milled	14.3	1745	87.2	8.9	2.8	0.7	1.2
Wheat							
whole grain	12.5	1586	82.4	13.3	2.5	2.4	1.8
milled, 70% extraction	12.0	1728	84.9	13.0	1.4	0.3	0.7
Pseudo-cereals							
Buckwheat							
whole grain	11.3	1586	83.2	11.6	2.7	7.4	2.5
undermilled flour	12.0	1724	83.7	12.3	2.4	0.7	1.6
Grain amaranth							
whole grain	12.3	2006	74.2	14.7	8.2	7.6	2.9
Quinoa							
whole grain	11.0	1640	88.4	13.8	6.9	4.3	2.4
Various food products							
Amaranth							
leaves	89.3	1017	42.1	33.6	0.9	12.1	23.4
Cassava							
root	65.5	1636	93.9	2.9	0.6	2.9	2.6
Irish potato							
tuber	78.3	1582	86.2	9.2	0.5	1.8	4.1
Mung bean							
whole seed	10.6	1594	69.1	25.6	1.3	4.9	3.9
Soya bean							
whole seed	10.2	1862	35.6	39.1	19.7	4.7	5.6

Table 1. Continued.

Food	Ca (mg)	Fe (mg)	Vit.A (mg)	Vit.B_1 (mg)	Vit.B_2 (mg)	Niacin (mg)	Vit.C (mg)
Cereals							
Barley							
whole grain	58	7.0	0	0.36	0.12	6.0	0
Barnyard millet							
whole grain	46	4.8	0	0.37	0.11	4.5	0
Finger millet							
whole grain	?	6.0	0	0.37	0.11	1.5	0
Foxtail millet							
whole grain	37	6.2	0	0.48	0.14	2.5	0
milled	8	2.3	0	0.23	0.08	1.9	0
Job's tears							
whole grain, hulled	54	0.8	ø	0.48	0.10	2.7	0
Maize							
whole grain – yellow	16	3.2	0.3	0.34	0.13	2.4	0
Pearl millet							
whole grain	56	10.1	0	0.35	0.16	2.0	0
Proso millet							
milled	13	2.1	0	0.17	0.06	3.5	0
Rice							
hulled grain	18	3.2	0	0.39	0.08	5.8	0
milled, polished	27	2.2	0	0.11	0.06	2.4	0
parboiled	8	1.4	0	0.23	0.09	3.0	0
Rye							
whole grain	43	3.4	0	0.53	0.22	1.9	0
Sorghum							
whole grain	25	4.3	0	0.37	0.20	4.4	0
milled	20	4.2	0	0.12	0.03	3.5	0
Wheat							
whole grain	55	3.8	0	0.42	0.14	5.3	0
milled, 70% extraction	18	1.2	0	0.20	0.07	1.5	0
Pseudo-cereals							
Buckwheat							
whole grain	50	3.4	0	0.41	0.20	2.3	0
undermilled flour	25	3.2	0	0.34	0.11	1.7	0
Grain amaranth							
whole grain	282	3.8	0	0.16	0.36	1.1	0
Quinoa							
whole grain	128	5.3	0	0.15	0.43	1.2	0
Various food products							
Amaranth							
leaves	1439	27.1	61	0.37	2.05	6.5	215
Cassava							
root	75	2.6	0	0.14	0.12	1.7	99
Irish potato							
tuber	41	3.7	ø	0.46	0.18	7.4	83
Mung bean							
whole seed	117	7.9	0.1	0.59	0.29	2.8	4
Soya bean							
whole seed	252	9.5	ø	0.73	0.24	2.4	0

ø = trace

Table 2. Annual cereal production in 1979–1981 and 1994 in South-East Asia and in the world (FAO, 1995).

		Burma (Myanmar)	Cambodia	Indonesia	Laos	Malaysia
Area (× 1000 ha)						
Maize	1979–1981	128	87	2 761	29	7
	1994	180	49	3 040	38	21
Rice	1979–1981	4 684	1 154	9 063	722	722
	1994	6 477	1 700	10 646	639	665
Sorghum	1979–1981	•	•	•	•	•
	1994	•	•	•	•	•
Wheat	1979–1981	90	•	•	•	•
	1994	115	•	•	•	•
Millets	1979–1981	179	•	•	•	•
	1994	206	•	•	•	•
Others	1979–1981	52	•	•	•	•
	1994	37	•	•	•	•
Total	1979–1981	5 133	1 241	11 825	751	729
	1994	7 015	1 749	13 686	676	686
Production (× 1000 t)						
Maize	1979–1981	166	85	4 035	31	8
	1994	271	64	6 617	77	40
Rice	1979–1981	12 637	1 248	29 570	1 025	2 053
	1994	19 057	1 800	46 245	1 653	2 040
Sorghum	1979–1981	•	•	•	•	•
	1994	•	•	•	•	•
Wheat	1979–1981	83	•	•	•	•
	1994	109	•	•	•	•
Millets	1979–1981	80	•	•	•	•
	1994	156	•	•	•	•
Others	1979–1981	18	•	•	•	•
	1994	14	•	•	•	•
Total	1979–1981	12 984	1 334	33 605	1 056	2 061
	1994	19 607	1 864	52 862	1 730	2 080

The global average yield of cereals has increased tremendously during recent decades, from 2.19 to 2.83 t/ha. This is an increase of 29% in the period from 1979–1981 to 1994, and is mainly attributable to higher yields of paddy rice (which has risen from 2.74 to 3.65 t/ha), wheat (from 1.86 to 2.45 t/ha), and maize (from 3.34 to 4.33 t/ha). Yields of barley have increased considerably (from 1.90 to 2.19 t/ha), whereas sorghum (1.46 versus 1.39 t/ha) and millets (0.68 versus 0.69 t/ha) have remained at the same level. The increase in yield

Table 2. Continued.

	Papua New Guinea	Philippines	Thailand	Vietnam	South-East Asia	World
Area (× 1000 ha)						
Maize	1	3 267	1 412	383	8 075	125 636
	1	3 136	1 200	530	8 195	131 528
Rice	.	3 513	8 986	5 579	34 423	143 703
	.	3 350	8 482	6 500	38 459	146 452
Sorghum	1	11	220	3	235	44 891
	1	.	183	4	188	43 718
Wheat	.	.	.	.	90	234 891
	.	.	.	.	115	215 921
Millets	.	.	.	.	179	37 644
	.	.	.	.	206	37 710
Others	.	.	227	2	281	130 372
	.	.	199	4	240	113 817
Total	2	6 790	10 625	5 965	43 060	717 137
	2	6 486	9 881	7 034	47 215	689 146
Production (× 1000 t)						
Maize	1	3 174	3 103	410	11 013	420 408
	2	5 400	3 800	950	17 221	569 557
Rice	1	7 747	16 967	11 808	83 056	393 949
	1	10 150	18 447	22 500	121 893	534 701
Sorghum	2	20	237	3	262	65 525
	1	.	300	5	306	60 951
Wheat	.	.	.	.	83	437 543
	.	.	1	.	110	527 982
Millets	.	.	.	.	80	25 465
	.	.	.	.	156	25 982
Others	.	.	246	4	268	230 447
	.	.	328	5	347	231 426
Total	4	10 942	20 316	12 222	94 524	1 573 337
	3	15 550	22 576	23 455	139 727	1 950 599

undoubtedly reflects the research efforts and the increased area planted with improved cultivars.

Table 2 shows that there was a large increase in production in South-East Asian countries between 1979–1981 and 1994.

The total population of the 9 South-East Asian countries increased from 360 million in 1980 to 476 million in 1994 (a 32% increase). During this period, annual cereal production rose from 95 million t to 140 million t (an increase of

48%), the harvested cereal area increased from 43.1 million ha to 47.2 million ha (an increase of 9.2%), and the yield rose from 2.20 to 2.96 t/ha (an increase of 35%). In spite of the extremely rapid population growth in South-East Asia, the overall effect is a significant improvement of the general food situation: the annual per capita availability of cereals increased from 263 kg in 1980 to 293 kg in 1994. These figures are not solely related to direct human consumption in South-East Asia; probably around 10% are used for other purposes. Part of the production is exported outside the region, an important portion is used for feed and industrial use, and a minor part is saved for seed.

Rice is by far the leading cereal in South-East Asia. Other cereals are mostly planted as secondary food crops or used for feed or industrial purposes. The average yield of paddy rice for all South-East Asian countries is 3.06 t/ha, which is 15% below the world average. The highest score is for Indonesia (4.34 t/ha), the lowest is for Cambodia (1.06 t/ha).

Maize is the second most important cereal, covering only about 20% of the area under rice. Indonesia, the Philippines and Thailand are major producers, whereas Vietnam and Burma (Myanmar) also produce a considerable amount. Maize is often planted as a secondary crop after rice, or as the main cereal crop where irrigated rice cannot be grown. About 20% of the production is used for animal feed, and the demand for feed is still increasing. The average yield of maize for all South-East Asian countries is 2.10 t/ha, which is 51% below the world average. The highest score is for Thailand (3.17 t/ha), the lowest for Cambodia (1.32 t/ha).

Sorghum is an important crop in Thailand, but is rather insignificant in the rest of South-East Asia. It is eaten mixed with rice or replaces rice in times of food shortage, but its more important uses are as feed and raw material.

Wheat, globally the leading cereal, is a minor crop in South-East Asia, although it is rather important in Burma (Myanmar). It is grown on small areas in the north of Thailand and in North Vietnam. The major constraints to wheat production in the region are climatic conditions and disease problems resulting from high relative humidity.

Burma (Myanmar) is the only South-East Asian country producing millets to a reasonable extent. Barley is grown on a very small scale in Thailand. These cereals have little economic importance in other countries in the region. Minor cereals and pseudo-cereals are generally not recorded in the statistics. They may be cultivated solely by certain ethnic groups, mainly for subsistence.

Cereal production in Burma (Myanmar) increased from about 13 million t in 1979–1981 to 19.6 million t in 1994. Rice is the dominant crop, but maize, wheat, millets and other cereals are becoming increasingly important. The only cereals Burma (Myanmar) imports are wheat and flour (in relatively small amounts). Rice is an important export commodity.

The harvested areas of rice in Cambodia and Laos in 1994 were respectively about 1.7 and 0.6 million ha, with production being 1.8 and 1.6 million t respectively. Import of cereals in Laos (mainly rice) had fallen to about 8000 t by 1993, while in Cambodia it had increased to 106 000 t by that year.

Indonesia became self-sufficient in rice in 1984; however, in some years there is a relatively modest shortage. The country imports an increasing amount of wheat and wheat-flour mixtures, totalling 2.6 million t in 1993. With a yield of 2.6 t/ha, a cropping area of about 1 million ha would be needed to meet the de-

Table 3. Imports and exports of cereals in 1993 in South-East Asia (FAO, 1994).

	Burma (Myanmar)	Cambodia	Indonesia	Laos	Malaysia	Papua New Guinea	Philippines	Thailand	Vietnam	South-East Asia
Imports (× 1000 t)										
Barley	.	.	.	.	1	.	5	8	.	14
Maize	.	.	494	.	1 797	3	1	9	1	2 305
Rice	.	84	24	4	389	120	202	.	1	824
Wheat + flour[1)]	.	22	2 583	4	1 096	102	1 825	617	288	6 537
Others	.	.	3	.	2	3	1	4	.	12
Total	.	106	3 105	8	3 285	227	2 036	638	289	9 695
Imports (× 1 000 000 US$)										
Barley	.	.	.	.	0.2	.	0.9	2.1	.	3.1
Maize	.	.	68.0	.	222.5	0.6	0.4	2.2	1.2	294.9
Rice	.	25.0	72.0	1.2	109.9	36.0	37.1	.	0.2	281.5
Wheat + flour[1)]	.	4.8	449.6	1.9	185.0	15.3	303.6	118.5	44.6	1 123.1
Others	.	.	0.8	.	0.6	0.4	0.2	2.1	.	4.0
Total	.	29.8	525.6	3.0	518.7	52.3	342.8	124.8	46.0	1 643.0
Exports (× 1000 t)										
Barley	.	.	.	.	ø	.	.	ø	.	ø
Maize	40	5	61	.	4	.	x)	213	70	393
Rice	209	.	351	.	.	.	.	4 989	1 765	7 313
Wheat + flour[1)]	.	.	.	.	99	.	.	9	.	108
Others	.	.	ø	.	.	.	ø	15	.	15
Total	250	5	412	.	103	.	x)	5 226	1 835	7 830
Exports (× 1 000 000 US$)										
Barley	.	.	.	.	0.1	.	.	ø	.	0.1
Maize	4.6	0.5	7.9	.	0.6	.	0.5	28.4	7.7	50.3
Rice	38.3	.	57.8	.	.	.	ø	1 301.7	318.0	1 715.9
Wheat + flour[1)]	.	.	.	.	15.6	.	.	2.3	.	17.9
Others	.	.	ø	.	.	.	ø	5.6	.	5.6
Total	42.9	0.5	65.8	.	16.3	.	0.5	1 338.1	325.7	1 789.8

[1)] flour in wheat equivalents; x) no data; ø quantity smaller than unit.

mand! Recent Indonesian studies have shown that East Timor has potential for wheat cultivation. The import of maize for feed is increasing. There is a minor import of barley for breweries.

Total cereal production in Malaysia, which is completely dominated by rice, remained stagnant at about 2.1 million t from 1979–1981 to 1994. However, imports of wheat, maize and other grains are steadily increasing.

Papua New Guinea hardly produces any cereals for domestic consumption; it relies on imports.
Cereal production in the Philippines increased from about 10.9 million t in 1979–1981 to 15.6 million t in 1994. Small amounts of cereals were exported, but wheat and wheat-flour mixtures were imported at an increasing rate.
Rice has traditionally been an export commodity of Thailand. Its production increased slightly from 17.0 million t in 1979–1981 to about 18.4 million t in 1994. The cultivated area has decreased but yields have increased. Cereal production as a whole increased from 20.3 million t to 22.6 million t in the same period. Thailand's total rice exports in 1993 were about 5 million t, valued at US$ 1300 million. Thailand also exports a considerable quantity of maize. Similar to other South-East Asian countries, Thailand's import of wheat and wheat-flour mixtures has sharply increased.
In Vietnam, rice production increased sharply from about 12 million t in 1979–1981 to 22.5 million t in 1994. Vietnam has become a rice exporter in recent years, but its wheat imports are increasing.

1.3 Botany

1.3.1 Taxonomy

All true cereals are monocotyledons belonging to the *Gramineae*, the grasses, one of the largest plant families with about 650 genera and 10 000 species. *Gramineae* are distinguishable from other families by their typical long and narrow leaves alternating in two opposite vertical rows, their cylindrical stems (culms) with conspicuous nodes and their internodes which are hollow or filled with soft tissue. The inflorescence is usually terminal on the culm and its basic units are termed spikelets (functionally comparable to the flowers of other families).
The classification of the grasses has not yet been agreed and no wholly satisfactory overall account is available. At present the family is subdivided into 6 subfamilies with 40 tribes. Important characters for classification are the spikelet structure, the internal leaf anatomy, the photosynthetic metabolism, the basic chromosome number and the embryo structure. The currently widest accepted classification of the cereals described here is summarized in Table 4.

1.3.2 Morphology (see Figures 2 and 3)

Cereals are tufted, annual herbs with erect stems (culms). Usually several erect branches (tillers) arise from the axils of leaves at the base of the stem and behave ultimately like true stems.
Seminal roots arise from the germinating embryo but are very soon replaced by an adventitious nodal root system that arises from the culms and tillers. The roots are fibrous and usually penetrate 1–2 m into the soil. Maize also has stout prop roots arising from the lower nodes above the soil surface.
The stem is cylindrical, with elongated, usually hollow internodes (but pith-filled in maize and sorghum), connected by short, harder, disc-shaped solid nodes that look very different from the internodes and from which the buds and leaves originate. The lower internodes usually remain very short. The in-

Table 4. Classification of the true cereals (Clayton & Renvoize, 1986).

Family *Gramineae*

Subfamily	Tribe	Subtribe	Genus (approx. number of species)	Species
Bambusoideae	*Oryzeae*		*Hygroryza* (1)	*H. aristata*
			Oryza (20)	*O. sativa*
			Zizania (3)	*Z. palustris*
Chloridoideae	*Eragrostideae*	*Eleusininae*	*Eleusine* (9)	*E. coracana*
			Eragrostis (350)	*E. tef*
Panicoideae	*Andropogoneae*	*Coicinae*	*Coix* (5)	*C. lacryma-jobi*
		Digitariinae	*Digitaria* (230)	*D. cruciata*
				D. exilis
		Sorghinae	*Sorghum* (20)	*S. bicolor*
				S. propinquum
		Tripsacinae	*Zea* (4)	*Z. mays*
	Paniceae	*Cenchrinae*	*Pennisetum* (80)	*P. glaucum*
		Setariinae	*Brachiaria* (100)	*B. ramosa*
			Echinochloa (35)	*E. colona*
				E. crus-galli
			Panicum (470)	*P. miliaceum*
				P. sumatrense
			Setaria (100)	*S. italica*
Pooideae	*Triticeae*		*Hordeum* (40)	*H. vulgare*
			Secale (4)	*S. cereale*
			Triticum (15)	*T. aestivum*
				T. turgidum

ternodes have a soft meristematic zone immediately above the nodes which has the important function of bending the stem upright again by differential growth when the plant has lodged because of rain or trampling.

The leaves are arranged in two rows along the stem and consist of a sheath, a ligule and a blade. The sheath clasps the stem tightly and gives mechanical support to the meristematic zone of the internode. At its upper end the sheath passes into a parallel-veined, typically long and narrow blade, which also has a meristematic zone at its base permitting it to continue its growth despite the removal of its distal parts by e.g. grazing or cutting. A short membranous or ciliate rim, the ligule, is present at the junction of sheath and blade. Its function might be to prevent rain entering the sheath. The base of the blade or the top of the sheath often bears auricles (ear- or teeth-like appendages).

The inflorescence is a specialized leafless branch system, which usually terminates the stem. Morphologically, its basic units, called spikelets, are partial inflorescences, but functionally they can be compared with the flowers of petaloid plants. The spikelets are arranged in various ways, ranging from a single spike or raceme through an intermediate stage of several spikes arranged digitately or along an axis to a many-branched panicle. The spikelet structure is essential for the identification of grasses; on the outside two opposite rows of scales are

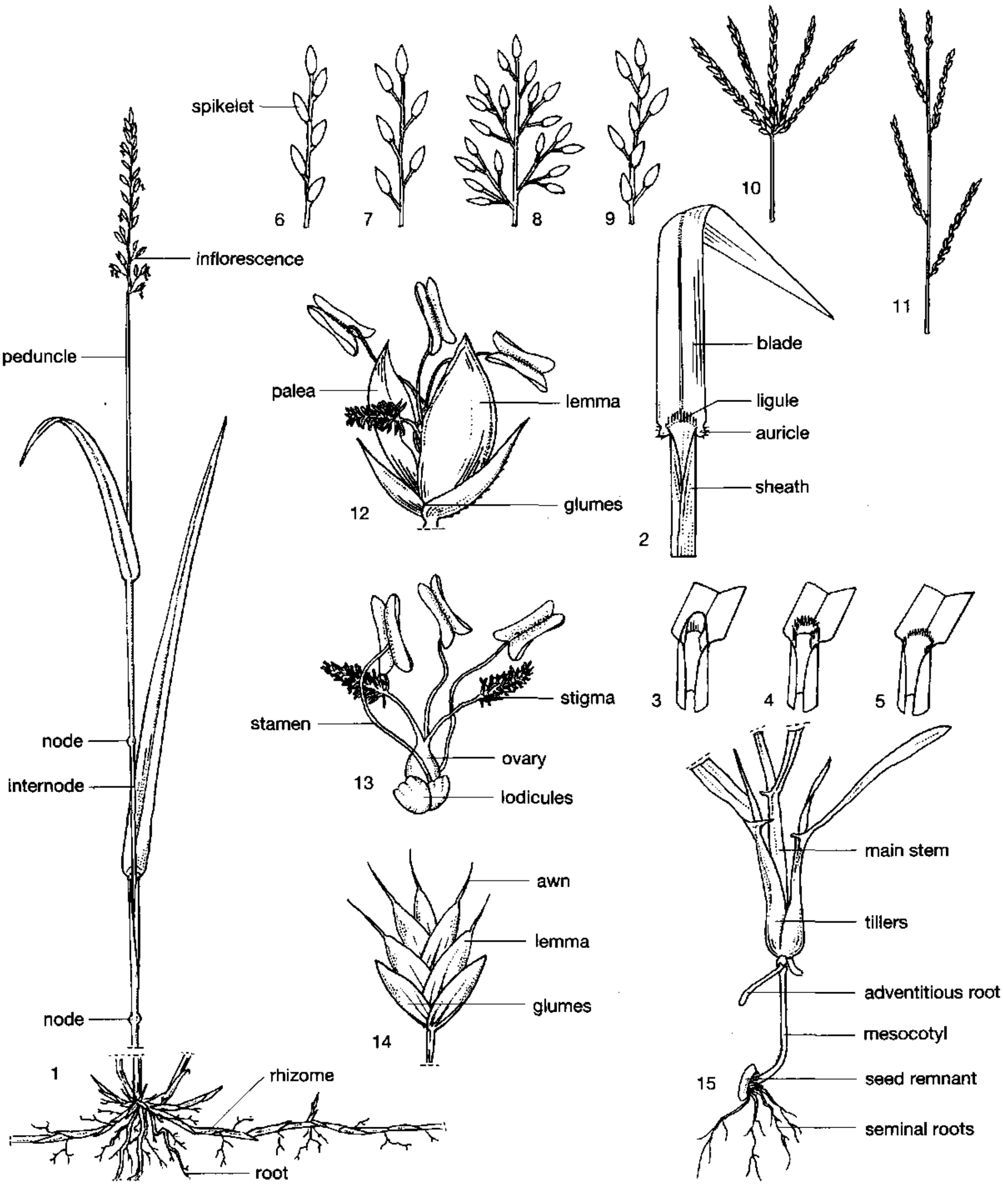


Figure 2. Grass morphology – 1, habit; 2, leaf; 3, membranous truncate ligule; 4, membranous fringed ligule; 5, ligule consisting of ring of hairs; 6, spike; 7, raceme; 8, panicle; 9, spike-like raceme; 10, digitately arranged spikes; 11, racemose inflorescence of spikes; 12, single-flowered spikelet; 13, floret (lemma and palea removed); 14, five-flowered spikelet; 15, young plant with tillers.

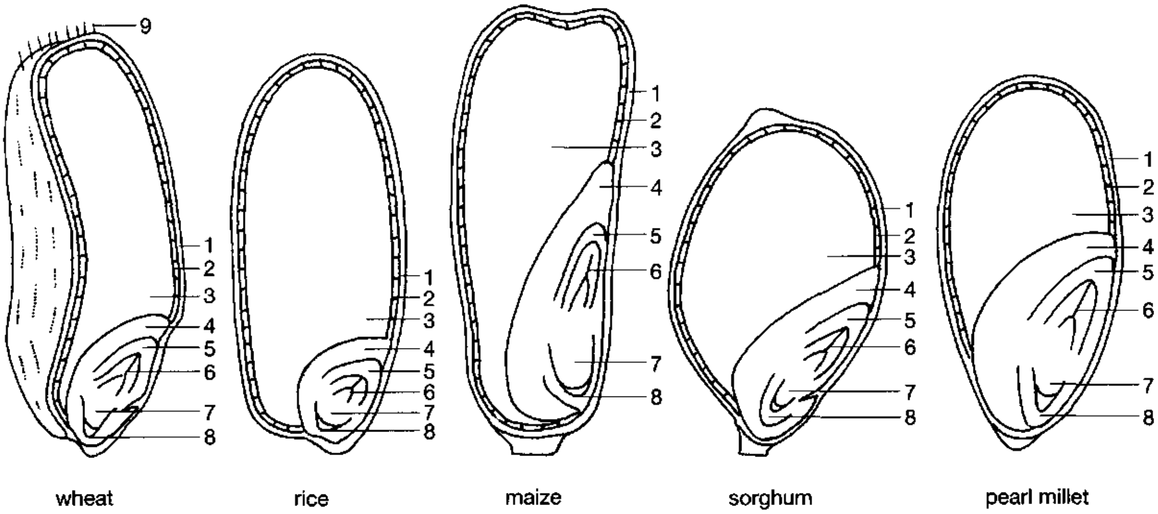


Figure 3. Schematic cross-section through five cereal grains – 1, fused fruit wall (pericarp) and seed coat (testa); 2, aleurone layer; 3, endosperm; 4, scutellum; 5, coleoptile; 6, plumule; 7, radicula; 8, coleorhiza; 9, brush.

visible, arranged alternately along an axis (rachilla); the two lower scales, the glumes, are empty, but the remainder form part of a floret, whose floral parts are enclosed by the lemma on the outside and a delicate membranous scale, the palea, on the inside; glumes and lemmas often terminate in one or more long stiff bristles termed awns; the floral parts consist of two or three tiny scales, the lodicules (they have a function in opening the floret by their ability to swell), three stamens (6 in rice) each with a delicate filament and a 2-celled versatile anther and a pistil consisting of a superior single-loculed ovary with a single ovule and 2 styles, each ending in a feathery stigma. This basic pattern of a spikelet structure may be modified by reduction, suppression or elaboration. Bisexual spikelets are the rule, although some of their florets are often unisexual or barren. Separate male and female spikelets are occasionally borne on the same plant, rarely on separate plants. The florets open for only a few hours to expose the sexual organs to wind pollination. Cross pollination is usually ensured by protandry; the pollen is viable for less than a day.

The fruit (grain) is usually a caryopsis, with a thin pericarp adhering firmly to the seed; sometimes it is a utricle (with free soft pericarp), e.g. in finger millet, or an achene (with free hard pericarp). The fruit is surrounded by the husk, which consists of the hardened palea and lemma. The husk of wheat, maize, millet and some sorghum types is easily removed by threshing, but the husk of barley and rice is tenacious and is traditionally removed by pounding and winnowing (nowadays by machine). The outer layers of the caryopsis are (beginning at the outside): the outer and inner pericarps (derived from the ovary), the true seed coat or testa and a protein-rich aleurone layer.

The seed consists of an embryo at the base of the abaxial face and a starchy endosperm. The embryo is peculiar, with no homologue among the angiosperms; it has a flat haustorial cotyledon (the scutellum) and a special outer sheath (the coleoptile) protecting the plumule during soil penetration.

1.3.3 Growth and development

Stages of growth and development

Unlike the cultivation of root and tuber crops or vegetables, cereal production implies completing the whole life cycle from seed to seed. The following is a practical subdivision of the life cycle in externally visible growth stages:
- vegetative phase: leaf initiation, tillering, flower initiation;
- reproductive phase: stem elongation, spikelet and floral development, anthesis;
- ripening phase: grain filling, grain ripening.

Standardized development stages of the leading cereal crops have been defined on the basis of visual observations. For rice a scale is used in which the development stages of photoperiod-sensitive rice are defined, including a time range adaptable to cultivar and location (Stansel, 1975). The Decimal Code (Zadoks et al., 1974) is widely applied to most cereals, including transplanted rice, but not yet to maize and sorghum. Crop development is divided into 10 stages, each of which is subdivided into a maximum of 10 steps (Table 5). When observing a plant population, the criterion for assigning it to a certain stage is that more than 50% of the individual plants show the characteristic in question.

During the vegetative phase, tillering is of paramount importance, as it is the natural mechanism enabling individual plants to correct for suboptimal planting density, in order to attain an optimal crop canopy. Tillers produce fewer leaves than the main stem, and this tends to synchronize their development with that of the main shoot. The number of tillers further depends on species and cultivar; and increases with applications of nitrogen-rich fertilizer and shallow sowing. Modern maize cultivars have no or very few tillers; therefore, the crop has no buffer for correcting poor emergence and thus correct sowing density is crucial.

The real start of the reproductive phase (inflorescence initiation in the apex which is still at ground level) can only be observed by studying the apex, split lengthwise, under the microscope (Kirby & Appleyard, 1981). In most cereals meiosis takes place during booting (Decimal Code 41), but in rice meiosis occurs earlier (Decimal Code 39). Environmental stress during inflorescence initiation or during meiosis easily leads to a serious reduction of yield. Anthesis may last one to three weeks for the whole crop of a self- or cross-pollinating cereal.

The transport of assimilates to the grain ceases when the dry matter content

Table 5. The Decimal Code for cereal development stages (Zadoks et al., 1974; Wibberley, 1989).

Stages	Observations
0 germination	
00 dry seed	
01 start of imbibition	
05 radicle emerged from caryopsis	
07 coleoptile emerged from caryopsis	coleoptile elongates to bring crown just beneath the soil surface
09 leaf just at coleoptile tip	field emergence: coleoptile appears above earth

Table 5. Continued.

Stages	Observations
1 seedling growth	
10 first leaf through coleoptile	apex at ground level; spikelet ridges begin to develop above the upper leaf ridges
11 first leaf unfolded	ligule visible
12 2 leaves unfolded	
19 9 or more leaves unfolded	
2 tillering	
20 main shoot only	
21 one tiller	secondary tillers develop from primary tillers
29 9 or more tillers	
3 stem elongation	
30 pseudostem (leaf sheath) erection	in rice: vegetative lag phase
31 first node detectable (above ground)	stage 31 is used as indicator for the terminal spikelet stage
36 6th node detectable	
37 flag leaf just visible	
39 flag ligule just visible	opposite auricle stage in rice
4 booting	
41 flag leaf sheath extending	superfluous tillers perish
43 boots just visibly swollen	mid-boot stage
47 flag leaf sheath opening	
5 inflorescence emergence	
51 first spikelet visible	
59 emergence of inflorescence completed	
6 anthesis (flowering)	
61 beginning of anthesis	in rice: usually immediately following heading
69 anthesis complete	
7 milk development	
71 caryopsis water-ripe	
73 early milk-ripe grain on full size	increase in solids of liquid endosperm
77 late milk-ripe	
8 dough development	
83 early dough ripe	rapid increase of dry matter
87 hard dough	inflorescence loses chlorophyll
9 ripening	
91 caryopsis hard	
92 caryopsis hard	harvest-ripe (caryopsis can no longer be dented by thumbnail; in rice: over 90% of spikelets ripened)
93 caryopsis loosening in daytime	
94 crop overmature	straw dead and collapsing
95 seed dormant	
96 viable seed giving 50% germination	
97 seed not dormant	
99 secondary seed dormancy lost	

reaches about 60%. This is the start of the ripening phase. Harvest-ripe seed (Decimal Code 92) has a dry matter content of 80–90%. Mature seed, well dried in the field to a moisture content below 14%, will germinate easily when wetted by rain. Some cereals have a short dormancy period: indica rice 1–3 months, some millets a few weeks, sorghum 1–4 weeks.

Source–sink relationships

The leaf canopy is the driving force for interception of solar energy (the source), while a sufficient number of panicles must provide the storage capacity for the assimilates (the sink). Variation in rate and extent of canopy development, expressed as Leaf Area Index (LAI), is one of the main causes of yield variation. Canopy development and decline during the life cycle of a crop are strongly influenced by environmental factors (temperature) and the availability of water and mineral nutrients. The green leaf area including the green inflorescence are the 'source' of the flow of assimilates to the 'sinks'. Substantial amounts of assimilates have already been stored in the stem and leaf-sheaths before and during anthesis. Grain filling can continue to some extent under adverse conditions because of the translocation of these reserves. Stems and leaf-sheaths are an additional source of reserves for the main sink, the grain. Under normal conditions, these stored reserves also gradually flow to the maturing grain and continue to do so after the leaves senesce. Nitrogen, an important nutrient for achieving a high protein content in the grain, is mainly taken up before anthesis.
Understanding the source–sink relationships is helpful to overcome imbalance in yield-determining factors, and consequently to ensure good grain yield. The grain yield may be either source-limited or sink-limited. When it is source-limited, increased availability of assimilates results in higher yields, indirectly by an improved build-up of plant parts, directly by a better grain filling. Source–sink relationships between all plant parts exist throughout the plant's lifetime, starting with the germinating seed which functions as source for the young shoot and radicle. Higher yields are obtained by reducing all possible constraints to source and sink functions.

Yield-determining factors

Agronomists use the following simple formula to analyse grain yield:
grain yield (g/m^2) = plant density ($plants/m^2$) $\times$ inflorescences per plant $\times$ grains per inflorescence $\times$ mean grain weight (g).
Plant density and number of well-developed inflorescences per plant are inversely related. The inflorescence may be divided further into the number of spikelets per inflorescence and florets per spikelet. The number of florets per spikelet is usually rather stable (in wheat: up to 9), but only a small proportion of the florets are fertile (in wheat: 2–5). The average weight of grain varies greatly, and is a function of the total quantity of assimilates transported to the grains and the number of $grains/m^2$.
The potential yield of a grain crop depends on its capacity to use incident solar radiation for the production of grain. The potential grain yield (Y) is determined by the following parameters (Hay & Walker, 1989):

$Y = Q \times I \times \varepsilon \times H$

Q = quantity of incident solar energy over the crop period. Depends on daylength and weather, varies with latitude, season and region.
I = intercepted fraction of Q. Depends on leaf area and morphological characteristics (canopy structure) that determine light extinction. In practice, this factor is a major cause of yield variation.
ε = efficiency of conversion of radiant into chemical energy, expressed as dry matter produced per unit of intercepted radiation. A high ε is an interesting target for breeders.
H = harvest index, i.e. harvested (useful) product as a fraction of total (aboveground) dry matter.

Modern cereal cultivars have medium-short, stiff straw to withstand lodging and to tolerate high nitrogen gifts, and an adequate canopy structure to maximize light interception. They have a high yield potential, translated into increased total dry matter production, more inflorescences per unit land, larger inflorescences, improved floret survival, and heavier grains. An example is the yield of winter wheat cultivars in western Europe. The long-straw wheat cultivars dating from before 1900 had a harvest index of only 35% and yields of about 2 t/ha. At present, the best farmers achieve grain yields of about 10.5 t/ha with a harvest index slightly above 50%.
How far can the genetic yield potential be raised? It seems possible to further increase the harvest index (H), thus the potential yield, to some extent, but not by a spectacular amount. Consequently, there seems little scope for further genetic improvement of the yield capacity of cereals. However, yield can be increased dramatically by improved cultural practices.
Another question is whether root and tuber crops surpass cereals in energy capture. The total dry matter production of these two types of food crops is very similar, but the root and tuber crops have the potential to produce a much larger amount of edible dry matter per ha and per day than cereals because of their favourable harvest index (up to 80%). However, the gap between this yield potential and the yield realized on the farm is larger than for cereals, the main reason being a lack of dissemination of research results. At present, average world yields (edible portion) of rice and maize in terms of energy per ha per day are superior to cassava (*Manihot esculenta* Crantz) and yams (*Dioscorea* spp.). Only sweet potato (*Ipomoea batatas* (L.) Lamk) appears superior to cereals (de Vries et al., 1967). The advantage of cereals over non-cereal energy crops is not their yield of edible energy per crop, but the fact that a moderate energy yield may be secured in a relatively short cropping period, and that cereal grain can easily be stored due to its compactness. Moreover, several ecological and socio-economic factors such as climate, soil, irrigation water, need for labour and inputs (fossil energy), suitability for mechanization, food habits and possibilities for marketing influence the choice between a cereal crop and a root or tuber crop.

1.4 Ecology

Cereals are grown in all regions of South-East Asia, under conditions varying greatly in climate and soil. These ecological conditions have been studied extensively, mainly for the three leading crops rice, maize and wheat. Temperature, incident radiation and daylength are important site-specific factors determining the potential yield, i.e. the yield realized when growth-limiting factors (water, nutrients) are optimal and growth-reducing factors (diseases, pests) are absent. The potential yield is reduced to the attainable yield under the prevailing suboptimal supply of growth-limiting resources (water, nutrients), but in the absence of growth-reducing factors. The attainable yield is reduced to the actual yield by biotic (diseases, pests) and abiotic (soil pollutants, extreme weather) growth-reducing factors.

1.4.1 Climatic factors

Temperature

Seasonal temperatures tip the scale in demarcating which cereal can be grown in a certain area or season, and are the main constraint to the further expansion of cereals to lower or higher latitudes and altitudes. Air and soil temperature, and for rice the temperature of the irrigation water, affect the total cropping period as well as all the growth processes from germination to grain filling. High temperatures generally promote flowering and low temperatures delay flowering. Critical and optimal temperature values for all main cereals have been thoroughly studied, especially for rice, wheat and maize. These values vary with the cultivar and the plant development stage. The optimum day temperature range for maize is 21–30°C, for rice it is 20–35°C. These values are much lower for cereals grown in the temperate areas: 10–24°C for wheat, 10–25°C for rye. It is well known that in temperate areas the highest cereal yields are obtained when ripening coincides with declining temperatures. This effect is attributed to the extension of the grain-filling period. Also, at least for wheat, cool temperatures are favourable for the total quantity of carbohydrates transported to the grain and – vice versa – extreme high temperatures will shorten the grain-filling period and thus diminish the mean kernel weight. The harvest index is negatively influenced by higher temperatures. Low soil temperatures retard germination and emergence, giving pathogens more chance to cause seedling death.

The symptoms of cold injury are similar for all cereals: loss of vigour, slow and stunted growth, leaf discolouration, reduced tillering, leaf senescence, irregular heading, increased susceptibility to diseases, incomplete panicles, sterility, degeneration of spikelets, late maturation, low yield, shrivelled seed and inferior grain quality. Cold injury is a common cause of low yields. Sterility is mainly due to cold injury during booting and anthesis. In rice it has frequently been observed at higher elevations in South-East Asian countries. Local landraces in Java, however, seem to be adapted to highland conditions.

High temperatures during anthesis also cause injury resulting in sterility of the spikelet. The range of minimum–optimum–maximum temperatures during meiosis is 11–33–41°C for rice and 9–33–42°C for maize (Goldsworthy & Fisher, 1984).

A common index to quantify the influence of temperature on cereals is 'growing degree-days' (GDD), i.e. the cumulated daily mean temperatures above a certain zero-growth base temperature. This base temperature is low for cereals with a C3-cycle photosynthetic pathway (e.g. 2.6°C for wheat) and high for C4-cycle cereals (e.g. 9.8°C for maize, 11.8°C for pearl millet) (Jones, 1985).

Radiation

Although the light is more intense in the tropical zone, the daily useful photosynthetic period is longer during summer months in temperate areas and in the subtropics. Hence potential and attainable yields during summer in temperate and subtropical areas are 10–25% higher than in the tropics. Large regional and seasonal fluctuations exist due to cloudiness. This explains why yields of irrigated crops during the dry season tend to be 10–20% higher than yields during the wet season.
In the early stages of leaf area expansion, both leaf area index (LAI) and crop dry matter increase exponentially. Once a young crop reaches a leaf area index of about 5 and maximum light interception is attained, crop photosynthesis does not increase any further, hence the growth rate is constant and linear. In this phase the biomass of a healthy and vigorous cereal crop will increase by 150 to 200 kg/ha/day (Lövenstein et al., 1992).
The maximum energy utilization of a full-grown canopy of wheat and rice, both with a C3-cycle photosynthetic pathway, is estimated to be 6% (Hay & Walker, 1989). The photosynthesis of maize, sorghum, and millets, and of the pseudo-cereal amaranth follows a C4-cycle pathway, characterized by a higher light saturation point and by lower respiration losses than C3-cycle plants. Maximum utilization of energy measured on C4-cycle crops reaches values up to 8.9%. In contrast to C4-cycle plants, C3-cycle plants (rice, wheat, barley, quinoa, buckwheat) suffer from high carbohydrate losses due to high photorespiration at high temperatures. In general, C4-cycle plants are more adapted to hot climates with high light intensities than C3-cycle plants (Jones, 1985).
The utilization of photosynthetic active radiation (PAR) during the crop cycle is subject to many limiting factors such as below-maximum leaf area, extreme low or high temperatures, water deficit, poor soils and poor crop management. This may lead to values between 2–4%, while the average daily radiation in itself is limited due to cloudy weather and/or short daylength. A value of LAI 4–5 is needed for maximum interception of PAR, but this varies greatly between species and cultivars. LAI often increases to values well over 4 during crop growth but then declines below 3 due to leaf senescence and diseases.

Daylength

Photoperiodic daylength is the interval between civil twilight before sunrise and civil twilight after sunset. At the equator, daylength hardly varies during the year. At 10°N (southern parts of the Philippines, Thailand and Vietnam) it varies from about 11.30–12.40 hours and at 20°N (northern parts of the Philippines, Thailand and Vietnam) from about 10.50–13.20 hours. All cereal crops exhibit a more or less pronounced photoperiodic response, i.e. the daylength influences the time span of the vegetative period from germination to anthesis. Local cereal cultivars show a photoperiodic response that fits the latitude and growing season. Near the equator only short-day cultivars are usually found. At higher latitudes the local cultivars cultivated during the summer require longer days, while those used for winter cultivation may be either long or short-day. Traditional rice cultivars in South-East Asia are short-day crops; long days delay flowering and prolong the total cropping period. In some cases a long-day reaction may be an advantage, since late-maturing cultivars often outyield early-maturing ones. Many modern cereal cultivars for tropical and subtropical areas are almost daylength insensitive, which makes them in principle suitable for a wider geographical area. Another advantage is that the farmer can plant them at any moment of the year when temperature and water availability are suitable, without much variation in crop duration.

Under natural conditions the photoperiodic sensitivity serves as a mechanism to achieve crop growth during a period of peak water availability, with grain maturation during a dry period. In the northern part of South-East Asia, long-day maize cultivars are sown at long intervals at the beginning of the rainy season. All these fields will flower and mature in a short time span at the end of the rainy season.

Water

Under the climatic conditions of South-East Asia, the potential evapo-transpiration (ETP) is in the range of 4–8 mm/day (4–8 l/m^2/day). Important factors determining ETP are soil structure, texture and moisture content, soil cover, crop type and stage, and canopy development. The total water requirement mainly depends on environmental conditions, crop type and growth stage. Because of the difference in photosynthetically active leaf area, a full-grown cereal crop needs more water than during the juvenile stage or at maturation.

Soil moisture may be supplied exclusively by rain, by irrigation alone or by rain water supplemented with irrigation. Cereals can cope with a range of soil moisture conditions. Their roots penetrating to a depth of 1–2 m are capable of extracting water from saturated soils to soils near wilting point. Pearl millet is especially noted for its dense root system and high root suction potential. Although moisture stress at any time may reduce yields, cereals do have certain critical periods in which they are extremely sensitive to drought. Early moisture stress hampers germination and tillering. Maize is very sensitive during anthesis and in the period of grain filling up to the milky stage. Rice is most sensitive during anthesis and the milk development stage; sorghum is very sensitive during ear emergence and during flowering and seed formation (Doorenbos & Pruitt, 1984). Rainfed cereals often fail to establish after a small shower which is sufficient to initiate germination but not enough to sustain the seedlings.

The water use of a crop is also strongly associated with its photosynthetic pattern. The water-use efficiency (water used per g dry matter produced) is around 500 g for barley and 700 g for rice (both C3-cycle cereals) but is only 280 g for pearl millet and 350 g for maize and sorghum (all C4-cycle cereals). The lower water use of C4-cycle plants makes them more suitable for drier areas.

The ability to withstand drought differs among cultivars. Drought resistance is based on plant characteristics such as earliness and the development of a deep rooting system. Drought-resistant cultivars are extremely important for regions with unreliable rainfall and lack of irrigation. On the other hand, soil drainage should be adequate. All cereals except rice are rather sensitive to wa-

terlogging. Flooding for some days or even some hours may cause wilting, root rot or other irreversible damage.
Ideally, a dry period is needed to facilitate the harvest of a cereal crop. Yet rice and maize have become important food crops even in the year-round per-humid equatorial zone of Sumatra and Kalimantan.

1.4.2 Soil factors

Cereal crops are traditionally grown on a wide range of soils varying from heavy clay to light sandy loams, as long as the nutrient and water requirements of the crops can be met. Cereals differ in their adaptation to specific soil types. Maize and wheat are rather sensitive to salinity, whereas rice and barley are more tolerant. Millets are grown on less fertile soils with low precipitation because of their ability to give a reasonable yield when other cereals fail. Rice is a marshy plant for which the physical soil conditions are not so important.
Cereals thrive at pH values from 5.5–7.0. Many soils in South-East Asia are very acid, with a pH-H_2O below 5.0, inducing toxicity of Al, Fe and Mn. These soils are often low in available P or liable to P fixation, and low in K, Mg and S. Their nutrient storage capacity is low, necessitating fertilizer application to be split between several dressings. Liming is recommended to raise the pH to at least 5.5.
The soil fertility of land submerged for rice production is strongly influenced by the anaerobic conditions. Major chemical changes take place which have a large influence on soil nutrient transformations and availability. The pH tends to be neutral, the supply of N, P, Si and Mo is improved, but Zn and Cu availability decreases, whereas reduction products like methane and hydrogen sulphide may reach toxic levels.
Erosion is a main cause of declining cereal yields. Cereal fields in the heavy rainfall areas of South-East Asia are very erosion-prone.

1.5 Agronomy

1.5.1 Production systems

From shifting cultivation to permanent cropping systems

Shifting cultivation is still practised in some provinces of Indonesia (Kalimantan, Irian Jaya), Vietnam and the Philippines, mainly with upland rice and maize. Cereals and pseudo-cereals of minor economic importance but vital for subsistence, such as sorghum, millet, Job's tears and buckwheat are also produced in this traditional system. Although the area under shifting cultivation still amounts to several million ha, it only accounts for a minor percentage of the total cereal production.
Permanent cropping instead of shifting cultivation has been practised for thousands of years. The planting of irrigated rice on terraces was a milestone in agricultural development. Better tools, the introduction of animal traction, the use of farmyard manure or chemical fertilizers, improved seed, disease and pest control measures, timing of planting, improved grain storage, crop rota-

tion, all elements of crop husbandry in optimal combination help make the system more productive. Increased demand for food from the steadily increasing population drives farmers to intensify their use of external inputs. However, the increased use of agro-chemicals, in South-East Asia mainly insecticides on rice and N fertilizers on rice and maize, is jeopardizing the sustainability of the system and bringing about soil and water pollution.

Rice-based cropping systems

Rice-based cropping systems are often classified according to the water supply of the rice crop as:
- lowland rice grown on irrigated land,
- lowland rice grown on flooded land (rainfed),
- upland rice grown as a rainfed crop,
- deep-water rice (floating rice) grown in areas of deep flooding (up to 5 m or more).

In literature the terms 'lowland rice' versus 'upland rice' are commonly used to indicate irrigated or flooded versus rainfed, non-irrigated and non-flooded cultivation. Some authors use the terms 'wetland rice' and 'dryland rice'.

The most common cropping system in South-East Asia is the cultivation of irrigated rice during the rainy season, followed by secondary crops, e.g. maize, soya bean, groundnut, tobacco, mung bean and vegetables, which are planted at the end of the rainy season and the beginning of the dry season. Double cropping – in some areas even triple cropping – of lowland rice is practised when the supply of irrigation water is sufficient. In areas with rainfed land only, upland rice or maize is grown during the wet season, followed by a secondary crop if rainfall is still adequate. In Indonesia, in areas where water cannot be controlled properly, a system called 'surjan' is promoted. It entails planting lowland rice on sunken beds 3–4 m large. These are alternated with raised beds used for growing vegetables, maize or other upland crops.

In the northern parts of Thailand, the Philippines and Vietnam, cereals such as wheat, maize and millets are grown during the cool, dry season, whereas during the hot rainy season the land is used for lowland rice. The rice–wheat cropping system is found in a very large area of the zone between 25°N and 40°N.

1.5.2 Planting

Information of importance for the cultivation of the main cereals and pseudocereals is summarized in Table 6.

Planting material

Traditionally, the grower saves a portion of the grain at harvest as seed for the next season. During cultivation little if any extra care will be given to the part of the crop destined for seed, but some farmers select particular plants or parts of the crop for seed. If the own seed is insufficient, the farmer has to procure seed from other farmers or from the local market. Seed of improved cultivars for replacement of landraces is often available from the public or private seed

Table 6. Agronomic and other data relevant for the cultivation of cereals and pseudo-cereals in South-East A (various sources).

Crop	Photo-synthetic pathway	Optimum temp. (°C)	Drought tolerance	1000-kernel weight (g)	Sowing rate (kg/ha)	Density at harvest (plants/m²)	Pollination	Crop cycle (days)	Yield (t/ha) average	Yield (t/ha) high	Hyb cvs
Cereals											
Barley	C3	15–30	++	35	100	200	self	90–120	1.7	4	no
Maize	C4	21–30	+	250	20	6	cross	70–200	2.1	6	yes
Rice	C3	20–35	–	28	50	25	self	100–210	3.1	6	yes
Rye	C3	10–25	++	35	100	200	cross	120–180	1.0	4	yes
Sorghum	C4	22–35	+++	14	10	12	mixed	100–210	1.5	4	yes
Wheat	C3	10–24	–	40	125	250	self	80–115	1.0	4	no
Barnyard millet	C4	25–35	++	4	7	5	self	50–90	0.8	2	no
Finger millet	C4	20–30	++	3	13	40	self	100–180	0.8	2	no
Foxtail millet	C4	25–35	+++	3	10	40	self	90–120	0.9	2	no
Pearl millet	C4	25–35	+++	8	7	4	cross	75–180	0.8	4	yes
Proso millet	C4	18–30	+++	7	10	5	mixed	60–120	0.6	2	yes
Job's tears	C3	25–35	+	85	12	5	cross	200	1.5	3	no
Pseudo-cereals											
Buckwheat	C3	15–25	++	20	40	100	cross	70–130	0.6	2	yes
Grain amaranth	C4	25–40	++	1.0	3	10	self	120–180	0.8	4	no
Grain chenopod	C3	15–30	++	3	8	100	self	120–150	0.8	3	no

– intolerant; + low tolerance; ++ medium tolerance; +++ high tolerance

industry or from farmers who had adopted a new cultivar earlier. Numerous on-farm comparison trials with farm-saved seed and commercial seed of local and improved cultivars have shown that a good genetic, physiological, physical and sanitary quality of the seed is the most important means to assure sustainable high yields (see section 1.9). Most farmers are well aware of the advantages of good seed, but will only purchase certified seed on a regular basis when there is a marked advantage over the use of farm-saved seed.

Tillage and sowing

The surface of a seed-bed for cereals should be regular, to enable sowing at a uniform depth. Normal tillage for seed-bed preparation starts with hoeing or ploughing, to be followed, if needed, by harrowing. Ridges may be needed for irrigation, or during the rainy season to improve drainage; they are made after ploughing or during hoeing.

Tillage for irrigated rice is different: after ploughing and harrowing, the land is soaked and puddled.

Cereal crops are direct-sown, with the exception of irrigated rice, which is usually sown in a nursery and transplanted later. The most common method in temperate regions is sowing in rows by machine drilling or, for maize, precision sowing at a uniform depth of 2–4 cm. Machine drilling uses less seed and promotes a uniform stand. In South-East Asia this method is rather uncommon because cereal farms are small, sowing machines expensive, and the soil surface irregular. The normal practice is to dibble the seed in pockets. Broadcasting followed by harrowing is practised for small grains (wheat, barley, rye, millets), for the nursery seed-bed of lowland rice, or for direct sowing of lowland rice. Dry-seeded lowland rice known as 'gogo rancah' occurs in some areas of Java.

The optimal sowing density in terms of number of kernels per m^2 or kg seed per ha depends on the species and the cultivar (weak or strong tillering) and on expected field emergence and crop establishment. Shallow sowing, high N fertilizer dose and a low sowing rate stimulate tillering. Too dense sowing not only wastes seed but also results in excess tillers dying, which weakens the plants. High plant densities cause stem etiolation and increased susceptibility to lodging. Although farmers tend to use higher seed rates than strictly needed, very dense sowing or planting hardly occur in practice. Slow and uneven germination, often observed on dry, hard soil, or caused by inferior seed quality, results in uneven stands with abundant weed growth and low yield.

The data on sowing rate and plant density presented in Table 6 are average values. The percentage of kernels, sown out per m^2, that results in harvestable plants, is highest for species with large seeds. It may reach 90% in maize and 70% in wheat and barley. Small-seeded crops show a much lower percentage of plant establishment. In areas with limited rainfall, the plant density practised for crops such as maize, sorghum and millets is strongly reduced. Thinning-out after field emergence is sometimes practised. Pseudo-cereals show self-thinning when sown very densely.

Intercropping

Subsistence farmers in tropical lowlands lacking irrigation facilities for rice cultivation sometimes intercrop their rainfed cereals (maize, upland rice, sorghum) with crops such as cassava, sweet potato, groundnut and other pulses, and vegetables. Stalks of growing maize and sorghum are used as supports for climbing beans. Intercropping with pulses may add some nitrogen to the soil, to the benefit of the cereal. But the main advantages of intercropping are a better use of available space, reduction of risk for complete crop failure, better soil protection against erosion, reduction of diseases, pests and noxious weeds. A disadvantage of intercropping is that mechanization of sowing, weeding and harvesting operations becomes difficult. In lowland rice, the borders and bunds are often used for planting vegetables and root and tuber crops.

Unlike several other crops (taro, groundnut, pineapple, Capsicum pepper), which tolerate some shade, cereals produce best under unshaded conditions, hence they are less suited for agroforestry systems. Research reports on intercropping of tree crops with cereals attribute the low yields to reduced radiation and, to a lesser degree, competition with the trees for nutrients and water. In trials with cereals and other crops under coconut in India, pearl millet and kodo millet (*Paspalum scrobiculatum* L.) yielded remarkably well, almost as high as in the open, but the yield of maize (1.2 t/ha) cultivated under coconut was only 37% compared to the yield in the open (Ohler, 1984).

Crop rotation

To obtain a maximum grain yield it is recommended to rotate cereals with non-cereal crops as a general control measure to reduce the build-up of diseases and pests. The important exception is irrigated rice, which is grown continuously on the same land, often without noticeable yield depression. However, very intensive cropping does stimulate the build-up of populations of rice diseases and pests such as leafhoppers transmitting the tungro virus, and brown planthoppers transmitting grassy stunt and ragged stunt virus. Monoculture also favours the build-up of populations of certain weed species such as *Cyperus* in irrigated rice. Farmers sometimes rotate cereals with non-cereals in an attempt to control these weeds.
However, most farmers practise crop rotation not because of the beneficial effect of other crops on the cereal crop, but because of the beneficial effect of the cereal on the succeeding dicotyledonous crops such as tobacco, cotton, vegetables, pulses, roots and tubers. This positive effect may be attributed mainly to the reduction of plant parasitic nematode populations and reduced weed competition.

1.5.3 Husbandry

Weeding

In young cereal crops, some weeds of *Gramineae* are difficult to distinguish from the cereal plants. In South-East Asia manual weeding by pulling out or hoeing is most common, though mechanical weeding using animal traction or small tractors is becoming more popular. On well-prepared and puddled land, irrigated transplanted rice is very competitive because when planted it has a head start over the weeds. If water control is complete in lowland rice crops, most weeds can be eradicated by alternating between draining the fields for a few days followed by flooding to the top of the young rice plants.
Weed control with herbicides is gaining popularity. Of the pre-emergence or pre-planting herbicides, roundup (glyphosate) is often used against grasses and sedges (e.g. nutgrass) and paraquat against broad-leaved weeds. Other popular pre-emergence herbicides are atrazine, butachlor and propachlor. Popular post-emergence herbicides used in maize, sorghum, millets and wheat include dinoseb and 2,4-D. Weeds are no longer harmful once cereal crops have attained a full-grown leaf canopy. The application of herbicides, when carried out incorrectly or with the wrong products, may be hazardous for the environment. There are alternatives to chemical weed control, and farmers need to be informed about them.

Mechanization

Animal traction with oxen and buffaloes is commonly used by farmers in South-East Asia for soil tillage, but 2-wheel tractors are gradually becoming popular. Small motor-powered threshing machines are also used widely. Yet cereal cultivation is still very labour-intensive. This can be illustrated by comparing the labour requirement for rice in South-East Asia (about 1200 hours/ha, yield 3.6 t/ha, output 3 kg/hour), with labour for mechanized rice farming in the United States (20 hours/ha, yield 6 t/ha, output 300 kg/hour). A century ago wheat growers in western Europe needed 200 hours/ha using horse power for tillage and harvest, with a yield of 2 t/ha, hence an output of 10 kg/hour. Nowadays, large-scale farmers in western countries obtain quadruple yields (8 t/ha) by using herbicides for weed control and tractor-driven machinery for ploughing, sowing, weed control, spraying, harvesting and threshing, reducing labour requirements to 15 hours/ha, hence an output of about 500 kg/hour. The greatest progress in the reduction of manual labour was achieved by the introduction of herbicides for weed control and by the invention of the combine, a machine which harvests and threshes the grain in one single operation (Leonard & Martin, 1963). The downside of this is the exorbitant use of fossil energy and of herbicides. As costs of labour rise, the use of motor-driven machinery in South-East Asia will increase, but it is unlikely that the millions of small cereal farmers will be able to attain the same degree of mechanization as big farmers on the great plains in Europe, America and Australia. The development of simple, relatively cheap and well-designed machinery (2-wheel tractors, spraying equipment, threshing machines) has brought a certain degree of mechanization within reach of the small farmer.

Irrigation

Cereals other than lowland rice are usually grown as rainfed crops, but in some regions, maize, sorghum and wheat are cultivated under irrigation. Various factors determine the total quantity of irrigation water and the frequency of application required for undisturbed crop growth and a high yield: evapotranspiration, rainfall, topography, soil type, seepage and percolation losses, crop duration, cultural practices. Dry hard soil must be made tillable by one or more pre-irrigations. In a trial to measure the influence of water management practices on rice, the water-use efficiency (grain weight in g per litre of water) ranged from 0.6 (deep continuous flooding with 15 cm water, yield 8.9 t/ha) to 1.4 (continuous soil saturation with 1 cm water, yield 9.0 t/ha) (De Datta, 1981).

Furrow irrigation is the most common method used for cereals other than lowland rice. Irrigating implies a certain risk of waterlogging and causing soil salinity by salts accumulating near the surface. These salts are either brought in with the irrigation water, or by capillary rise from a high water table. In the first case, the remedy is to ensure that the salts are leached beyond the root zone, either by natural rainfall or by irrigation. In the second case, the water table must be lowered, by avoiding excess irrigation or by installing a drainage system.

Plant nutrition

Nutrient removal The uptake of minerals from the soil solution by cereals (rice, maize, wheat) has been extensively investigated. A good insight into nutrient uptake and distribution can be obtained by analysing data on nutrient removal (Table 7).

The data illustrate that the grain takes up much N and P, while the straw is

Table 7. Nutrient removal of some cereals, in kg per t of harvestable product (De Datta, 1987, for rice cv. IR 36; Halliday & Trenkel, 1992).

Crop		Nutrient removal (kg/t)				
		N	P	K	Mg	Ca
Rice	grain (5 t/ha) + straw	22	3	26	2.8	2.9
Rice (cv. IR 36)						
a. with N fertilizer (174 kg/ha)						
	grain (9.8 t/ha)	14.6	2.7	2.6	•	•
	straw (8.2 t/ha)	9.2	0.6	28.3	•	•
b. no fertilizer						
	grain (3.4 t/ha)	10.0	2.9	2.9	•	•
	straw (2.8 t/ha)	6.4	0.7	21.1	•	•
Maize	grain (6.3 t/ha)	15.8	2.8	3.8	0.9	0.2
	straw	10.0	1.6	12.2	2.7	1.7
Wheat	grain (4.5 t/ha dry matter)	22.2	4.9	4.6	•	•
	straw (4.5 t/ha dry matter)	6.4	0.7	18.4	•	•

richer in K, Mg and Ca and moderately rich in N. If the straw is returned and incorporated into the soil, the removal of K, Mg and Ca is greatly reduced. Straw and other crop residues remaining in the field can be ploughed in. Commonly, for practical reasons, the straw which is not taken away for other uses will be burned on heaps in the field. Although the remaining ash enriches the soil with minerals, the other advantages of organic material are lost. Moreover, burning means considerable losses of nitrogen, and the remaining soluble minerals are easily leached. However, one advantage of burning the straw is that it may destroy certain diseases and pests which could contaminate a following crop.

Nitrogen Nitrogen is the most important element for cereal cultivation. It is an essential element of proteins in all plant tissues, including the kernel. An optimal N supply increases the leaf area, stimulates growth, delays leaf senescence, improves tillering and tiller survival, increases the number of grains per ear and raises the protein content of the grain. Too high doses of N stimulate excessive vegetative growth, especially of leaf tissues with low dry matter content. Luxury consumption of N makes the plant susceptible to diseases and pests. Also, plants may form longer and weaker stems that are susceptible to lodging. By experience, farmers learn to apply doses of N fertilizer to obtain high grain yields without too much risk of crop loss by lodging. In South-East Asian countries the use of fertilizers, especially of urea in lowland rice, is often extremely high, far beyond the recommended doses. However, as Integrated Pest Management (IPM) becomes more widespread, the application of N will become more balanced.

The N efficiency in upland cereal cultivation is 50–60%, but in irrigated rice it is generally only 25–30% as a consequence of ammonia volatilization, denitrification in the anaerobic zone, leaching losses and runoff. Split application with one or more top dressings is recommended in order to guarantee a more regular supply of this very soluble element and to reduce losses. In addition to correctly timing the N fertilizer gift, losses are minimized by incorporating the fertilizer in the soil, by using ammonium (NH_4) instead of nitrate (NO_3) fertilizer, and possibly by applying slow-release fertilizer and nitrification inhibitors. In upland cereal cultivation, 50–60% of the N is often applied as basal dressing and the rest in one or two split applications.

Fertilizer recommendations With the exception of farmers practising shifting cultivation, most subsistence farmers and practically all cash crop cereal farmers of South-East Asia apply fertilizer. Farmyard manure is an excellent fertilizer to improve both the chemical fertility and the physical properties of the soil. However, supplies of farmyard manure or other organic fertilizers are far from sufficient, and therefore cereal farmers depend on inorganic fertilizer for a reasonable yield.

It is difficult to give general recommendations, because appropriate fertilizer recommendations are tailored to cultivar, season, soil type, water supply, and the fertilizing of preceding crops. In South-East Asia, recommendations for rice range as follows: 75–140 kg/ha for N, 10–20 kg/ha for P, 0–35 kg/ha for K (Halliday & Trenkel, 1992). Official recommendations for hybrid maize in South-East Asia are 90–180 kg N, 20–25 kg P and 0–50 kg K, and for local maize cultivars are 30–90 kg N, 15–20 kg P and 0–25 kg K. Many farmers do not follow official recommendations but rely on own experience.

Most tropical soils are very acid (pH > 5.5). The acidity is aggravated by heavy applications of acid-forming N fertilizer, urea being the worst. Liming is still not very common. The lime or calcium carbonate equivalent needed to raise the pH by 0.5 is about 1.5 t/ha on light, sandy soils, about 2.5 t/ha on loam and 4.0 t/ha on heavy clay or organic soil. The best lime source is magnesium limestone (dolomite).

Fertilizer application, which is a necessity in primary crop production, is practically environmentally harmless if carried out in accordance with official (and correct) recommendations. Any pollution which may occur beyond an acceptable low level is mainly the result of faulty fertilizer practices (Halliday & Trenkel, 1992).

Application methods For most cereal crops the fertilizer is applied in granular form by manual broadcasting. Mechanical distribution is not common in South-East Asia. Plant or row application is generally more effective than broadcasting because the fertilizer is placed close to the stem base where the roots are most concentrated. Plant or row application is rather common for maize and sorghum, which are cereal crops with a large inter-row distance and a low planting density. The fertilizer is worked into the topsoil or left on the soil surface to penetrate slowly when dissolved in rainwater.

A common practice for lowland rice is to apply the total amount of P and K as basal dressing at planting (because these elements do not leach out easily), and N in two or three split applications, as basal dressing and in one or two top dressings, one during tillering (about 3 weeks after planting) and the next facultatively at inflorescence emergence.

Foliar application is seldom applied because it is expensive and the amount of macro-nutrients per dressing is limited. In the case of nutrient deficiencies it may be useful to spray with the required element, usually Mn, Zn or Cu.

1.5.4 Crop protection

Cereals are affected by many diseases and pests. The relative importance of cereal diseases and pests is indicated in Table 8.

Most diseases of cereals are caused by fungi. Some bacteria from the genera *Pseudomonas* and *Xanthomonas* cause losses, especially under high relative humidity. Several viral diseases are devastating in rice, maize, sorghum and other cereals. Contrary to other food crops, cereals are not very susceptible to nematodes.

Borers are among the most harmful insect pests of rice and maize. Hoppers damage the plants by sucking and they transmit viral diseases. They have be-

Table 8. Major diseases and pests in cereals (various sources).

	Maize	Rice	Sorghum	Wheat	Millets	Observations
Diseases						
Fungal diseases	xxx downy mildew rust smut leaf blight	xxx blast	xxx downy mildew rust leaf spot ergot anthracnose	xxx rust smut Fusarium leaf blight foot rot	xx downy mildew rust smut leaf spot ergot	
Bacterial diseases	x	xx leaf blight	x	xx bacterial stripe	x	
Viral diseases	xx	xxx tungro	xx	xx	xx	vectors: aphids, hoppers
Nematodes	x	x	x	x	x	relatively unimportant in cereals
Pests						
Borers	xxx	xxx	xx	x	xx	major chronic pests
Plant & leaf-hoppers	x	xxx	xx	x	x	virus vectors, major and secondary pests
Midges	x	xx	xxx	x	xx	major pest
Corn-ear & army worms	xxx	x	xxx	xx	xx	major pest
Aphids	xx	x	x	xx	x	virus vectors
Bugs	x	x	xxx	xx	x	
Shoot flies	x	x	xxx	x	xx	
Birds	xx	xx	xxx	xx	xxx	sometimes serious
Rats & other rodents	xx	xxx	xx	xx	xx	often serious
Snails	x	xxx	x	x	x	devastating when occurring

x minor; xx secondary; xxx major.

come a major pest since the early 1960s as the result of the widespread application of synthetic insecticides for the control of stem borers (Brader, 1982; Heinrichs & Mochida, 1984). Birds, such as weaver birds, parakeets and sparrows, may cause considerable damage to all grain crops. Rats and other rodents may be very harmful to grain crops at all stages.

Crop losses

Yield losses of food grains before harvest are mostly below 5%, but may reach up to 30% (Thurston, 1984). Exceptionally the whole crop may be destroyed by a disease or pest. Losses cannot be completely avoided, even with adequate crop protection measures. Crop loss assessment is supremely important because it correlates crop damage with yield reduction, enabling farmers to improve crop husbandry, especially their planning and timing of crop protection measures, and to establish economic thresholds in relation to the costs of control equipment and materials. Yet crop losses are rarely assessed adequately (Jago, 1993). For example, in Malaysia rice stem borers were considered to be the most serious pest of rice. Chemical control as a preventive method was recommended. However, surveys showed only a low incidence of rice stem borers, with less than 5% of bored tillers. Apparently, rice stem borers were under natural control.

Simulation models can be used to analyse the development of diseases and pests with the help of collected data. EPIPRE is such a model. It uses linear regression to analyse disease or pest effects on crop yield. It is a field-oriented, computer-based, interactive system, which stores specific data from every registered field in a data bank. At intervals, the farmer observes disease and pest incidence in his field and communicates his observations to the EPIPRE database. Combining various data, EPIPRE calculates the probability of disease and pest development and of yield loss in this field. If the expected loss outweighs the expected costs, a recommendation to spray the field with a biocide is issued to the farmer. The strong involvement of the farmers in this Integrated Pest Management (IPM) project taught them to distinguish symptoms of all kinds of diseases and pests and made them conscious of environmental effects of chemical control measures (Zadoks, 1980).

Control methods

Although a large part of the global cereal area is cultivated without any crop protection, the number of farmers practising certain control measures is increasing. The following control methods may be distinguished: control by cultural practices, control by resistant cultivars, biological control, chemical control, and integrated pest management.

Cultural practices With appropriate cultural practices, damage by diseases and pests can usually be kept at a low level. One general control measure is crop rotation to reduce the build-up of harmful populations of diseases and pests. Other methods are based on removing potential sources of infestation. The use of clean seed is a very important preventive measure. Rice fields can be left inundated to control soilborne diseases. Infection by fungi is reduced by a lower plant density. The supply of nitrogen fertilizer should be minimized; the higher the N content of the plants, the more susceptible they are to many diseases and pests. Another control method is proper timing of the cropping period. For example, maize is only vulnerable to downy mildew in the first weeks after field emergence; sowing early when the infection level is low can avoid severe damage. Army worm, a pest of maize and sorghum, can be controlled by drawing the plough furrows across the paths of migrating larvae, with the steep side of the furrows facing the oncoming 'army'; pits about 30 cm deep are sunk at intervals in the furrow; the larvae move along the furrows and gather in the pits where they can easily be destroyed (Häfliger, 1979).

Resistant cultivars About twenty years ago, resistance as a control method against diseases and pests gained scientific attention through the work of the international agricultural research centres. The International Rice Research Institute (IRRI) developed several rice cultivars with resistance to leafhoppers and planthoppers. IR 26, a cultivar resistant to brown planthopper, was successfully cultivated over extensive areas in the Philippines, Vietnam and Indonesia. However, it was only effective for 2–3 years, because a new virulent biotype of the insect became abundant (van Vreden & Ahmadzabidi, 1986). Cultivar IR 36, released in 1976, was resistant to brown planthopper, green leafhopper, gall midge, stem borers, blast, bacterial blight, grassy stunt, and tungro; it became the most successful cultivar of any improved food crop (Litsinger, 1989). Resistant cultivars of other cereals have also been successfully bred and released (Hagan, 1991; Hunger, 1991; Peters & Starks, 1991; Wellso et al., 1991).
The first resistant cultivars were monogenic by nature, but modern ones have multiple genes for resistance. Combining two or more major genes in a single cultivar results in better and more sustainable (vertical) resistance. Horizontal resistance, a type of durable resistance governed by many minor genes, is becoming important in breeding programmes. Resistance to stem borers in various rice cultivars is polygenic but of a low level. Many rice cultivars with resistance to blast have been bred. Breeding for resistance to bacterial and viral diseases has been successful for other cereals. However, it will never be possible to combine resistance to all diseases in one cultivar, and the occurrence of new races or biotypes in the field is unpredictable.

Biological control Two types of biological control can be distinguished. Natural biological control is the control of pests by their naturally occurring enemies (predators, parasites or pathogens) in the agro-ecosystem. This occurs everywhere and is of prime importance. The other type is classical biological control, which is the introduction of natural enemies to an area where they originally did not occur. In rice, classical biological control has been successful in only a few cases, using exotic parasites to control exotic pests, e.g. the control of *Chilo suppressalis* in Hawaii and of *Marasmia exigua* in Fiji. In these relatively small and well-isolated regions, the parasites could easily spread and maintain themselves, meeting little competition from other natural enemies.
The use of exotic parasites to control indigenous pests has never been successful. Therefore, most research on biological control is now focused on natural biological control. Most rice insect pests in South-East Asia are indigenous and

have their own indigenous natural enemies, but little research has been carried out on methods to maximize their impact. To maximize the benefit of the action of predators and parasites, an inventory should be made and regularly updated, and outbreaks investigated to determine their causes (Ooi & Shepard, 1994). This may lead to the development of practical pest surveillance and forecasting techniques and to recommendations for chemical intervention that take into consideration the pest/predator ratio, instead of the pest population alone.

Chemical control Many farmers treat their rice crop routinely 1–5 times with insecticides. The application of fungicides is rather limited. Many farmers and policy makers believe that insecticide is a necessary input for ensuring high yields. Strong promotion of insecticides by the government and by private companies in many areas has led to over-use, provoking outbreak of insect pests that normally do not cause problems. Usually, the farmers' practice of pesticide application is not very effective, because of inadequate application technology, less than optimal timing and choice of pesticides, and the habit of mixing different products. In mixed spraying, the concentration of each component is often lower than recommended. This results in pest resurgence and secondary pest outbreaks, and leads to much waste of pesticides and to environmental pollution.

Some fungi can be controlled with chemicals, seed treatment being most effective (with 3 g of a mixture of thiram and carbofuran per kg of seed, the quantity of pesticide per ha is very minor), but chemical control of bacteria is difficult. Some viruses can be controlled by eliminating their insect vectors with chemicals.

The use of pesticides has reached levels at which they pose great health risks to the farmer and cause considerable damage to the environment. The risk of residues for the consumers is present, although less with cereals than with vegetables. Another negative effect of pesticides is the destruction of predators, parasites and other natural enemies of the pest. The disturbance of the natural balance has led to a vicious circle of an ever-increasing use of pesticides without reaching the desired 100% control. Many pests have developed resistance to pesticides, thus forcing farmers to spray more frequently and at higher doses. For lowland rice it has been shown that indiscriminate pesticide use leads to larger pest-related yield losses than not applying pesticides at all (Rola & Pingali, 1993).

Chemical control should only be applied if the economic threshold for damage is surpassed, if no other control methods are available or effective and if adequate precautions are taken for safe use. The International Code of Conduct on the Distribution and Use of Pesticides (FAO, 1986) gives guidelines for the safe use of pesticides.

Integrated pest management Integrated Pest Management (IPM) is identical to Integrated Pest Control (IPC), which was defined by the FAO as: '... a pest management system that, in the context of the associated environment and the population dynamics of the pest species, utilizes all suitable techniques and methods in as compatible a manner as possible and maintains the pest populations at levels below those causing economic injury.' Utilization of natural biological control is the cornerstone of IPM (Brader, 1979).

The success of IPM training programmes for rice farmers in several countries proved that high yields can be obtained without chemical pesticides. It is based on the following principles:

- communities of indigenous natural enemies keep insect pest populations in check most of the time; this naturally occurring control is the cornerstone of pest management, and therefore the conservation of these natural enemies, by reducing insecticide use as much as possible, receives full attention in IPM farmer training;
- resistance is an important component of IPM; cultivars with resistance against several diseases and insect pests are widely cultivated;
- good crop management practices (water, fertilizer) result in a healthy crop, able to tolerate fairly high infestation levels without suffering economically important yield loss.

As a result of these three factors, diseases and pests in non-treated rice fields do not usually cause important yield losses. In Indonesia, 'IPM farmer field schools' have been set up. The philosophy behind them is that by learning in theory and practice farmers will become IPM experts and trainers (van de Fliert, 1993).

Many of the farmers trained in IPM see chemical control as a last resort. Biocides should not be used before the economic damage threshold has been reached, and then should be applied at the lowest effective dose, at the moment when diseases or pests are most vulnerable, using formulations that are the least toxic to beneficial organisms. Spot treatment, if adequate, is preferable to blanket spraying.

1.6 Harvesting and post-harvest handling

1.6.1 Harvesting and threshing

In the maturation stage of the kernel, starch turns from being watery, milky and doughy to being hard and white. Once the hard-dough stage has been reached the total dry matter stored in the kernel does not increase any more, and the moisture content has fallen to about 35%. The whole plant starts yellowing and the moisture content of the grain decreases further to 13–15%. From this moment, the grain can be harvested, but the drier the grain at the harvest stage, the better its storage quality. Premature harvesting reduces yield and quality because the kernels are light and shrivelled, whereas delayed harvesting causes losses due to lodging, sprouting, shattering and damage by rain, rats and birds. Cereal stems collapse and break soon after the right harvest stage has passed.

The traditional way of harvesting is either to cut off the panicles or spikes with a knife, leaving the rest of the plant (the straw) behind, or, more commonly, to cut the whole plant with a scythe or sickle. Maize is harvested manually by picking the cobs. Mechanical harvesting and threshing with combine machines, the common method in large-scale cereal production areas in temperate regions, is rare in South-East Asia.

Threshing to separate the grain from the husk is carried out by beating, treading, or mechanically, using small threshing machines. Maize is threshed manually or by a maize-sheller. In rice, the husks are removed traditionally by pounding the grain to break off the husk, or mechanically in hullers, producing brown rice in which the bran remains attached to the grain.

1.6.2 Drying and cleaning

Harvested grain with a moisture content above 14% should be dried as soon as possible to avoid deterioration caused by fungi and insects. Dry seed is hygroscopic, in equilibrium with the relative humidity of the surrounding atmosphere. Often, harvested cereal is left in the field for a few days to dry before threshing, or shelling in the case of maize. Small farmers in South-East Asia usually dry their grain in the sun. Spreading out the grain for 3–5 days on a drying floor in a layer of 5–10 cm is sufficient to reduce the moisture content to 11–13%. Grain is often artificially dried with heated air before storage. It is mechanically loaded and circulated in a batch dryer or a bin dryer. Multipass drying in a continuous flow of hot air, for rice at 38–54°C, lowers the moisture content to about 14% (Grist, 1986).

The grain needs to be cleaned to remove all particles which might affect the milling quality. Small farmers mostly clean the grain by hand winnowing, taking advantage of the wind. In a hand or machine-operated winnower all the light material such as chaff, straw and dust is blown away. To a certain extent, cleaning prevents storage losses. Dirty grain is more vulnerable to fungal and insect infestation because dirt contaminates the grain and attracts moisture.

1.6.3 Storage conditions

Stored grain must be protected against diseases and pests and any increase in air humidity. The lower the temperature and relative humidity, the longer the storage time without noticeable loss of consumption quality. For example, rice grain can be held in good condition for two years when stored at 18°C and a moisture content of 13%, which is in equilibrium with a relative humidity of 65%. A high air humidity causes heat production by increased respiration and, consequently, the germination capacity will decrease. These conditions are also favourable for fungi, mainly *Aspergillus* and *Penicillium* species. They produce mycotoxins which frequently cause food and feed poisoning. Wheat with lower than 14% moisture, stored at a temperature below 20°C remains fungus-free and can be kept for many years, while with 17% moisture and at 15°C the fungus-free period is at most 30 weeks and at 20°C it is only 6 weeks.

Seed grain is usually treated differently to food grain. Seed must be properly selected, threshed, cleaned and dried, and preferably kept in airtight containers. Small farmers often keep their seed grain unthreshed under the roof of the house, or above the cooking place where it is well protected and dried by smoke and heat.

If the stored grain is not dry enough (water content > 14%), ventilation will be needed to reduce fungus development and fermentation. On the other hand, if the grain has been properly dried (water content < 13%), airtight storage will be the best method, because in that condition the grain respiration will cause the oxygen content to decrease, whereas the carbon dioxide content will increase, leading to an atmosphere preventing insect damage. In a humid climate, well-dried grain in an open store will absorb water from the air when ventilated, with increased risk of fermentation and infection with fungal diseases. In a dry climate, ventilation may further reduce the water content of the stored grain.

1.6.4 Post-harvest diseases and pests

Diseases and pests are the main cause of losses during storage. As infestation often starts in the field, timely harvesting is recommended. While it is being dried in the open the grain is exposed to rodents and birds, and to infestation by insects, fungi and bacteria.

Many insect pests of stored grains, such as the rice weevil (*Sitophilus oryzae*) and the lesser grain borer (*Rhyzopertha dominica*) require a high moisture level. Well-dried grain provides a poor environment for these pests. Although seed damaged by insects may still be capable of germinating, it will be very susceptible to fungal attack both during storage and after sowing. Many farmers do not use chemical insecticides to control insect pests because of the dual destination of the stored grain, for food and for seed. Insect control by natural compounds of plant origin, such as the leaves of neem (*Azadirachta indica* Juss.) or neem oil, is not widespread, although it is reasonably effective. Some farmers mix sand and ashes with the grain; the effect is based on scratching the insect's cuticle, causing it to die from dehydration. Sun drying is a cheap and effective form of insect control, since most insects will leave the grain when temperatures reach 40–44°C (Clements, 1988).

Rodents cause damage to stored grain in two ways. The obvious effect is the eating of the grain. The less obvious, but probably more important damage is caused by biting holes in plastic storage bags, which results in increased seed moisture content and subsequently insect and fungal infestation. Rodents may be controlled by storing the grain in rodent-proof containers, by application of rodenticides or by traps.

The micro-organisms of stored grain are essentially the same throughout the world, consisting chiefly of airborne species of *Alternaria*, *Aspergillus*, *Cladosporium*, *Fusarium*, *Penicillium* and *Rhizopus*. Fungi carried over from the field to the store include *Epicoccus* spp., *Helminthosporium oryzae* and *Magnaporthe grisea* (syn. *Piricularia grisea*) (Grist, 1986). Grain contaminated by fungi often contains dangerous levels of mycotoxins, such as aflavotoxin (from *Aspergillus* spp.), ochratoxin (from *Aspergillus* spp. and *Penicillium* spp.), ergotoxins (from *Claviceps purpurea*) and trichocenes (from *Fusarium* spp.) (Sharma & Salunkhe, 1991). Mycotoxins are very stable and persist in foods and feeds for a long time. Since decontamination is costly and impractical, prevention of contamination is very important.

1.7 Utilization and processing

1.7.1 Dry milling

Most cereals are subjected to some kind of processing of the whole grain before they can be used as food. The most common processing is dry milling, i.e. mechanical milling between rollers or grinding between two stones. Two steps can be distinguished in the milling process, i.e. reduction of the size of the kernels, followed by separation of the fractions.

The type of milling depends on the type of cereal and the purpose for which the flour will be used. Milling wheat separates the bran and embryo from the endosperm. The wheat grain contains about 82% of white starchy endosperm. It is not possible to separate this completely from the 18% of bran, aleurone and embryo, and to obtain a white flour with 82% extraction rate. White flour with about 70% extraction is often used for bread. Wholemeal is light brown and contains all the fractions of the milling of cleaned wheat, while intermediate flours vary in colour from white to light brown.
Rice grain is subjected to a different milling process than most of the other cereals. The bran layers are removed by polishing the grain in a rice mill. Abrading the pericarp, testa and some germ leaves a white grain. Rice can be milled into flour, but this is not common practice. In India, Bangladesh and Pakistan the parboiling of rice is an ancient tradition. Unhusked rice is soaked in water and then steamed or boiled. This process softens the husk but produces other changes, because the water-soluble components, especially the vitamins, migrate into the grain together with some of the oil. The grain structure is modified so that the aleurone layer is retained with the grain when the bran layers are milled off. Parboiling thus improves the nutritional value of the polished grain.
Maize is milled to produce maize meal, which may be sieved to remove the pericarp and germ. Sorghum and millet grains are traditionally pounded to produce flour.

1.7.2 Bread baking

The most important cereal product is bread made from wheat. Bread is made by baking a dough whose main ingredients are wheat flour, water, yeast and salt. The flour is wetted and the protein begins to hydrate and forms gluten, a cohesive protein which binds the flour particles together into a dough. Air bubbles are kneaded into the dough and eventually the dough becomes spongy, with the bubbles trapped in the gluten network. Enzymes in the yeast start to ferment the sugars present in the flour, which are broken down to alcohol and carbon dioxide. The carbon dioxide gas mixes with the air in the bubbles and causes the dough to expand. The extent of leavening depends on the amount of gluten and on the amount of carbon dioxide additives. Baking powder and eggs can be added instead of or as well as yeast. Rye contains only little gluten, but in combination with wheat flour it may give an acceptable bread dough. Wheat flour is often mixed with flour of other cereals (maize, rice, sorghum) or cassava starch for economic reasons, or with pseudo-cereals, e.g. of grain amaranth or buckwheat, to improve the nutritive value of the bread.

1.7.3 Pasta and whole-grain foods

Pasta is the collective term for macaroni, spaghetti, vermicelli and noodles. It can be prepared from flour of wheat, maize, sorghum and rice, and from mixtures, e.g. with buckwheat. Hard durum wheat (*Triticum turgidum* L.) is especially suited for this purpose. It is milled to produce coarsely ground endosperm particles known as semolina. Semolina is used in the manufacture of pasta and is also cooked unprocessed as couscous. To prepare pasta, dough is first made by mixing semolina and water. After kneading, the dough is heated to 49°C and extruded through a press to form a thin sheet which is cut into strips. A modification of this process, in which the dough is extruded through special dies to make shaped products, was first introduced about 50 years ago (Pomeranz, 1987). The pasta is cooked in boiling water until it is soft and is then ready to be eaten.

1.7.4 Breakfast cereals and porridge

Apart from bread baking, cereal starch can be made digestible and acceptable for humans by cooking. If the cereal is cooked with an excess of water and only moderately heated, as in boiling, the starch gelatinizes and is easily hydrolyzed by enzymes of the digestive system. Breakfast cereals are products that are consumed after cooking. They fall into two categories: those made by a process that does not include cooking and which therefore have to be cooked domestically (hot cereals) and those which are cooked during processing and which require no domestic cooking.

Many cereals and pseudo-cereals are used to make porridge. In Africa, maize grits are boiled with water. Barley meal is used for making a type of porridge in many countries in the Far East, the Middle East and North Africa. Buckwheat groats are used for porridge in Europe and North America.

Maize, wheat and rice are the cereals generally used for flaking. To make corn flakes, a blend of maize grits plus flavouring materials, e.g. sugar, malt syrup or salt, is pressure-cooked to a moisture content of about 28%. When the colour of the grits has changed from chalky-white to light golden brown, the grits have become soft and translucent, no raw starch remains, and the cooking is complete. The dried grits are then flaked on counter-rotating rollers, and the flakes thus formed are toasted (Greenfield & Southgate, 1992; Kent & Evers, 1994).

1.7.5 Malting, brewing and distilling

The essential process involved in brewing is the conversion of cereal starch into alcohol to make a palatable, intoxicating beverage. Fermentation is mediated by yeasts, usually belonging to *Saccharomyces cerevisiae*. Two processes are involved. First, the starch has to be converted to soluble sugars by amylolytic enzymes. If the grain's own enzymes are employed this is called malting. Second, the sugars have to ferment into alcohol by the enzymes of yeasts. All cereals are capable of undergoing malting, but barley is particularly suitable. Malting barley has a low content of husk, a high starch and a low protein content. In Africa, many malts are produced from sorghum and millets.

Malt is sprouted barley or another cereal crushed in water to hydrolyze starch by enzymatic action into soluble sugars. The solution extracted from the malt is called 'wort'. It forms the feedstock for fermentation for brewing beer or distillation of spirits (Briggs, 1978). The separation of the liquid wort from the solid remains of the malt is carried out by a process called lautering. The liquid is allowed to pass through the spent grains while retaining the fine solids, thus giving sweet wort. At this stage syrups may be added if the amount of fermentable sugars needs to be increased. Hops are also added at this stage. Now the wort is boiled, producing the bitter taste from the hops. After filtering it is transferred to tanks where yeasts are added together with air. Fermentation takes place for 7–9 days. Carbon dioxide may be added back when the beer is bottled or casked. The 'green' or young beer is run off from the aggregated yeast cells and cooled and aged before filtering and carbonating. Depending on the type of beer, sugar may be added to the casks to allow a second fermentation.

An essential difference between beer and saké (rice beer) is that for saké the natural enzymes present in the grain are expressly inactivated before the saccharifying phase of saké brewing. Enzymes are derived from the fungus *Aspergillus oryzae*. The alcohol content of beer depends on the tolerance of the yeast strain used and is usually 5–12%. However, the alcohol content of saké is up to 19%.

Distillation is used to produce potable spirits with an alcohol content above that of fermented drinks. Spirits produced from grains are of two major categories: whisky (or whiskey) and neutral spirits. The difference is that in whiskies care is taken to retain flavours and colour carefully introduced during production, while in neutral spirits the introduction of flavours and colour during production is avoided. The various types of whisky differ in their origin, their carbohydrate source and the manner of their production. Beer for distillation of neutral spirits is produced as economically as possible, flavour being undesirable. The cheapest available cereal can be used and it is more economical to use enzymes derived from micro-organisms than those from malt.

1.7.6 Wet milling: starch and gluten

Wet milling is a maceration process in which the dry flour is soaked in water or an alkaline solution to extract starch and gluten. The objective is to bring about a complete dissociation of the content of the endosperm cells, and the release of the starch granules from the protein network in which they are enclosed. The starch may further be separated in amylose and amylopectin. Although the grains of all cereals contain starch, those most widely processed by wet milling are wheat and maize.

All wet processes for the manufacture of starch and gluten from wheat comprise the steps of extracting the crude starch and crude protein, purifying, concentrating, and drying the two products. To obtain pure gluten it needs to be separated from the germ and bran by first dry milling with conventional methods. Consequently, white flour is used as starting material for wet processing to separate starch and gluten.

Vital gluten is separated from wheat by processes which permit the retention of the characteristics of natural gluten, i.e. the ability to absorb water and form an extendable, elastic mass. Vital gluten is used to improve the texture and raise the protein content of bread and to fortify weak flours, composed of mixtures poor in gluten. It is also used as a binder and to raise the protein level in meat products, breakfast foods, pet foods, dietary foods and textured vegetable products (Kent & Evers, 1994).

Maize is wet-milled to obtain starch, oil, cattle feed and the products of hydrolyzed starch (i.e. liquid and solid glucose and syrup).

1.7.7 Animal feed and industrial uses

Apart from human food, animal feed is by far the largest use for cereals, both as whole grain and as milling by-products. The treatments applied to cereals by animal feed processors are both expensive and time-consuming, and obviously would not be undertaken unless such treatments offer considerable advantages over the feeding of untreated whole grain. Both cold and hot, dry and wet, mechanical and chemical methods of treatment may be used, with the objective of improving palatability, avoiding wastage, improving digestibility and nutritive value, and encouraging consumption, thus leading to more efficient use of feed and faster growth. The actual treatment used will depend on the kind of cereal involved and the proportion of that cereal in the feed. It also depends on the type of animal for which the feed is intended, particularly whether it is for ruminants or for monogastric animals, and probably also for what stage in the animal's life cycle (Kent & Evers, 1994).

Rice bran and other milling by-products have traditionally been used for livestock feed rather than for human use because the removal of bran from the grain mixes an enzyme with oil in the bran, which eventually gives rise to rancid odours and flavours. The growing interest in rice bran as a foodstuff is because of its benefit in cholesterol reduction. This health benefit is attributed to the oil component of the bran, which constitutes about 20%. The technology to process rice-bran oil is similar to that used for other vegetable oils. In the near future the use of edible rice-bran oil may gain popularity (Luh, 1991; United Nations, 1985; Young et al., 1991).

Ethanol is produced by the enzymic action of yeast on sugars, which are themselves produced by the hydrolysis of starch. It can be regarded as a modification of the brewing process, in which starch separated from the grains is the starting material, and pure (96%) ethanol is produced by distillation of the aqueous solution. Ethanol made from cereals can be used as a partial replacement of gasoline for fuel of internal combustion engines. The process is a useful way of dealing with surplus grain whenever it arises.

In the United States, maize starch is important as raw material for the sweetener industry. Enzyme technology is used to produce dextrose and high-fructose syrups, mainly for sweetening soft drinks (Inglett, 1984).

Maize cobs, hulls of oats and rice and the fibrous parts of other cereals are rich in pentosans, condensation products of pentose sugars. Pentosans are the starting material for the manufacture of furfural. The commercial process for manufacturing furfural involves boiling pentosan-containing material with strong acid and steam for several hours. The pentosans are dissociated from the cellulose, then hydrolyzed to pentose sugars, and finally the pentose sugars undergo cyclo-hydration to form furfural, a heterocyclic aldehyde (Kent & Evers, 1994; Pomeranz, 1987). The most important use for furfural is in the manufacture of nylon.

Wheat and maize starches are applied in paper coating and as adhesives in the manufacture of paper, boards and plywood. They can also be used in paints, in plastics and to produce crude latex in the manufacture of rubber. Rice hulls can be a source of high-grade silica. Rice hull ash is used as a constituent of cement, since it is more acid-resistant than Portland cement. Furthermore it is a silica source in glass and ceramics industries. Rice hulls heated to temperatures up to 700°C yield amorphous silica which is suitable for making solar-grade silicon for solar cells (Kent & Evers, 1994).

1.8 Genetic resources and breeding

1.8.1 Genetic resources

Thanks to Vavilov the importance of the centres of origin and/or diversity of cultivated plants for plant breeding is now recognized. Central America is the centre of origin of maize, whereas rice originates in South-East Asia/China, sorghum in North-East Africa, proso millet in China, barnyard millet in India, finger millet in East Africa, pearl millet in West Africa, and wheat, barley and rye in the so-called Fertile Crescent of West Asia. The process of domestication and diffusion of these crops has taken thousands of years and has given rise to numerous landraces in all production areas. Modern plant breeders rely on a continuous renewal of genitors for desirable characteristics, which means that they need wild relatives of crops, landraces and improved cultivars from their own region as well as from other production areas. In turn, tremendous genetic erosion is provoked by the adoption of improved cultivars, especially in areas with high production potential.

The International Plant Genetic Resources Institute (IPGRI, Rome, Italy) has the mandate to promote and coordinate conservation of genetic variation. Loss of genetic variation is partly counteracted by two complementary approaches: ex situ conservation in genebanks, and in situ conservation on-farm or in the natural habitat.

Genebanks

Ex situ conservation is effected through genebanks, which store samples of seed or planting material under controlled conditions of temperature and humidity. The aim is to conserve as much as possible of the existing genetic diversity, ensuring its availability as resource material for plant breeding and research in the future. Table 9 reviews collections of cereal accessions in the genebanks of the International Agricultural Research Centres (IARCs), national genebanks of global importance, and genebanks in South-East Asia.

In situ conservation

In situ conservation means that valuable genetic diversity is maintained in its natural habitat, allowing adaptation and evolution to continue. This method is particularly appropriate, at least theoretically, for habitats that are under threat and for areas that are still farmed in a traditional way, where landraces are often enriched by gene exchange with wild relatives. The problem with in situ conservation as conceived at present is that unless crops are permanently guarded, security is low. Natural habitats may dry out or disappear as a result of the intensification of agriculture. As a result local materials may be replaced by foreign genetic material. Paying farmers cash to conserve their landraces in situ appears to be financially unsustainable.

It has been argued that crop conservation and development at the farmer or community level should be recognized as complementary to institutional efforts, and the formal crop improvement and conservation efforts should be integrated more at the local level (Altieri & Merrick, 1987; Brush, 1991; Hardon & de Boef, 1993; Vaughan & Chang, 1992). These efforts seek to support and enhance, rather than to replace the community management of plant genetic resources. Various national and international institutions are making efforts to integrate the conservation of biodiversity of traditional crops in rural development. Germplasm in the form of landraces, breeding lines or mixtures of modern cultivars is put directly at the disposal of farmers, to be used and developed according to their own needs and practices; this is called 'participatory breeding' (Eyzaguirre & Iwanaga, 1996).

1.8.2 Breeding

In the past the overall main objective was to breed for yield and broad ecological adaptability; resistance to diseases and pests was considered as part of the yield-determining factors. At present, the main objectives are tending to shift to breeding for the maintenance of high yields by durable resistance and by introducing genes for resistance to new biotypes of diseases and for tolerance of adverse conditions. In the case of self-pollinating (self-fertilizing) crops such as rice, wheat, finger millet and barley, the breeding process leads to very homozygous and uniform pure-line cultivars. The selection of cross-pollinating cereals like maize, sorghum, pearl millet and rye, requires a different approach, the result being a 'selection' with a narrow composition compared with the original population, but still rather heterogenous with a high degree of heterozygosity. Composite and synthetic cultivars have been developed for maize and sorghum. Composites are a deliberate mixture of selections, multiplied as open-pollinated cultivars. Synthetic cultivars are composed of a mixture of some well-defined populations or inbred lines, which continue to show the effects of heterosis in later generations.

Hybrid cultivars offer the advantage of easy combination of alleles for disease resistance or other desired characters. A hybrid cultivar is the F_1 offspring of two more or less homozygous lines, showing heterosis for yield and a high uniformity as most attractive characteristics. In cross-pollinating crops, well-combining inbred lines are used as the parents. The classic example is hybrid maize, which has become very successful all over the world, but is not suitable for marginal growing conditions. Hybrid sorghum is also widely grown, and hybrid pearl millet is becoming popular. Hybrid wheat remains largely in the research phase; apparently its advantages do not outweigh the high cost of the seed. In contrast to seed production of self-pollinating crops, the cultivar maintenance and seed production of hybrids are difficult and expensive.

Hybrid rice is widely cultivated in China; about 18 million ha or 55% of the total area. The seed production is based on cytoplasmic male sterility. Parent lines are selected on strong heterosis effect. The seed yield may attain 2.5 t/ha. It is difficult to synchronize the flowering of the parental lines. The yield of these hybrids on the farm is about 5 t/ha, i.e. 15–20% higher than that of convential seed. IRRI and the National Agricultural Research Systems (NARSs) are jointly developing parental lines and cultivars suitable for South-East Asian countries. Photoperiod-sensitive and temperature-sensitive genic male sterility systems are being in-

Table 9. Approximate numbers of cereal accessions in international genebanks, national genebanks of global importance, and South-East Asian genebanks (Altieri & Merrick, 1987; Bettencourt & Konopka, 1990; T. Hazekamp (IPGRI), pers. comm.; Subandi (CRIFC), pers. comm.).

Genebank		Barley	Maize	Rice	Sorghum	Wheat
International						
CIMMYT	Mexico	9 000	13 000			140 000
ICARDA	Syria	16 000				11 000
ICRISAT	India				35 000	
IITA	Nigeria		1 200	11 000		
IRRI	Philippines			90 000		
WARDA	Ivory Coast			2 000		
National (global importance)						
AICMMP	India					
AICSIP	India				2 000	
AICWP	India					17 000
CRI	India			15 000		
NBPGR	India	500	2 200	13 000	600	15 000
NIAR	Japan	6 000	4 000	12 000	5 000	7 000
NSSL	United States	15 000	14 000	11 000	19 000	1 800
VIR	Russia	1 800	18 000	6 000	10 000	34 000
South-East Asia						
CRIFC	Indonesia		1 100	8 400	300	550
MARDI	Malaysia			5 500		
NCSRC	Thailand		1 800		1 500	
NPGRL-IPB	Philippines		1 500	1 000	2 000	
NSSLGR	Thailand			16 000		

vestigated, as well as chemical emasculators. So far, farmers in South-East Asia have been reluctant to adopt hybrid rice. This is because the hybrids may show similar characteristics to open-pollinated cultivars regarding growth and resistance to diseases and pests, and the grain quality may vary from poor to acceptable. A major disadvantage is that the seed is 4–10 times more expensive than open-pollinated seed, because of the complicated system of seed production and the low seed yield from the crosses of the parental lines. Furthermore, the farmers are obliged to buy F_1 seed for each planting.

Landraces versus improved cultivars

The traditional local seed supply systems that have evolved over hundreds of generations of farmers, have led to a multitude of landraces. A landrace may be

Table 9. Continued.

Genebank		Millets					Pseudo-cereals
		Barnyard millet	Finger millet	Foxtail millet	Pearl millet	Proso millet	
International							
CIMMYT	Mexico						
ICARDA	Syria						
ICRISAT	India	600	2 500	1 400	21 000	1 200	
IITA	Nigeria						
IRRI	Philippines						
WARDA	Ivory Coast						
National (global importance)							
AICMMP	India		4 500	1 300		1 100	
AICSIP	India						
AICWP	India						
CRI	India						
NBPGR	India		*	300	500	100	*
NIAR	Japan	400	*	1 300	*	400	*
NSSL	United States		1 200	500	500	500	*
VIR	Russia	100	200	4 700	550	9 000	*
South-East Asia							
CRIFC	Indonesia						
MARDI	Malaysia						
NCSRC	Thailand		1 200	500	500	500	
NPGRL-IPB	Philippines						
NSSLGR	Thailand						

* available, but not quantified.

defined as a mixture of genotypes resulting from biotic and abiotic selection pressures in specific agro-ecological and socio-economic conditions (Louwaars & van Marrewijk, 1996). On the large-scale, highly mechanized farms in the world-leading cereal production areas of the temperate zone, these landraces have been replaced by genetically uniform cultivars that react favourably to high fertilizer applications, in particular to high nitrogen fertilization. In South-East Asia, the area under high-yielding cultivars/varieties (HYVs) – especially of rice and maize – is increasing, but landraces still remain widely cultivated, both for subsistence farming and as cash crops. Possibly 75% of the lowland rice area and 45% of the maize area are planted with HYVs, whereas almost all upland rice still consists of landraces.

Landraces usually compare favourably to HYVs in adaptation to specific agro-ecological conditions, production systems and people's taste. The high degree of heterogeneity of a landrace implies a lower yield potential but a more stable yield compared with the very uniform HYV. The individual farmer may find that his traditional local cultivars with their high yield stability under adverse conditions and low demand for external inputs represent better value than the higher costs and risks involved in maximizing yield and profit of HYVs.

In practice, the distinction between landraces and improved cultivars is not always clear, since selection in landraces may lead to improved local cultivars. Also, simultaneous growing of landraces and HYVs leads to introgression of new genes into the landraces. Plant breeders attempt to combine the superior characteristics of introduced HYVs with lines from landraces to create improved cultivars well adapted to local conditions.

The Green Revolution

In this century, modern wheat cultivars with a high yield potential have gradually become widely cultivated in industrialized countries in the temperate regions. These cultivars have a more favourable harvest index than traditional landraces. Their main feature is short straw, which implies a favourable response to high nitrogen fertilizer gifts without lodging problems. Another important feature of these new wheat cultivars is their superior resistance to fungal diseases. However, often the resistance is broken down by the rise of new fungal biotypes within a few years, and the cultivar must be replaced. Every year new cultivars with higher yield potential are released.

In the sixties, similar high-yielding cultivars for tropical and subtropical regions were very successfully created for rice (IRRI) and wheat (CIMMYT). In the period 1965–1975, the wide introduction of these cultivars combined with increased fertilizer application and improved cultural practices (irrigation, use of pesticides) caused an enormous boost in rice and wheat production, known as the Green Revolution. This Green Revolution enabled many developing countries to meet the steadily increasing demand for food resulting from population growth and urbanization. Next to their merits, HYVs in combination with their technology package proved to have some negative properties. Firstly, the HYVs of rice were either resistant or highly susceptible to diseases, and sometimes resistance broke down by mutation of the pathogen, leading to crop failure. These HYVs of rice were genetically very uniform, lacked multigenic resistance to diseases and pests, and lacked tolerance of adverse conditions. At present, rice breeding at IRRI and other institutes is putting much emphasis on multigenic, durable resistance. Secondly, HYVs were found to have some negative social effects. Resource-poor farmers who could not afford the high costs of extra inputs were confronted with decreasing prices and could not compete with richer farmers. In some cases, small farmers who risked planting HYVs had a crop failure and lost their investments, and in the worst case they became landless farm labourers or migrated to the cities (Lipton & Longhurst, 1985).

1.9 Seed supply

1.9.1 Seed sources

Seed-supply systems

Traditionally, at harvest the grower saves a portion of the grain to use as seed for the next season. If the own seed lot is insufficient, the farmer has to procure seed from other farmers or from the local market. In South-East Asian countries, the supply of genetically improved non-hybrid cereal seed is primarily an activity of the public sector. The low net profit from seed production of self-pollinating cereal crops is not appealing to private enterprises. The seed market is more profitable for cross-pollinating crops and for hybrid cultivars. The production and handling of cereal seed require high investments because of the bulky nature of transport, storage and processing. Yet the international trend for market liberalization is pushing governments to strive for increased involvement of the private sector, including in the cereal seed industry. In western countries, the private sector has been very active in spreading improved germplasm developed by public breeding programmes. The Asia and Pacific Seed Association (APSA, Bangkok, Thailand) stimulates cooperation between both sectors and among countries in the region.

Seed price

The price of cereal seed primarily depends on the multiplication factor, which may vary from very low (e.g. for wheat 8–30) to very high (e.g. for sorghum up to 400). The price of the seed must compensate the producer for all extra expenses: cost of breeder seed or foundation seed, extra labour for processing, losses by roguing and cleaning, cost of seed inspection, storage, and distribution.

For the farmer, seed costs represent only a small part of the total production costs, particularly for small-seeded cereals such as sorghum which have a low sowing rate. Farmers will be reluctant to buy seed if they are not convinced that the expected superior physical, physiological and sanitary quality will increase their profit. Cash-constrained small farmers often perceive little benefit in purchased seed; they may compensate for uncertain quality (germination) of their own farm-saved seed by using higher sowing rates (Cromwell et al., 1992).

Seed replacement rate

The seed replacement rate is the percentage of the total seed requirement (in amount or area) which is annually renewed by seed from the formal sector. It is an important parameter for evaluating the seed situation for a certain crop in a given area. For rice, for instance, a replacement rate of 20% is judged appropriate. In most countries in South-East Asia the rate hardly reaches 10%, Indonesia being an exception with 25%. Clearly, the seed replacement rate for crops with a high degree of cross-breeding (sorghum, maize) should be high, e.g. 30–50%, since these cultivars easily interbreed with landraces or other culti-

vars. For hybrids, commonly used for maize and sorghum, the seed replacement rate should be 100% because farm-saved seed shows so much genetic decline that the farmer should purchase new seed for each new planting.
Accurate data on areas planted with landraces or improved cultivars and the replacement rates are scarce. Also, a low seed replacement rate does not mean that farmers do not accept new cultivars. New cultivars also disseminate through unregistered local seed-supply systems. They often become mixed with landraces during seed handling or by genetic introgression.

Seed production planning

Commercial seed production is a concern for specialist enterprises. The multiplication factor and the replacement rate are important parameters for planning a seed production project. It is important to plan adequately for the amounts of breeder seed, basic seed (foundation seed), and market seed (certified seed) required.
While planning seed supplies, the government has to take into consideration the risk of crop failures due to natural disasters. In time of shortage, farmers' families may be forced to consume the seed lot. Some national seed policy authorities take measures to secure seed stocks for emergency situations.

1.9.2 Seed crop husbandry

Crop husbandry for cereal seed production is principally the same as that for grain for consumption. The differences are related to the objective of a seed crop: extra care is needed because it is not yield maximization but the supply of first quality seed that is important. For good genetic seed quality, contamination with alien pollen or with other seed lots must be avoided. Isolation distances depend on the nature of pollen transport and the degree of cross pollination. For the production of certified seed of self-pollinating cereals (rice, wheat, barley, finger millet) an isolation distance of 10 m between the fields is normally judged to be sufficient, whereas for maize, sorghum and pearl millet at least 200 m is required. Careful roguing (the removal of off-type plants during crop growth) is most important, especially during the first multiplication stages.
To ensure good physical quality of the seed, much attention should be given to weeding out species such as red rice or wild sorghum which are difficult to remove later by seed cleaning. The physiological quality of the seed is improved by proper cultural practices and by harvesting in a dry period. The amount of N fertilizer applied must be carefully controlled, because too much nitrogen results in weak plants, prone to fungal diseases; however, potassium is beneficial. The sanitary quality is upgraded by respecting the prescribed crop rotation period, stringently controlling diseases and pests, and removing and destroying diseased plants.

1.9.3 Seed conditioning

Seed conditioning starts with threshing or shelling. Seed drying and cleaning is an important part of post-harvest handling because it provides an opportunity to upgrade the physical, physiological and sanitary quality by mechanically removing impurities. Seed cleaning may be combined with grading by size. The most common machines used for cleaning are the air-screen cleaner, the indented cylinder and the gravity table. Fumigation with an insecticide is often applied to kill all insects and insect eggs.

Cereal seed has to be stored at least until the next sowing season. Some seed lots must be stored for two seasons, as an insurance against harvest failure. Deterioration by diseases and pests or physiological loss of viability during storage must be avoided. The principle is to store seed in a clean, dry and cool place. A prerequisite for good storage of cereal seed is that it should be dried to a moisture content of 13% maximum, in equilibrium with a relative humidity of about 65%. It is better to dry to 10–12%, which means an equilibrium with 45–60% of relative humidity. Storage in airtight containers is ideal. This is relatively easy for small quantities, e.g. farm-saved seed or breeder seed, and is sometimes also done in modern seed storage. Harrington's rule of thumb is worth quoting here (Harrington, 1972): for each 5°C decrease in temperature and/or for each 1% decrease in seed moisture content (about 10% decrease in relative humidity) seed life is doubled.

Nucleus seed and breeder seed have to be stored for long periods, but since relatively small amounts are involved, more ideal storage conditions can be created. Cereal seed is often dressed with fungicides and insecticides to protect against diseases and pests. The insecticide lindane and the fungicides thiram and captan are widely used.

1.9.4 Seed legislation

Governmental control of seed quality of cereal crops is more advanced than for other crops because of the significance of cereals to the national economy and food supply, and because the government itself is the only large seed producer.

All South-East Asian countries have a Seed Act intended to regulate and encourage the release of cultivars, the production and dissemination of high-quality market seed and the control of seed quality. The Philippines and Thailand are among the South-East Asian countries which are member of the International Seed Testing Association (ISTA, Zurich, Switzerland). This organization standardizes testing procedures for germination capacity, purity and health. Yet all countries refer to ISTA rules to some extent when defining seed quality.

In most countries an independently operating national seed control system has been established, mandated to control that seed legislation is being implemented properly. The objective of seed legislation is to guarantee that farmers have a constant supply of superior seed material. A national cultivar release committee is responsible for the release of new cultivars, whereas a national seed certification agency controls the cultivar identity and purity of the seed lots for certification. Full seed certification means official control of cultivar identity and purity through field and store inspection and labelling, and post-control plots (seed samples sown out to check the cultivar identity and the purity). Physical, physiological and sanitary quality control are carried out through laboratory testing.

Full certification of all the seed produced by the formal sector, meaning that only certified seed lots may enter the market, is very expensive. The modern concept of seed quality control is based on the breeder being responsible for the continuous supply of true-to-type breeder seed, and on the seed producer being responsible for the quality of the basic, foundation and market seed he produces. Seed producers should perform their own inspection and all seed entering the market should be 'truthfully labelled' (TL seed) with a label indicating cultivar name, lot number, date of production, date of testing, germination capacity, purity, moisture content. This enables the government's role to be restricted more to guidance than to control.

1.10 Pseudo-cereals

Four non-graminaceous grain crops have been included in this volume. The three most important ones are grain amaranth (*Amaranthus* L.), grain chenopod (*Chenopodium* L.) and buckwheat (*Fagopyrum esculentum* Moench). At present, these three pseudo-cereals are only sporadically found in South-East Asia, but in view of their success in East Asia it might be worthwhile introducing them in locations with suitable ecological conditions. They were domesticated in a similar way as the true cereals. In the past, these pseudo-cereals were important as staple food crops in large areas, where they currently survive only as secondary food crops for subsistence or cash. Other uses, e.g. as forage, are of minor importance. In most industrialized countries they have been ousted by higher-yielding true cereals. For some decades, however, there has been renewed interest in these crops because of their excellent nutritional value (high content of essential amino acids).

The botany of pseudo-cereals is quite different from the true cereals. The seedling forms a taproot and a main stem. The plant does not tiller but exhibits branching as a mechanism to compensate for inadequate plant density. A clear disadvantage compared with true cereals is the large spread in time of anthesis and seed maturity. The seed is a less strong sink of assimilates than in true cereals, and the harvest index is much lower (around 30%). The climatic conditions needed for the satisfactory performance of pseudo-cereals are optimal in warm temperate areas during the summer months. Buckwheat (with a C3-cycle photosynthetic pathway) is cultivated during spring or autumn in subtropical areas, whereas the grain chenopod quinoa (with a C3-cycle photosynthetic pathway) is much cultivated in subtropical areas and in the highland tropics. Grain amaranth (with a C4-cycle photosynthetic pathway) is cropped from warm temperate to subtropical areas and also in the highland tropics.

Pseudo-cereals are cultivated similarly to millets. Generally, manual weeding is practised. Chenopod and amaranth are very competitive to weeds. They respond well to nitrogen fertilizer, whereas buckwheat does not tolerate high doses of nitrogen. Pseudo-cereals are more susceptible to insect pests than cereals. Crop losses reported as a consequence of diseases and pests are relatively moderate. Ripening per plant is rather uneven, and seed shattering is a problem. Hence, the choice of harvest time is a compromise between a high percentage of unripe seed and large seed losses by shattering. After harvesting, field drying is more difficult than for true cereals because of uneven ripening and the great leaf mass. Well-cleaned and dried seed can be kept for a long time, as with true cereals.

The small-seeded pseudo-cereals are processed by milling, comparable to methods used for small-grain cereals. The whole grain is also toasted to produce a nut-like flavour.

Although research and breeding of pseudo-cereals have received much less attention than in the leading cereals, quite a lot of work has been done in countries where their economic importance is obvious. Substantial research has been done on buckwheat in Japan, Korea, China, India, Nepal and Russia, and much research has been done on grain amaranth in Latin America, India and Nepal. Quinoa research has mainly been executed in the Andean countries of South America. Renewed interest in pseudo-cereals in western countries like the United States has led to research and breeding activities with the emphasis on large-scale cultivation with combine harvesting for bulk production.
Organic farming practices for the production of health food are gaining ground.

1.11 Cereal research in South-East Asia

The research attention on cereals in South-East Asia is primarily focused on rice, maize and wheat. Most of the cereal research in the region is conducted by the International Agricultural Research Centres (IARCs) in collaboration with the National Agricultural Research Systems (NARSs). The rice cultivars produced by IRRI and the wheat cultivars produced by CIMMYT have been especially widely adopted by farmers. Also, but to a lesser extent, cultivars and breeding material of maize from CIMMYT, cultivars of millet and sorghum from ICRISAT, and barley cultivars from ICARDA have diffused to farmers' fields, as well as cultivars developed by the NARSs. The rise in average yield over the last 50 years is partially attributable to agricultural research, although it is difficult to quantify these effects.

1.11.1 International and national institutions

At the International Rice Research Institute (IRRI) in Los Baños, the Philippines, the following research issues are currently receiving much attention (IRRI, 1995):
- development of a new plant type of semi-dwarf indica rice with high yield potential (up to 15 t/ha) and multiple resistance to diseases and pests;
- hybrid rice development with effective seed production (male sterile and restorer lines with synchronized flowering);
- causes of long-term productivity decline in intensive cropping systems;
- optimization of technology for rice-based cropping systems;
- development of sustainable production technology for upland rice;
- development of environmentally sustainable and economically viable pest management technology;
- biotechnology, mainly to develop DNA-marker-assisted breeding and genetic transformation protocols.

The International Maize and Wheat Improvement Center (CIMMYT) in Mexico, with a branch in Bangkok, Thailand, reports the following research priorities (CIMMYT, 1994):
- improvement of wheat and maize yield potential and resistance to biotic and abiotic stress;
- development of drought-tolerant maize cultivars;
- improvement of the nitrogen recovery in wheat from 50% to 65%;
- gene mapping and marker-assisted selection in maize and wheat;

- optimization of technology for the rice–wheat cropping system (collaborative programme with IRRI).

The International Crops Research Institute for the Semi-Arid Tropics (ICRISAT) based in India performs research on sorghum and pearl millet (ICRISAT, 1994, 1995; Ramakrishna, 1993). Research priorities are:

- development of improved genetic material, with special attention for drought tolerance;
- integrated management strategies for control of *Striga*, insects and abiotic stress in sorghum;
- control of downy mildew, *Striga* and insect pests in pearl millet;
- development of forage cultivars of sorghum with related technology.

The research on cereals done at the NARSs in all South-East Asian countries has mainly been applied research, directed to the development of adequate technology packages for extension officers and farmers. Soil fertility and crop protection have received particular attention. Many cultivars suitable for regional ecological conditions have been selected on the basis of breeding material from the IARCs. Now that the NARSs are becoming stronger in breeding and applied research, the IARCs are shifting to 'upstream' research.

Cereal research in all South-East Asian countries has much in common. Everywhere rice is the priority crop, followed by maize. Little attention is given to sorghum, and even less to millets, other cereals of secondary importance and to pseudo-cereals. Only Burma (Myanmar), Vietnam and Thailand contribute some research on wheat.

1.11.2 Special topics

Crop modelling

Computerized simulation models are used in advanced cereal research to quantify the influence of ecological and biological yield-determining factors on crop yield. Crop modelling is a useful tool for assessing the effect of prevailing weather conditions (temperature, radiation, rainfall) on crop performance to optimize resource use efficiency (fertilizers, irrigation water, pesticides), to characterize the ecological zones of production areas (quantification of yield potential and risks), to analyse biotic stress caused by epidemic diseases and pests for the benefit of IPM programmes, and to evaluate plant ideotypes for specific environments (Elings & van Keulen, 1994; Goudriaan & van Laar, 1994; Lövenstein et al., 1992). EPIPRE is an example of a simple epidemic and yield loss model implemented in an IPM application (see 1.5.4). Another example of the application of dynamic simulation models in crop research is Systems Analysis and Simulation for Rice Production (SARP), a project coordinated by IRRI with NARSs in Indonesia, Malaysia, the Philippines, Thailand and other Asian countries. This project was initiated by Wageningen Agricultural University and the Research Institute for Agrobiology and Soil Fertility (AB-DLO) in the Netherlands (Aggarwal et al., 1995; ten Berge et al., 1994). The project covers research on potential production (crop responses to light and temperature, crop development and morphogenesis), crop and soil management (water and nitrogen management for different soils and cultivars), biotic stress, and crop protection (damage mechanisms of diseases and pests), and studies the optimization of rice agro-ecosystems (agro-ecological zonation, timing of crops and crop sequences, the rice–wheat system, and water use).

Biotechnology

Biotechnology has become a major tool in international plant-breeding research (Komen et al., 1995). Anther culture is used to create doubled haploid lines. This technology is especially useful for highly heterozygous crops such as maize, sorghum and pearl millet. Embryo rescue by tissue culture is used to cross parents whose embryos normally abort (often in interspecific crosses). Diagnostic techniques with isozyme electrophoresis are applied for detection of resistance genes and identification of genotypes. At present, much emphasis is put on molecular markers, many of which have already been placed on the genetic maps of rice (by IRRI), wheat and maize (by CIMMYT) and sorghum and pearl millet (by ICRISAT), using a technique called RFLP (Restriction Fragment Length Polymorphism) or PCR (Polymerase Chain Reaction)-based methods, e.g. RAPD (Random Amplified Polymorphic DNA). Linkages of molecular markers to QTL (Quantitative Trait Loci), resistances and quality features have been determined. The association between marker alleles and genes controlling agronomically important traits enables breeders to shorten and facilitate the selection process. This has proved to be especially useful in selection for desirable alleles in backcrossing programmes. Efforts with transgenic maize plants containing crystal protein genes from *Bacillus thuringiensis* have resulted in cultivars with resistance to insects.

Apomixis

Apomixis is the phenomenon of natural asexual seed production, the seed producing a clone of the mother plant. The creation of apomictic cereal cultivars would mean that farmers could rely on cheap farm-saved seed with a superior genetic composition (Jefferson, 1994). Apomixis makes it possible to clone any superior plant with hybrid vigour resulting from a crossing or with useful genes introduced from genetic engineering. Genes which control apomixis are found in some wild plant species, such as in the genus *Tripsacum* L., an ancestor of maize, and in the genus *Pennisetum* Rich. In these genera, apomixis is being transferred to the cultivated species by wide hybridization and backcrossing (Ozias-Akins et al., 1993; Savidan & Berthaud, 1994). In both programmes of apomixis transfer, molecular markers are used to assist in the selection of the apomictic mode of reproduction. Research is in progress to introduce apomixis through molecular biology into diverse cereal crops. Since the introgression of new genes requires sexuality, apomictic plants would spell the end of plant breeding, unless the apomixis is facultative and may be switched off temporarily for crossing. Farmers' applications are still a long way off.

Nitrogen fixation

Sorghum and millets are grown largely on rainfed, marginal soils by resource-poor farmers who cannot afford nitrogen fertilizer that can increase yields. In recent years, research has indicated that certain bacteria living in the rhizosphere of sorghum and pearl millet can fix atmospheric nitrogen symbiotically and partially satisfy the nitrogen requirement of these crops. A maximum nitrogen gain of 33 kg/ha per crop was obtained. Statistically significant increases in grain yield have been obtained in maize, pearl millet, sorghum and rice, inoculated with nitrogen-fixing bacteria such as *Azospirolla, Azobacter chroococcum* and *Azospirillum brasilense* (Wani, 1986). Seed inoculation might become a practical application.

1.12 Prospects

1.12.1 Consumption

Cereals are the dietary mainstay of mankind, providing about 60% of the required energy (Johnson, 1984). The simulation models for food strategies being made to predict the future food situation (Luyten, 1995; Meadows et al., 1991; Penning de Vries et al., 1995) take into account that the world food supply is largely determined by the cereal situation. The following assumptions regarding cereal consumption in South-East Asia seem to be justified:

- In the next century, in an optimistic scenario, the annual population increase is expected to slow down gradually from about 2% at present to about 1.6% in the year 2020. The world population might increase from 5.4 billion in 1996 to about 8.1 billion in 2020, and the population in South-East Asia from 0.46 to about 0.71 billion. The annual world demand for cereals might double during that period, from the present 2 billion to 4 billion t; in South-East Asia from 0.16 to 0.32 billion t.
- In South-East Asia, rising family income will mean that the direct consumption of cereals will decline, largely in favour of more luxury alternatives, mainly vegetables and animal products. However, indirect consumption will increase as a result of greater demand for animal feed. The outcome will be a slightly increased cereal consumption per capita. Cereal products considered as 'health food' will become more popular.
- Only a minor part of the consumption of bread and other wheat products in South-East Asia will be met by locally produced wheat or by wheat substitutes, thus wheat imports will rise. The import of maize, mainly for chicken and pig feed will also increase. Only with strong support of the public sector will most countries be able to remain self-sufficient in rice.

1.12.2 Production and trade

Rising labour costs may compel production systems to change to larger units using less labour-intensive technology. Direct sowing of rice will become common practice, which implies the use of more herbicides. The use of fossil energy to power machinery will increase sharply. The worlwide trend towards the bulk production of cereals implies a farming system characterized by farms that are large in size but small in number. However, many scientists point to the negative aspects of such a system: great dependence on purchased inputs, high risk of farm failure, poor system diversity, loss of biodiversity, high risks to environmental quality, high risks to human health, low reliance on rural communities. In the 1990s there is a growing movement in industrialized countries to arrive at an integrated, sustainable production system: use of solar energy, prevention of overconsumption, promotion of biodiversity, and organic farming without chemical pesticides.

Because bulk transport is easy and relatively cheap, cereals have become the main food commodity traded nationally and internationally, of utmost importance to balance national food shortages or surpluses. The spectacular increase in the world cereal production since the Green Revolution in the 1960s, however, has gradually levelled off. Since 1985, population growth has outpaced the increase in grain production, hence production per capita has declined. There are two main reasons for this. First, new land for cropping is becoming scarce. Even in those regions with an expanding economy the area planted with cereals is tending to decrease because farmers are switching to more remunerative crops (vegetables, fruits) or activities (meat, dairy products). Secondly, the increase in yield per ha is tending to level off. It seems to be becoming more difficult to create new cultivars yielding significantly more than existing ones, or to improve cropping techniques bridging the large gap between actual and potential yield. Another reason is the decline of cereal yield in the former Soviet Union.

It is of the utmost importance for global food security and thus for economical and political stability in the world, that sufficient reserves of cereals are maintained. Many countries have sufficient cereals in store to meet several months of their national annual need. However, an alarming development is the shrinking cereal stocks in the world, mainly caused by the rapidly increasing demand for feed cereals in China and by yields below long-term prospects. Between 1990 and 1995 annual world cereal production stabilized at around 1.9 billion t, whereas the surplus quantity in store decreased from 0.38 billion t (21% of the annual consumption) in 1992 to 0.26 billion t (14%) in 1995.

World trade regulations as agreed in the GATT (General Agreement on Tariffs and Trade) strive for increased liberalization of cereal trade as a function of demand and supply. This is in contrast to the tendency of governments to subsidize national cereal production and to prohibit export in periods of national shortage. Food experts do consider free global trade as an important step to food security. Rising cereal prices automatically stimulate farmers to increase their production, while consumers are stimulated to buy alternative staple foods, livestock farmers to use non-cereal feed, and the industry to search for other raw materials. Consequently, consumer prices will be lowered. Yet, in the short term, the replacement of a notable part of the cereal consumption by any other energy food is not feasible. In periods of worldwide cereal shortage, the poorest cereal-importing countries will face big problems in supplying this staple food to low-income classes. So, national policies are directed to guaranteeing an adequate supply of this staple.

1.12.3 Research priorities

Future research priorities reflect the expected demand for cereals and market trends. At present, policy makers point to the urgent need to match the basic food production with the population explosion.

In the coming 25 years, governments will probably be willing to strengthen their NARSs out of necessity. The expected increase in cereal demand can only be matched by raising land productivity to almost double the present level. This increase in yield might partly be achieved by genetic improvement, but will also largely be brought about by improved cultural practices, including the use of external inputs. With increased effectiveness of research at the NARSs, the research programmes of the IARCs will move to more fundamental or complex research. More research will be devoted to crop diversification, away from rice.

For the main cereals, the use of advanced technology will become normal practice (e.g. molecular markers in breeding programmes), although it may be a decade or more before some impact will appear. Genetic transformation will also gradually be incorporated in breeding programmes. The perpetual fight against newly arising biotypes of diseases and pests will remain an important objective for breeders. The NARSs may restrict their breeding work more to the development of interesting lines for the private seed sector, which is likely to become much stronger than at present. Researchers will be obliged to meet strong demands from society, e.g. relating to the environment and to food quality. And increasing urbanization and industrialization will cause labour costs to rise, forcing farmers to mechanize.

G.J.H. Grubben, Soetjipto Partohardjono & H.N. van der Hoek

Amaranthus L. (grain amaranth)

Sp. pl.: 989 (1753); Gen. pl. ed. 5: 427 (1754).
AMARANTHACEAE
2n = 32 (*A. caudatus*, *A. hypochondriacus*); 2n = 34 (*A. cruentus*); some confusion in species identities and chromosome counts warrants further studies

Major species and synonyms
- *Amaranthus caudatus* L., Sp. pl.: 990 (1753), synonyms: *A. mantegazzianus* Passerini (1865), *A. edulis* Spegazzini (1917).
- *Amaranthus cruentus* L., Syst. nat. ed. 10, 2: 1269 (1759), synonyms: *A. paniculatus* L. (1763), *A. sanguineus* L. (1763, pro parte).
- *Amaranthus hypochondriacus* L., Sp. pl.: 991 (1753), synonyms: *A. flavus* L. (1759), *A. frumentaceus* Buch.-Hamilt. ex Roxb. (1832), *A. leucocarpus* S. Watson (1875).

Vernacular names General: Grain amaranth, amaranth (En). Amarante (Fr). Amaranto (Sp). Indonesia: bayam (general), bayem (Javanese, Sundanese, Balinese). Malaysia: bayam. Papua New Guinea: aupa. Philippines: halom, kulitis. Cambodia: phti:. Laos: hôm. Thailand: phakkhom-suan. Vietnam: rau d[eef]n.
- *A. caudatus*: Love-lies-bleeding, red-hot-cattail, foxtail (En, ornamental form). Queue de renard (Fr). Indonesia: bayam ekor kucing. Malaysia: bayam selaseh. Thailand: phakkhom-baidaeng (Bangkok). Vietnam: rau d[eef]n du[oo]i.
- *A. cruentus*: Cock's comb (En, ornamental form). Brède (Fr). Laos: hôm dè:ng.
- *A. hypochondriacus*: Prince of Wales' feather, prince's feather (En, ornamental form).

Origin and geographic distribution Grain amaranths are crop species of New World origin (*A. caudatus* from Andean Peru and Ecuador, *A. cruentus* and *A. hypochondriacus* from Mexico and Central America). Paleobotany suggests some domesticates appeared as early as 4000 BC. The closest relatives are generally weeds of river banks, ditches and disturbed mesic habitats, distributed over large tropical and subtropical regions. Little is known about the ecogeography and evolutionary dynamics of these putative ancestors. There are two hypotheses on the origin of grain amaranth:
- the 3 cultivated species were independently domesticated from weedy species in 3 regions: *A. caudatus* from *A. quitensis* Kunth in South America, *A. cruentus* from *A. hybridus* L. in Central America, and *A. hypochondriacus* from *A. powellii* S. Watson in Mexico;
- the 3 cultivated species had a single origin: first *A. cruentus* arose from *A. hybridus* in Central America; subsequently, hybridization with local weed populations led to the selection of *A. caudatus* and *A. hypochondriacus*.

None of the hypotheses is conclusively supported by hybridization studies.
Grain amaranth cultivation was recorded in Incan and Aztec civilizations. It is now much reduced in importance, although recently it has been rediscovered as a crop. Three very significant dispersal events were:
- post-Columbian migration of ornamental types to Europe;
- 18th Century introductions of leafy (vegetable) types (mainly *A. cruentus*) to Africa;
- colonial transfers of grain types to India, Nepal and Sri Lanka and then recent dispersal to many South-East Asian and African countries, by migrants from the Indian subcontinent.

Thus, on a small scale these species are now cultivated in all continents and over a wide range of climatic conditions.

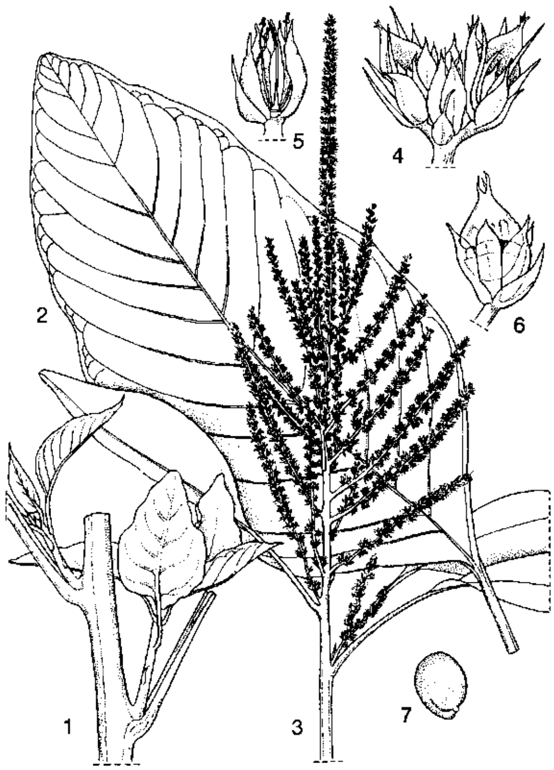
Uses The primary use of grain amaranth in human food includes many forms of milled and popped/puffed seed products. Sweet snacks (alegria, laddoo) of popped amaranth and various flour mixes with other cereals are traditional and common in Mexico, Guatemala, India and Nepal. Useful formulations have been developed for feeding infants, and for many potential baking and breakfast cereal products. Amaranth seed can be milled to whole-grain flour for use in baking. Bread made from amaranth flour is usually described as nutty and pleasant tasting. Amaranth meal or flour is especially suitable as the sole or predominant cereal ingredient for unleavened (flat) bread. For making yeast-raised bread or other leavened foods, it must be blended with wheat meal or wheat flour because it lacks functional gluten. The whole grain can be sprouted for use as a nutritious vegetable.
In multiple-use cropping, seedlings are harvested once or several times as a vegetable, and the grain or total biomass is harvested at maturity for food or forage. Large-scale forage production has been reported, particularly in China and Argentina. In addition to their excellent nutritional qualities, amaranths are traditionally valued for their use in medicine, folk festivals, and as dye sources.

Production and international trade No data are available on grain amaranth production and trade. Ethnobotanists and germplasm collectors have nonetheless found numerous farmers in countries such as India and Nepal growing grain amaranth very profitably. Some reports from the 1990s mention several thousands of ha under the crop in China, similar large production areas in the Argentine pampas, and about 3000 ha in the United States. Conservatively, acreage estimates for India and Nepal range up to 4000 ha. In Peru, there are over 1000 ha under grain amaranth in the high Andean region alone. The United States imports a large quantity of seed from Mexico to satisfy its growing speciality market. The many international meetings and general surveys suggest that production and trade have certainly increased since 1980.

Properties Amaranth grain is renowned for the excellent quality of its protein because of the high lysine content (3.2–6.4%). The overall high protein score (13–18%) and 7–8% fat (oil) with potential antioxidant properties, make grain amaranth interesting for human nutrition. The starch mainly consists of amylopectin, with only 5–7% amylose. The rather small starch granules (1–3 μm in diameter) have drawn wide attention for industrial uses. Similarly, significant amounts of squalene (4–11% of the total oil fraction) may find an important world market niche in products such as lubricants in computer industry and in cosmetics. 1000-seed weight is in the range of 0.4–1.1 g.

Description Erect, monoecious annuals, much branched, up to 2.5 m tall, with extensively branched taproot. Leaves alternate, with long petioles, simple and entire. Flowers in axillary clusters (compound dichasia, also called glomerules), upper clusters often leafless and arranged like terminal, panicled spikes, unisexual; each flower solitary in the axil of a bract, with 2 bracteoles and (3–)5 tepals; male flower with as many free stamens as tepals; female flower with ovoid or oblongoid ovary, style branched into (2–)3(–4) stigmas; ratio of male to female flowers within glomerules varies with species and cultivar. Fruit a laterally compressed utricle, usually with circumscissile dehiscence. Seed lenticular, pale or ivory in grain cultivars to shiny black or brown in weedy and vegetable forms.

- *A. caudatus*. Inflorescence usually lax, long, thick and pendulous, almost unbranched in ornamental forms, usually branched in grain forms; individual glomerules quite large and relatively far apart, giving the spikes a peculiar knobby appearance; bracts not protruding beyond the utricle, with slender midrib; tepals strongly recurved, very broad towards the tip, the inner ones spatulate, the outer ones more obovate; style branches (stigmas) spreading. Seed predominantly pale (ivory), but some plants with reddish or dark seed occur; outside South America reddish-seeded forms are most common.
- *A. cruentus*. Inflorescence lax, relatively small, soft; bracts very small, not protruding beyond the utricle, with slender midrib; tepals 5, straight, the inner ones oblong and pointed; style branches (stigmas) erect. Utricle cap constricted into a narrow column below the base of the style branches. Seed usually pale yellowish, but dark seed also occurs.
- *A. hypochondriacus*. Inflorescence large, thick and erect, with prickly appearance because of the large (as long as the style branches) and long-pointed bracts; tepals long, slightly recurved, acute; style branches (stigmas) thickened at base. Utricle cap large, gradually sloping to the base of the style branches. Seed predominantly pale, but mixed with varying



Amaranthus cruentus L. – 1, branch with axils; 2, leaf; 3, inflorescence; 4, glomerule; 5, male flower (one tepal removed); 6, female flower with dehiscing cap; 7, seed.

amounts of dark forms. Ornamentals always with dark seed.

Growth and development Seedlings emerge 3–5 days after sowing, and vegetative development is rapid. Landraces vary in the mode of transition from the vegetative to the reproductive stage, depending mainly on photoperiod and temperature. Flowering begins 60–110 days after seedling emergence. Monoecy, protogyny and variable male/female flower ratios may frequently produce high rates (30–35%) of cross pollination but the crop is usually handled as a self-pollinated crop. Most types of grain amaranth mature in 5–6 months. However, in some highland areas they may take up to 10 months to mature. A single plant may yield as many as 50 000 or more seeds. Most cultivars show large inter-plant variation in growth and yield characteristics.

Other botanical information In addition to the difficulties of identifying *Amaranthus* grain species because of the highly variable expression of floral characters used in keys, numerous crop–weed hybrid populations exist, which are grouped as *A. hybridus* L., *A. quitensis* Kunth or as feral races of *A. hypochondriacus*. Even dark versus light seed colours appear polymorphic in all of these taxa. Morphological descriptors including taxonomic keys and various genetic markers have shown grain amaranth collections to be highly diverse. Several races or morphological groups have been successfully described on the basis of plant form, local adaptation and origin. However, this is likely to change when more information from genetically designed studies becomes available. Allozyme variation studies show a remarkable contrast with the morphological observations: crop and weedy species can be broadly identified as two, partially overlapping, taxonomic groups, but the three species are not distinct from each other. It has not been adequately recognized that hybridization occurs naturally in the weedy or cultivated populations. Genetic studies of certain key ecophysiological characters such as photoperiod response and sex ratio may clarify the relations between the different groups. Two important aspects are noteworthy:

- domestication involved an increase in grain yield, a great diversity of inflorescence forms and colours, and a selection for pale seed; early flowering (without a short-day requirement) also evolved in many non-tropical areas; weedy relatives are generally more branched, their seeds are dark and shatter readily;
- Mexico, Guatemala and the Andean region require extensive studies as primary centres of diversity, whereas India and Nepal too have developed rather rapidly as a secondary centre.

Typical vegetable amaranths (*A. blitum* L., *A. dubius* C. Martius ex Thell., *A. tricolor* L.) originated from South-East Asia but emigrants have taken them to other regions as well. Local uses of weedy *A. hybridus* L., *A. spinosus* L., *A. retroflexus* L., *A. viridis* L. and others as a forage or a vegetable have also produced wide uncontrolled dispersal.

Ecology Information on the wide adaptability of grain amaranth is abundantly available in the literature but often based on pooling of both wild and cultivated species. Grain amaranths are C4-cycle plants, giving higher yields at higher light intensities and temperatures, and being efficient in water use. In the weedy species and in *A. caudatus* the photoperiodic response is marked, but in populations of *A. cruentus* and *A. hypochondriacus* sampled from a wide range of latitudes and elevations it is either highly variable or rather weak. In Thailand, several *A. caudatus* and *A. hypochondriacus* accessions performed well under cooler, drier highland conditions whereas the Mexican *A. cruentus* accessions did better in a warmer and more humid environment.

Grain amaranth prefers well-drained neutral or basic soils (pH $>$ 6), but some landraces are remarkably well adapted to acid and saline soils.

Propagation and planting Grain amaranth is traditionally grown in small plots by direct sowing or transplanting, and in sole cropping as well as intercropping systems. In the Himalayan region, for example, black gram, soya bean, maize and millet fields are bordered with amaranth. Larger plantings and current experimental trials emphasize optimal plant density for achieving high yields, e.g. rows 50 cm apart and plants within rows thinned to 20 cm distance to give nearly 100 000 plants per hectare. Branching habit and flowering and fruiting pattern can be influenced by choosing planting time, plant density and cultivar. Although dense plantings ($>$ 200 000 plants per ha) show self-thinning, a yield-depressing effect may occur. The seed-bed must be well prepared, and the seed placed 1–2 cm deep in firm moist soil. With mechanical row drilling, only 1.5–3.0 kg seed/ha is used. In small-scale cultivation the seed is broadcast and then raked in, or sown in pockets, and the young plants are thinned out. In that case the sowing rate must be higher.

Husbandry Crop establishment is fast and grain amaranth competes well with weeds. The stand must be weeded manually or mechanically at least once during the first month. The weedy amaranths must be removed because their black seeds are impurities in the pale cereal seed. In semi-arid areas with rainfed cultivation, acceptable yields are obtained with only 200 mm rain during the growing season, provided initial soil moisture is high enough.

The mineral uptake is rather high. On poor soils, fertilizer applications of 100 kg N, 100 kg P and 200 kg K are needed for high yields. Too much nitrogen makes the crop susceptible to lodging and to fungal diseases and pests.

Besides research for large-scale production, attention for the traditional cropping practices of grain amaranth must not be neglected, since water and fertilizer inputs are usually minimal in these indigenous systems.

Diseases and pests Damping-off caused by *Pythium* may occur when the seed-bed is too wet. Wet rot caused by *Choanephora cucurbitarum* and some other fungal diseases (*Albugo, Alternaria, Cercospora, Phoma, Rhizoctonia*) may cause problems. The crop is more susceptible to these diseases under humid conditions, high plant density and high doses of nitrogen. Plant parasitic nematodes are reported to occur but do not seem a serious problem.

The pests reported to cause economic damage sometimes are mainly leaf-eating caterpillars of the genera *Heliothis*, *Hymenia* and *Spodoptera*, stinkbugs (e.g. *Lygus* on the inflorescence), stem-boring larvae of weevils, grasshoppers, and aphids. The trend to large-scale commercial production will most probably result in numerous diseases and pests, requiring screening for resistance and breeding.

Harvesting Grain amaranth is harvested once-over by cutting the inflorescences at full maturity before the seed shatters. The period from flowering to harvest varies from (3–)4–5(–6) months, depending on cultivar, ecological conditions and cultural practices. A few United States cultivars are now sufficiently uniform to be machine-harvested. The main difficulty in mechanical harvesting is that the central inflorescence matures and dries out while the numerous inflorescences on lower side-branches are still developing. High-density planting modifies plant structure to a point where a single inflorescence is formed, making mechanical harvest more efficient.

Yield Seed yields vary widely from as low as 500–800 kg/ha to as high as 2500–4000 kg/ha. Most of these data are estimates based on small-plot harvests. Overall, the common impression of low yields and poor marketability is quite erroneous, as has been demonstrated in Peru, Mexico, Nepal, India, Kenya and other countries.

Handling after harvest Plants are dried on the ground. Sometimes they are covered with cloth sheets. Careful and rapid handling assures clean seed. After threshing, the grain should be dried to 12–13% moisture content for good storage.

Genetic resources Several genebanks (e.g. Rodale Research Centre and the USDA Station at Ames in the United States, the National Board for Plant Genetic Resources (NBPGR) in India, and institutes in Bolivia, Guatemala, and Mexico) have thousands of accessions, albeit with extensive duplication and inadequate records.

Breeding Grain amaranth is an extremely interesting plant for genetic research: genetic studies have been initiated to identify marker loci for pigmentation patterns, inflorescence forms and seed characters. Selection in landraces has shown promise. Over a dozen cultivars have been released in Peru, Mexico, United States, Argentina, and India. Breeding is most advanced in the United States. Important selection criteria are suitability for mechanical harvesting, high yield potential, resistance to lodging (dwarf growth, strong stem), early maturity, non-shattering, good drying of the seed-head with synchronous dry-down. Most cultivars are either *A. cruentus* or *A. hypochondriacus*, some are derived from interspecific crossing. For successful breeding, more systematic cooperation at international level is necessary to meet local needs. Breeders will require a series of superior germplasm resources as well as a set of elite lines or gene pools, selected genetic stocks such as male-sterile lines and non-shattering types, and of wild–weedy relatives which have also proven to be useful. Research is needed on hybridization barriers among species as well as on the biosystematic identity of the individual species; only then can the information be indisputably related to species.

Prospects The potential importance of grain amaranth lies in its combination of agronomic characteristics, nutritional qualities and food applications. Grain amaranth is becoming popular for production and biological research. Prospects are good for new industrial products based on the crop, and for improved cultivars and agronomic practices. Confusing information on taxonomic, genetic and ecological aspects should be clarified, to assure this crop continues to make progress in its newly expanding global setting.

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Chenopodium L. (grain chenopod)

Sp. pl.: 218 (1753); Gen. pl. ed. 5: 103 (1754).
CHENOPODIACEAE
$x = 9$; $2n = 36$ (*C. quinoa*); $2n = 54$ (*C. album*)

Major species and synonyms
- *Chenopodium album* L., Sp. pl.: 219 (1753), synonyms: *C. candicans* Lamk (1778), *C. hybridum* Lour. (1790), *C. leiospermum* DC. (1805).
- *Chenopodium quinoa* Willd., Sp. pl. 1: 1301 (1799), synonyms: *C. guinoa* Krocker (1823), *C. leucospermum* Schrader (1834), *C. album* L. subsp. *quinoa* (Willd.) Kuntze (1891).

Vernacular names General: Grain chenopod (En). Chénopode farineuse, ansérine (Fr). Vietnam: rau mu[oos]i.
- *C. album*: Fat hen, white goosefoot, pigweed (En). Lamb's quarter (Am). Ansérine blanche, chénopode blanc (Fr). Cenizo (Sp). Indonesia: dieng, dieng abang, dieng putih. Cambodia: momiënh. Laos: hôm küa. Vietnam: rau mu[oos]i tr[aws]ng.
- *C. quinoa:* Quinoa, Peruvian rice, Inca rice (En). Quinoa, riz du Pérou (Fr). Quinua, arroz del Peru, trigo inca (Sp).

Origin and geographic distribution *Chenopodium* is a large genus (100–150 species) found in temperate zones throughout the world. Some species have naturalized in the mountainous districts of the tropics.
- *C. album*: There is considerable evidence that in prehistoric times seed of fat hen was harvested for human consumption in both the Old and the New World. It is now mainly known as a noxious weed with global distribution, occurring from 70°N to 50°S. Fat hen has been domesticated in the Himalayan region, where it is grown in Nepal and northern India. It is also cultivated in the hilly regions of northern Thailand and in some mountainous areas of Java (Tengger), Indonesia.
- *C. quinoa*: Quinoa was probably domesticated between 3000 and 5000 years ago in several regions of the Andes, including Argentina, Bolivia, Chile, Colombia, Ecuador and Peru, and in the coastal regions of Chile. The crop was widely cultivated during the time of the Incas. After the Spanish conquest, there was a marked decline in the cultivation and use of quinoa. The traditional growing area in South America is between 2°N latitude in Colombia and 40°S latitude in Chile.

Uses *C. album* is nowadays a subsistence food crop for isolated hill communities inhabiting the montane zone of the middle Himalayan range. Grains are used as pseudo-cereal and young shoots and leaves as a vegetable. The use as a vegetable has been reported from all continents, including South-East Asia (Java, Indonesia).

Fat hen seed is processed into flour for pancakes and bread, or is boiled and mixed with other ingredients to make a kind of gruel, or is roasted and ground for porridge, and used for preparing fermented and alcoholic beverages. The seed is also used for poultry and livestock feed.

C. quinoa grains are traditionally toasted or ground into flour. They can also be boiled, added to soups, or made into breakfast foods or pastas. When boiled like rice, the grains have a nutlike flavour, and remain separated, fluffy, and chewy. Quinoa has demonstrated value as a partial wheat-flour substitute for enriching unleavened bread. The plant is sometimes grown as a green vegetable, and its leaves are eaten fresh or cooked.

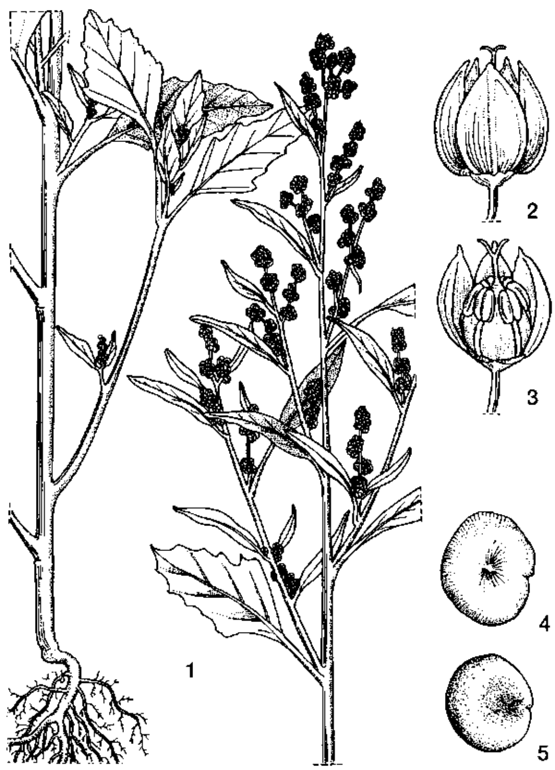
The leaves and stalks can also be used for animal feed.

Production and international trade Cultivation and use of *C. album* as a subsistence seed crop is limited to an estimated acreage of 1500 ha in the Himalayas.
An area of about 100 000 ha of *C. quinoa* is grown in the Andean countries. In the United States, an increasing demand for quinoa arose in 1980s and seed sales increased to 300 t in 1988. The seeds were mainly imported from South America. Grains, flour or pasta are now available in health food stores and supermarkets in North America and western Europe. In Colorado (United States), efforts were made to get the crop established at high altitudes and the first commercial crop was grown in 1988. In the United Kingdom, an application was found as a cover crop for game birds.

Properties Although little information is available on cultivars of *C. album*, it is assumed that the qualities of the seed do not deviate remarkably from those of quinoa. Seed of the weedy types, however, might be of inferior quality. Seed is about 1.0–1.8 mm in diameter. 1000-seed weight is about 1.4 g.
Quinoa seeds are very small, and vary in diameter from 1.8–2.6 mm. 1000-seed weight ranges from 2–6 g. Quinoa seed has an exceptionally high nutritional value. The energy value is 1450 kJ/100 g edible portion. The embryo takes up a greater proportion of the seed than in common cereals, resulting in an average protein content of 16%. The protein is high in the essential amino acids lysine, methionine, and cystine, making it complementary to true cereals for lysine, and to pulses for methionine and cystine. The seed contains about 60% starch and 5% sugar. The starch granules are extremely small. The small size of 2–4 μm gives the starch a fatty taste, and because of this property the starch can replace fat in diet products. The granules contain up to 20% amylose, and gelatinize in the 55–65°C range. The lipid content is 5%, half of which is linoleic acid. The seed contains 4% cellulose and fibre and 3% ash. The pericarp of quinoa seed contains saponins, soaplike components which foam when dissolved in water. Saponins reduce palatability due to their bitterness, and are toxic if they reach the bloodstream, since they damage the membranes of red blood cells. They are usually removed from the grain by vigorous washing and rubbing or by removing the whole pericarp. The content of saponins varies from almost zero in saponin-free cultivars to 4% in bitter cultivars.

Description Annual or rarely perennial herbs, sometimes with a pungent smell; young parts often densely to very densely clothed with minute, powdery, white or pink vesicles, usually soon losing their colour. Leaves alternate, petioled, herbaceous, variable in shape, entire, dentate-serrate or irregularly gashed. Inflorescence consisting of flower clusters, the clusters appearing solitary in leaf axils or arranged in axillary and terminal cymes, spikes or panicles; flowers hermaphrodite or female by abortion, sessile; bracteoles absent; tepals 2–5, free or shortly connate; stamens 1–5; pistil with depressed globose ovary, short style and 2(–5) stigmas. Fruit an utricle, often embraced by conniving tepals, thin-walled, indehiscent. Seed shiny or dull, smooth or finely tuberculate, lenticular; margin sometimes keeled; testa thinly coriaceous; embryo annular, surrounding the endosperm.

- *C. album*: Erect annual herb, 0.15–1.50(–3.80) m tall, not particularly pungent; young vegetative parts and outside of perianth densely clothed with mealy-white or red-purple vesicles, losing



Chenopodium album L. – 1, habit of flowering wild species; 2, flower; 3, flower (2 tepals removed); 4, fruit; 5, seed.

their colour sooner or later. Stem angular, ribbed, with longitudal dark green or red streaks. Lower leaves with long petioles, ovate-rhomboid, irregularly and coarsely dentate-serrate-laciniate or deeply gashed, higher ones gradually with shorter petioles, elliptical-oblong-lanceolate, less deeply incised or entire, 1.5–18 cm × 0.5–18 cm. Inflorescence large, axillary and terminal, leafy, paniculate, consisting of panicled clusters of flowers; flowers hermaphrodite; tepals distinctly connate at the base; stigmas 2. Fruit entirely enclosed by the incurved tepals. Seed nearly smooth, blackish-brown, 1–1.8 mm in diameter.

The cultivars can be distinguished from wild plants by their usually taller habit (up to 3.8 m), a large, leafless, exserted, compact and drooping inflorescence with bisexual and female flowers, 5 tepals, usually 5 stamens, non-shattering seed which is larger and predominantly black, brown or red.

- *C. quinoa*: Erect, annual herb, 0.7–3.0 m tall. Stem round at the base, becoming more angular where leaves and branches emerge, green, yellow, red, purple or orange, or green with stripes of another colour. At maturity the colour may change to pale yellow or to red. The reddish colours are due to betacyanins, not anthocyanins. Leaves alternate, with long petioles, the lower ones tend to be rhomboidal and the upper ones lanceolate; leaves of young plants are green under their layer of pubescence, but turning yellow, red, or purple as the plant matures. Inflorescence a panicle, having a principal axis from which secondary axes originate, compact or lax, 15–70 cm long; in the 'amaranthiform' type, clusters of flowers are directly inserted in the secondary axes, whereas in the 'glomerulate' type the clusters of flowers are inserted in tertiary axes originating from the secondary axes; flowers incomplete (as no petals are present), hermaphrodite; tepals 5, anthers 5, superior ovary with 2 stigmatic branches. Fruit sometimes covered by the perianth, which can easily be removed by rubbing; pericarp translucent, white, yellow, orange, pink, red, brown or black. Seed translucent, white, brown or black.

Growth and development Seedlings will emerge in approximately one week in a sufficiently moist soil with an average temperature above 10°C. One week later the first true leaves will appear, and flowering may start 50–70 days after emergence. The period between sowing and anthesis and from anthesis until maturity is very variable. Early and daylength-neutral cultivars may take 50–60 days to flowering and 90–110 days to maturity, whereas late and short-day cultivars need 4–5 weeks longer. Grain chenopods are predominantly self-pollinating, cross pollination is less than 10%.

Other botanical information The *C. album* which occurs wild worldwide is part of a very variable polyploid weed complex that has so many names (from species and subspecies to forma level) that it is impossible to describe and fix its polymorphy. In the montane zone of the central Himalayan region, forms selected from this complex are now cultivated for their grains and for their leaves. In Himachal Pradesh (India, northwestern Himalayas), four chenopod grain cultivars are distinguished mainly based on seed colour: 'Black', 'Brown', 'Red' and 'Earthen'. The cultivars Black, Brown and Red certainly developed from the *C. album* complex and are quite similar in all characteristics except the predominant seed colour. 'Earthen' however, is a deviating cultivar, and as well as having earth-coloured seeds the plants are smaller, the branching pattern is narrow-angled, the leaf type cordate or linear, and the seeds smaller (1000-seed weight is 0.8 g). 'Earthen' has not developed from the *C. album* complex; it is closer to *C. quinoa* but too different from it to suppose evolutionary relationship. Its taxonomic position is still unclear.

The cultivated grain chenopod of Java (perhaps more important as a leaf vegetable) is quite similar to *C. album*, but distinguishable from it by its usually larger size (up to 2.5 m tall) and larger leaves (rhombic-deltate, up to 14 cm × 14 cm) but especially by its bright reddish-purple young parts (colour disappearing in older parts). It has been classified as *C. album* L. subsp. *amaranticolor* Coste & Reyn., but at present most authors consider it to belong to a different species in the *C. album* complex: *C. giganteum* D. Don, which also occurs worldwide.

Several cultivars adapted to local growing conditions have been developed in the production centres of *C. quinoa* in South America. Sea-level cultivars from Chile showed the best adaptation to western European conditions because of their daylength-neutral nature. In the United Kingdom, Denmark and the Netherlands improved cultivars have been selected from Chilean landraces and from the progenies of hybrids.

Two other grain chenopods are cultivated on a small scale in tropical America. The first one is *C. berlandieri* Moq. subsp. *nuttalliae* (Safford) Wilson & Heiser ($2n = 36$), synonym: *C. nuttalliae* Safford. This 'huauzontle' occurs in Mexico, but its cultivation is declining. It is more important as a vegetable than as a grain crop. The second one is *C. pallidicaule* Aellen ($2n = 18$). 'Canihua' originated from the Andes and is important as a seed crop on the high plateau of Peru and Bolivia at altitudes between 3800–4300 m, where it can survive severe night frost of −10°C. It is a small, 20–60 cm tall, much branched, bushy plant with a shorter growing season than quinoa. Contrary to quinoa, canihua seeds do not contain saponins. They are smaller and coloured brown to dark brown. Flowers appear to be virtually cleistogamous.

Ecology *C. album* is cultivated in Himalayan valleys between 1500–3000 m altitude, but its wide distribution as a weed points to tolerance of climates with average temperatures ranging from 5–30°C. It tolerates night frost. In Java, it has naturalized at altitudes between 800–2300 m. In the long days of the temperate zone it grows to a large size and it is there that it offers the most serious competition to crops as a weed.

C. quinoa is a temperate or subtropical plant grown in areas with temperatures up to 35°C. Higher temperatures may cause sterility. Quinoa withstands light night frost but is sensitive to temperatures below −3°C. The upper limit of cultivation is 4000 m altitude. Some cultivars are insensitive to photoperiod, whereas others flower later under increasing daylength. In South America, quinoa is grown under marginal conditions where other cereals cannot easily be cultivated. It grows best when rainfall is well-distributed during early growth and conditions are dry during maturation and harvest. It can withstand excessive amounts of rainfall during early growth and development, except directly after sowing. Wet conditions during germination can reduce emergence when the soil is poorly drained. Quinoa is notable for its drought tolerance, especially during late growth and maturation. At the end of the ripening period the crop becomes very sensitive to rainfall, and if considerable rainfall falls during one day the seed, which is not dormant, may sprout prematurely. Early cultivars are more sensitive for sprouting than late ones.

Quinoa is grown in soils varying in acidity from pH 6–8.5. It tolerates soils that are infertile, moderately saline and have low base-saturation. Although adapted to poor growing conditions, quinoa responds extraordinarily well to fertilizer.

Propagation and planting The most common practice for grain chenopods is sowing 1–2 cm deep in rows 25–50 cm apart depending on the soil moisture content. Seed rate is 6–10 kg/ha, resulting in 100–150 plants per m^2. The seed-bed should be well prepared. The seed may also be broadcast, but when sown in rows it is easier to weed. Broadcasting requires about 20 kg of seed per ha. In Himachal Pradesh (India), *C. album* is often intercropped, e.g. with finger millet, potato, maize, rice, amaranth, foxtail millet, sesame, soya bean, taro, cowpea or common bean.

Husbandry Grain chenopods fit very well in crop rotations with other annual crops, e.g. Irish potato. Because of their well-developed rooting system, they can utilize nutrients left from the preceding crop, in particular phosphorus. In general, fertilization comparable to wheat or maize is recommended.

The most troublesome weed in quinoa cultivation is the related species *C. album* (fat hen). Fat hen has an almost identical habit and growing pattern to quinoa. The seeds of weedy fat hen are inferior in quality, and reduce the value of the harvested product. Therefore, land severely infested with fat hen should be avoided for cultivation of quinoa.

Diseases and pests Grain chenopods are rather susceptible to damage by diseases and pests. The most important disease is downy mildew (*Peronospora farinosa* f.sp. *chenopodii*), which causes much damage in growing areas all over the world. The disease is favoured by warm and humid weather. Some cultivars are partially resistant. Other fungal diseases are leaf spot (*Ascochyta hyalospora*), brown stalk rot (*Phoma exigua*), grey mould (*Botrytis cinerea*), and seed rot or damping-off (*Sclerotium rolfsii*). A virus disease is known as chlorotic mosaic.

Several cutworm species attack the young plants. The most serious insect pest is a leaf miner or leaf sticker, *Eurisaca melanocompta*. *Lyriomiza brasiliensis* is another leaf miner found on grain chenopods. Caterpillars (e.g. *Hymenia recurvalis*) destroy leaves and inflorescences. Several loopers, beetles, aphids, leafhoppers and thrips may also cause damage. Chemical pesticides are often applied. In temperate countries, insecticides are used to control aphids and caterpillars.

Birds attacking the crop before harvesting or during field drying probably cause the greatest crop losses. Bitter cultivars are less prone to such attacks than sweet ones.

Harvesting The crop matures in 4–5 months. It can be harvested after the leaves have senesced, when the panicle and the upper part of the stem have lost their specific colour. The harvesting methods commonly used for cereals can also be used for grain chenopods. Plants are cut, bundled and dried, threshed, and the grain is winnowed.

Yield For fat hen, yields of 0.2–0.6 t/ha are reported from farmers' fields in India. The average yield of quinoa in South America is around 0.8 t/ha. One reason for low yields may be that grain chenopods are not often grown alone but are usually intercropped. In temperate areas, quinoa may yield 1–4 t/ha.

Handling after harvest Due to their architecture, panicles do not dry easily. At harvest, seed moisture content may be around 20%. Artificial drying to 14% moisture may be necessary.

Genetic resources Germplasm collection of *C. album* is urgently needed, since the cultivation of fat hen in the Himalayas is definitely declining as a result of lack of crop improvement, and therefore farmers are substituting other, more profitable crops.

Peru and Bolivia have extensive collections of *C. quinoa* exceeding 2000 accessions. Other collections exist in Chile, Argentina, Ecuador, Colombia, the United States, Russia, Germany, England, Denmark and the Netherlands.

Breeding Cultivated Himalayan *C. album* has so far been neglected. It is practically unknown outside the region of cultivation.

Much breeding research is carried out on quinoa at agricultural research institutes in Peru, Chile, and other Latin American countries, in the United States (Colorado) and in some West European countries. The main breeding objectives are reduction of the saponin content, adaptation to specific environments, earliness, and resistance to premature sprouting and diseases. In Bolivia, two sweet cultivars were developed, 'Sajama' and 'Narino', which are most suitable for human consumption. 'Sajama' yields up to 3 t/ha. In the United Kingdom, Denmark and the Netherlands, breeding programmes are conducted and cultivars adapted to European conditions are in development.

Prospects Quinoa prices may rise and production may increase as a consequence of its importance as a health food. It has potential as a specific starch-producing crop. The malted grains and flour hold promise as a weaning food for infants. Quinoa is also one of the best sources of leaf-protein concentrate.

Quinoa seems particularly promising for improving income and health in marginal upland areas. It could probably be cultivated in tropical highland regions, such as elevated parts of South-East Asia.

Given their similarity, one would expect both fat hen and quinoa to be intensively screened and their potential researched.

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Coix lacryma-jobi L.

Sp. pl.: 972 (1753).
GRAMINEAE
$2n = 4x = 20$

Synonyms *Coix lacryma* L. (1759), *C. agrestis* Lour. (1790), *C. arundinacea* Lamk (1791).

Vernacular names Job's tears, adlay (En). Larmes de Job, larmilles, herbe à chapelets (Fr). Indonesia: jali, jali betul, jali watu. Malaysia: jelai batu, jelai pulut, menjelai. Philippines: adlai (Bisaya), kaudlasan (Tagalog), katigbi (Tagalog). Cambodia: skuöy. Laos: düay. Thailand: duai (general), maduai (northern). Vietnam: [ys] d[ix], bo bo, c[uw][owf]m g[aj]o.
Note: The Arabs, who introduced the plant to the West, named it 'Damu Ayub' (Job's tears), because its false fruit resembles a tear-drop. This name has been adopted in several other languages.

Origin and geographic distribution The origin of Job's tears is unknown, but it is indigenous to southern and eastern Asia. The form with soft-shelled false fruit (var. *ma-yuen* (Romanet) Stapf) has been cultivated since ancient times – 3000–4000 years ago in India, 2000 years ago in China – and was very important before maize and rice became widespread staple foods. At present it is cultivated as a minor cereal crop throughout the tropics and subtropics, especially in India, China, the Philippines, Thailand, Malaysia and the Mediterranean. Forms with hard-shelled false fruit are also occasionally cultivated. Plants escaped from cultivation occur as weeds.

Uses The form with soft-shelled false fruit (var. *ma-yuen*) can be easily husked and has large kernels which are eaten in the same way as rice, alone or mixed with it. They can be substituted for rice in all foodstuffs. In Malaysia the grain is roasted before husking and then used in porridge and in cakes. In Thailand it is also often used in the preparation of sweets and sometimes in soups and other foods.
Dough made from the flour will not rise because of the absence of gluten. A good mixture for bakery purposes is 70% wheat and 30% Job's tears.
The raw kernel tastes sweet and is often eaten as a snack. Both alcoholic and non-alcoholic drinks are prepared from it. In Japan a kind of tea, called 'dzu', is made from the parched grain. A beer made from the pounded grain is popular among Indian hill tribes and in the Philippines.
The whole grain is fed to poultry and the flour can replace maize flour in poultry feed. Outside Asia, Job's tears is mainly cultivated as a fodder, especially for cattle and horses. It is suitable for silage. Straw and leaves are used for thatching.
The grain and flour are very digestible and are believed to have medicinal value. Therefore, they are given to people in weak condition; in Vietnam they are considered beneficial to the lungs. The roots in particular are applied for medicinal purposes, a decoction of them being used as a vermifuge in China and to treat gonorrhoea in the Philippines. In India the roots, together with parts of other plants, are used against a wide range of ailments, e.g. against menstrual disorders.
Almost everywhere where Job's tears grows, the attractive, hard-shelled false fruits of the wild forms are used for necklaces, rosaries, bead curtains and the like. The whole inflorescence is sometimes used in dried flower arrangements.

Production and international trade Job's tears is mainly used and traded locally only. It is often considered as a reserve food in times of scarcity. Recent data on production and cultivated acreage are very scarce. A 1985 study on the Iban hill farming system in Sarawak concluded that 55% of the households cultivated Job's tears but seldom on more than 10% of the farm area.
In Thailand the production areas are found in the north and north-east but no exact data are available. About 4000–6000 t of grain are exported to Japan and Taiwan yearly.

Properties Per 100 g edible portion the husked grain of Job's tears contains: water 10.1–15.0 g, protein 9.1–23.0 g, fat 0.5–6.1 g, carbohydrates 58.3–77.2 g, fibre 0.3–8.4 g, ash 0.7–2.6 g. The energy value is about 1500 kJ/100 g. Job's tears is a nutritious grain, containing more fat and protein than rice and wheat. The root contains coixol which is analgesic and sedative.
The 1000-seed weight is 80–90 g.

Description Erect, perennial, strongly tillering, monoecious grass, often cultivated as an annual, up to 3 m tall. Culm filled with pith, glabrous, sometimes pruinose, branched in the upper part. Leaves large and sheathed; sheath short, glabrous or with long hairs at the apex; ligule short and membranous; auricles absent; blade linear to ovate-lanceolate, 8–100 cm × 1.5–5 cm, base rounded to almost cordate, apex acute, midrib prominent, margins rough, smooth or scabrid above. Inflorescence in axil of upper leaves, solitary or 2–7-fascicled, on peduncle 3–6 cm long; at the end of the peduncle a hollow, bony, globular to ovoid-elliptical cupule (a modified leaf-sheath), 5–15 mm long, shiny, white or blueish,

Coix lacryma-jobi L. – 1, habit flowering stem; 2, male inflorescence; 3, male spikelet; 4, female inflorescence with involucre partly removed.

comprising 2 racemes; female raceme enclosed by the cupule and consisting of a sessile spikelet accompanied by 2 barren pedicels; spikelet with 1 pistillate floret of which the 2 stigmas exsert from the mouth of the cupule; male raceme 3–5 cm long, exserted from the mouth of the cupule, with about 10 imbricate spikelets borne in pairs or threes, one pedicelled, the other(s) sessile; spikelet lanceolate to ellipsoid, 7–8 mm long, falling at maturity, containing 1–2 staminate florets, each with a lemma, a smaller palea and 3 stamens. False fruit (the cupule) variable in size, shape, colour and hardness, usually 8–12 mm long, grey, yellow-brown or purplish, soft or hard, containing the caryopsis. Caryopsis dark red in hard-shelled forms, pale brown in soft-shelled edible forms.

Growth and development Job's tears takes about 1–2 weeks to germinate, depending on the moisture content of the soil. The plant does not grow very fast; normally it requires at least 4 months of vegetative growth before it starts to flower. After flowering (and cross pollination) the crop needs about two months for grain filling. The crop is ready for harvest about 7 months from sowing. When most of the seeds are ripe, the plant starts to dry.

Other botanical information The genus *Coix* L. is now considered to comprise 4 closely related species, all occurring in South-East Asia, while some have also been introduced elsewhere:
- *C. aquatica* Roxb. (synonym: *C. lacryma-jobi* L. var. *aquatica* (Roxb.) Watt): a weed of ponds and lakes, sometimes used as fodder;
- *C. gigantea* Koenig ex Roxb. (synonyms: *C. lingulata* Hack., *C. lacryma-jobi* L. var. *palustris* (Koorders) Backer): a weed of moist or dry locations, erect, sometimes collected for food, false fruit often used for ornamental purposes;
- *C. puellarum* Balansa (synonym: *C. lacryma-jobi* L. var. *puellarum* (Balansa) A. Camus): a perennial occurring in India, Burma (Myanmar), Indo-China and Peninsular Malaysia, used for ornamental purposes;
- *C. lacryma-jobi* L. Mainly based on characteristics of the false fruit, 4 varieties are distinguished:
  - var. *lacryma-jobi*: false fruit ovoid, 8–12 mm × 6–8 mm, hard, not striate; usually collected from the wild, sometimes cultivated for food or ornaments (necklaces); it is the commonest (wild) type, distributed pantropically; many medicinal uses;
  - var. *monilifer* Watt: false fruit globose, 7–10 mm in diameter, flattened on one side, hard, not striate; a rare type, only known from Burma (Myanmar) and eastern India; uses unknown, but could be ornamental;
  - var. *stenocarpa* Stapf (synonyms: *C. stenocarpa* (Stapf) Balansa, *C. tubulosa* Hack. ex Warb.): false fruit cylindrical or roughly bottle-shaped, hard, not striate; mainly grown as an ornamental;
  - var. *ma-yuen* (Romanet) Stapf (synonyms: *C. ma-yuen* Romanet, var. *frumentacea* Makino): false fruit ovoid to pyriform, 8–12 mm long, quite soft, striate, shell-like; cultivated pantropically mainly for its edible false fruit as a cereal, and most information presented here concerns this variety; many local (unnamed) landraces exist; in Thailand glutinous and non-glutinous cultivars exist; in Brazil a high-yielding, early-maturing dwarf form with brown elongated false fruit has been selected.

Ecology Job's tears is a quantitative short-day plant and requires high temperatures, abundant rainfall, reasonably fertile soils, and prefers short, sunny days. In the tropics it occurs up to 2000 m altitude. It often grows wild in swampy locations.

Propagation Job's tears is usually propagated by seed (caryopsis). If not stored well, seed will quickly lose its viability under warm humid conditions. Seed is sown by dibbling, 5 cm deep, at the start of the rains, after ploughing or hoeing the field. Row spacing is 40–80 cm, the seed rate 7–15 kg/ha. When cultivated as an intercrop, it is sown at random or plants are grown along field borders. Propagation by cuttings is possible and recommended for fodder production. Propagation by seed gives deeper rooting, and, consequently, better drought tolerance and higher seed yield.

Husbandry Weeding is necessary up to 60 days after sowing or until Job's tears has reached a plant height of 40 cm. In general, plants are not given much care, but when young they need abundant water. They respond well to application of manure; chemical fertilizers or insecticides are not used.

Diseases and pests Job's tears is relatively little affected by diseases and pests. The most serious disease is smut (*Ustilago coicis*) which destroys the ovaries; it severely damages crops in Thailand, that is why it is recommended to treat seed with a fungicide or with hot water (60–70°C) for at least 10 minutes before sowing. Tar leaf spot (*Phyllachora coicis*) has also been reported from Thailand. Other diseases which may occur are rust (*Puccinia operata*) and *Ustilago lachrymae-jobi*.
Rats, birds and sometimes grasshoppers and termites may cause considerable losses.

Harvesting Job's tears can be harvested 4–8 months after sowing, depending on the cultivar and the season. Usually, whole plants are cut at the base when the grain is ripe. The stubble can be left in the field and will then tiller again. The new fresh leaves are an excellent fodder. In Thailand the crop is harvested with a sharp knife by cutting the top of the plant which bears the infructescences. In some cases (Malaysia) the stems are snapped first, to accelerate drying.

Yield Normal yield of husked grain varies from 2–4 t/ha. The hulling percentage is 30–50%. If cultivated for fodder, several cuts per year are possible.

Handling after harvest After threshing and husking, which is done manually or with the same tools as for rice, the grain is dried on mats in the sun. Under humid conditions, the storability of the grain is limited, but is better for whole than for husked grain.

Genetic resources There is considerable variation in cultivated and wild Job's tears. The greatest variation in wild forms can be found in India and Burma (Myanmar), and in cultivated Job's tears in Indo-China. During 1983–1984, edible forms of *C. lacryma-jobi* were collected in Thailand and stored at the National Genebank of Thailand.

Breeding In the course of time, Job's tears has been selected by farmers for easy husking, resulting in var. *ma-yuen*. However, the crop has a relatively long growing season, shows uneven ripening and variable yields. Nevertheless, large variation in Job's tears offers opportunities for breeding programmes. In Thailand, breeding work is being carried out to obtain resistance against smut disease. In Japan selection work focuses on the use as a fodder. In Brazil, a promising high-yielding 'dwarf' cultivar, probably introduced from Japan, has been selected and distributed.

Prospects Although enjoyed locally by many people, Job's tears is still decreasing in popularity in favour of higher-yielding cereals, mainly maize and rice. However, it has some advantages over these other cereals. It is less susceptible to diseases and pests, it can be grown where other crops are difficult to cultivate, and it does not need much care. Furthermore, it is more nutritious. In spite of these advantages, hardly any research attention has so far been given to Job's tears. Therefore at this stage it is most important to conserve the great diversity in germplasm collections.
Promising research on the crop as a fodder is in progress in Japan and Africa.

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M.H. van den Bergh & N. Iamsupasit

Echinochloa P. Beauvois

Ess. agrost.: 53 (1812).

GRAMINEAE

$x = 9$; $2n = 6x = 54$ (*E. colona* cv. group Frumentacea, *E. crus-galli* cv. group Esculenta).

Major taxa and synonyms

- *Echinochloa colona* (L.) Link cv. group Frumentacea, Hort. Berol. 2: 209 (1833); cv. group name proposed here. Synonyms: *E. frumentacea* (Roxb.) Link (1827), *E. crus-galli* (L.) P. Beauvois var. *frumentaceum* (Link) Trimen (1885), *E. colona* (L.) Link var. *frumentaceum* (Roxb.) Ridley (1925).
- *Echinochloa crus-galli* (L.) P. Beauvois cv. group Esculenta, Ess. agrost.: 53, 161 (1812); cv. group name proposed here. Synonyms: *Panicum esculentum* A. Braun (1861), *E. utilis* Ohwi & Yabuno (1962), *E. esculenta* (A. Braun) H. Scholz (1992).

Vernacular names General: Barnyard millet (En). Vietnam: l[oof]ng v[uwj]c.

- *E. colona* cv. group Frumentacea: Indian barnyard millet, sawa millet, shama millet (En). For wild *E. colona*: jungle rice (En). Indonesia: tuton, watuton (Javanese), jajagoan leutik (Sundanese). Malaysia: padi burong, rumput kusakusa. Philippines: pulang-puwit (Tagalog), guinga (Visaya), dakayang (Ilokano). Burma (Myanmar): myet-thi, pazun-sa-myet. Laos: khauz nôk. Thailand: ya-noksichomphu (central), yanokkhao (northeastern). Vietnam: c[or] l[oof]ng v[uwj]c, c[or] n[us]c, c[or] l[oof]ng v[uwj]c h[aj]t.
- *E. crus-galli* cv. group Esculenta: Japanese barnyard millet, Japanese millet (En). For wild *E. crus-galli*: barnyard grass, cock's foot (En). Crête-de-coq, pattes de poule (Fr). Indonesia: jawan (Javanese), jajagoan (Sundanese), gagajahan (Sundanese). Malaysia: padi burong, rumput kekusa besar. Philippines: bayokibok (Tagalog), lagtom (Bikol), marapagay (Ilokano). Burma (Myanmar): myet-ihi. Cambodia: smao bek kbol. Thailand: ya-plonglaman, ya-khaonok (central). Vietnam: c[or] l[oof]ng v[uwj]c.

Origin and geographic distribution Indian barnyard millet most probably originated from India where it has been domesticated from the wild *E. colona*. Wild *E. colona* originated from the tropics and subtropics of the Old World but can now be found in the tropics and subtropics all over the world and is very common in South-East Asia. Indian barnyard millet is known from ancient Egypt and East Africa but is at present widely grown as a cereal only in India, Kashmir and Sikkim. It has been introduced into the United States, Canada and Australia, especially as a forage. In continental South-East Asia, Indian barnyard millet is quite commonly cultivated but in Peninsular Malaysia it only occurs as a rare weed in cultivated fields.

Japanese barnyard millet most probably originated from Japan where it was domesticated from the wild *E. crus-galli* some 4000 years ago, and was later introduced into Korea, China and adjacent Russia as a cultivated cereal. Wild *E. crus-galli* is native to temperate Europe and Asia but has spread to temperate and tropical areas all over the world; it is also very common in South-East Asia. Japanese barnyard millet is only extensively cultivated in Japan, Korea and northern China.

In non-continental South-East Asia both barnyard millets are rare at present. However, it is thought that formerly one or both barnyard millets were commonly cultivated in Java. It is even believed that the name 'Java', meaning 'millet island', refers to the abundant occurrence of one or both barnyard millets in former times.

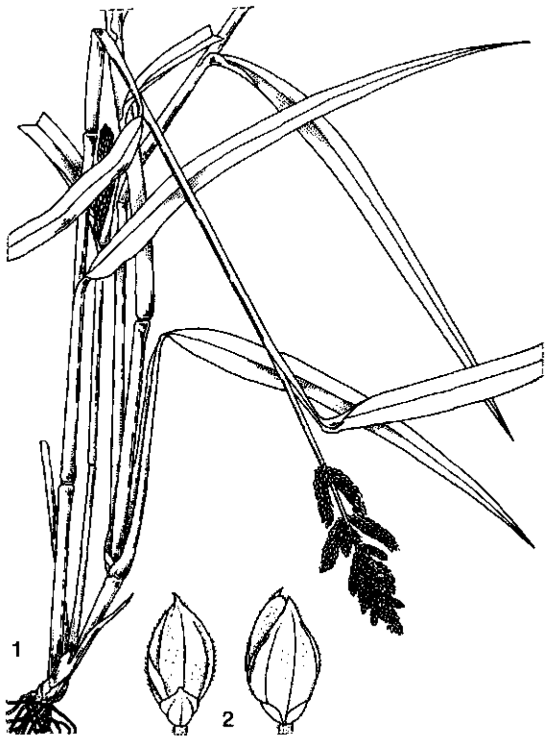
Uses In areas where the culta are grown as cereals, they are also used, prepared and eaten as cereals. The grains are cooked in water like rice, or parched and boiled with milk and sugar. They are also sometimes mixed with rice and fermented to make beer. In South-East Asia, both taxa and culta are used as grain crops in times of food scarcity. The coarse, tough seed coat and the characteristic flavour make barnyard millet less popular among rice and wheat eaters. The seed is used as a feed for cage birds. Although the wild taxa can be troublesome weeds, especially in paddy rice, they are used as excellent forages which can also be fed as hay. In Java, young shoots of both barnyard millets are eaten as a vegetable.

Production and international trade Both barnyard millets are not of great importance and are only locally produced, used and traded. Often they are grown as a substitute for rice when the paddy crop has failed. No statistics are available. World production of all millets together amounted to 36 million t in 1993 (pearl millet (*Pennisetum glaucum* (L.) R. Br.) 40%, foxtail millet (*Setaria italica* (L.) P. Beauvois) 24%, proso millet (*Panicum miliaceum* L.) 15%, finger millet (*Eleusine coracana* (L.) Gaertner) 11%, other millets (including barnyard millet) 10%). Millet production has been declining annually by about 2% since the 1980s. In Japan, barnyard millet cultivation fell from 104 000 ha in 1880 to 5000 ha in 1970.

Properties The approximate composition of the grain of Indian barnyard millet per 100 g edible portion is: water 11.9 g, protein 6.2 g, fat 2.2 g, carbohydrates 65.5 g, fibre 9.8 g and ash 4.4 g. Barnyard millet protein lacks gluten and therefore the millet alone is unsuitable to prepare bakery products. Compared with wheat and rice starches, the starch of barnyard millet has a higher gelatinization temperature, a higher water-binding capacity and a slower enzymatic hydrolysis. Because the release of sugars from millet-based diets is slow, millets are considered a good food for diabetics. The protein content of Japanese barnyard millet is nearly twice as high as that of polished rice. A mixture of 7 parts polished rice and 3 parts barnyard millet provides a favourable nutritive balance. The straw is considered superior to that of rice, oats or timothy in protein and calcium content.
The 1000-grain weight of barnyard millet is 3–4 g.

Description Annual or perennial herbs. Leaves usually without a ligule. Inflorescence consists of racemes arranged along a central axis; spikelets paired or in short secondary small racemes, typically densely packed in 4 rows, narrowly elliptical to subrotund, flat on one side, gibbous on the other, often hispidulous, sometimes prolonged at the base into a short cylindrical stipe, cuspidate or awned at apex; florets 2, the lower staminate or neuter, the upper perfect; glumes acute to acuminate, about one third the length of the spikelet; lower lemma often stiffly awned; upper lemma terminating in a short membranous, laterally compressed, incurved beak; upper palea acute, the tip briefly reflexed and slightly protuberant from the lemma.

- *E. colona* cv. group Frumentacea: Erect or geniculate ascending, often tufted annual, 0.6–2.4 m tall. Culm slender to robust; slender plants decumbent with strongly branched culms, rooting from the lower nodes; robust plants erect, only branching at the upper nodes. Leaf sheath glabrous, usually longer than the internode; ligular area minutely pubescent; leaf blade linear, 8–38 cm × 0.6–4 cm, subglabrous. Inflorescence usually erect, in decumbent plants with short racemes appressed to the triquetrous rachis, in erect plants with spreading lower racemes giving the inflorescence a larger pyramidal shape; pedicel 2–4-nate, up to 2 mm long; spikelet persistent, 2–4 mm long, acute but never awned; glumes and lower lemma typically membranaceous; lower glume about one third the length of the spikelet, upper glume somewhat shorter than the spikelet, ciliolate; lower lemma similar to upper glume; lower floret sterile, upper floret bisexual. Caryopsis broadly ellipsoid, 2–3 mm long, 1–2 mm wide.
- *E. crus-galli* cv. group Esculenta: Erect, tufted annual, up to 1 m tall. Culm usually robust, simple or branched from the upper nodes. Leaf sheath glabrous, usually longer than the internode; ligular area glabrous; leaf blade linear, 15–40 cm × 0.5–2.5 cm, glabrous. Inflorescence erect or slightly nodding, with spike-like racemes that are erect or sometimes incurved at the tip; primary axis densely white setose at the



Echinochloa crus-galli (L.) P. Beauvois cv. group Esculenta – 1, habit; 2, 2 views of a spikelet.

nodes; racemes 10–25, 1–5 cm long, purple, subsessile, densely multispiculate; rachis compressed and angular; pedicel short and mostly 2-nate; spikelet persistent, 3–4 mm long, shortly cuspidate, rarely awned; glumes and lower lemma chartaceous; lower glume about one third the length of the spikelet; upper glume usually shorter than the spikelet, cuspidate, veins and margins sometimes subspinulose; lower lemma similar to upper glume; lower floret sterile, upper floret bisexual. Caryopsis 2–3 mm long and wide.

Growth and development Barnyard millet is a very fast-growing grass. Seed germinates quickly, axillary shoots develop already in the second week after emergence and flowering starts 2–3 weeks later. It is self-pollinated. The wild forms flower throughout the year and form seed abundantly, provided sufficient water is available. *E. crus-galli* flowers earlier and more abundantly under short-day circumstances, but under long-day conditions all parts are robuster. Its seeds, especially of the weedy types, may show a rather long dormancy period of several months. In India, some cultivars of Indian barnyard millet mature in about 6 weeks. The crop cycle of Japanese barnyard millet varies from 65–115 days.

Other botanical information *Echinochloa* is a difficult genus, forming a complex of probably 30–40 species which are not reliably distinguishable from each other because of numerous intermediate forms. Its great diversity is caused by self pollination combined with easy adaptation to a wide range of aquatic and ruderal habitats. The genus can usually be recognized by its bristly sharp-pointed or awned spikelets in 4 rows with a recurved palea tip as best diagnostic character. Much confusion about names and identities exists and a thorough taxonomic revision is urgently needed.

The taxa and culta of *E. colona* and *E. crus-galli* are not easy to distinguish from each other. In general, *E. colona* is a more tropical grass with awnless, smaller spikelets having membranous glumes and *E. crus-galli* is a more temperate grass with awned, larger spikelets having chartaceous glumes, although awnless *E. crus-galli* occurs as well. In general, the culta are robuster plants, with larger and denser inflorescences bearing persistent spikelets. Hybrids between *E. colona* and *E. crus-galli* are sterile (both the wild and cultivated forms), but within each individual species, hybrids between the wild and cultivated forms are fully or at least partly fertile.

In India, 4 cultivar subgroups (races) can be distinguished within Indian barnyard millet (Intermedia, Laxa, Robusta, and Stolonifera), differing in qualitative and quantitative characteristics; some differences are (average values given in the sequence in which the 4 cv. subgroups were mentioned above): days to 50% flowering: 46, 63, 60, 46; plant height: 81, 111, 128, 70 cm; number of basal tillers: 11, 7, 6, 21; panicle length × width: 13 cm × 3 cm, 22 cm × 3 cm, 21 cm × 4 cm, 11 cm × 2 cm; number of primary inflorescence branches (racemes): 23, 39, 47, 16; raceme length: 28, 69, 31, 22 mm; number of spikelet rows: 5, 4, 5, 4. Farmers commonly grow several different subgroups together in the same field. The Indian cultivars include 'Anurag' (matures in 80 days), 'Gujarat' and 'Banti' (maturing in 80–90 days) and 'VI Madira' (matures in 90–100 days).

E. oryzoides (Ard.) Fritsch (synonym: *E. crus-galli* var. *oryzicola* (Vasinger) Ohwi) is native to Asia but has also been introduced into rice-growing regions of Australia, the United States (California) and Europe. It is a serious weed in rice fields, difficult to eradicate because it mimics the rice crop. It comes into flower a few days earlier than the rice crop and it disperses seed before the rice is harvested. In the Russian Caucasus, a cultivar of *E. oryzoides* (known as *E. macrocarpa* Vasinger) lacks the ability to disperse seed efficiently. It is harvested as a crop and used for alcohol distillation or cake baking.

E. stagnina (Retzius) P. Beauvois is another serious weed of paddy rice in tropical Asia and Africa. It has an aquatic habit with creeping stems and can be distinguished from *E. colona* and *E. crus-galli* by the presence of a ligule. It is renowned as a good forage plant and as a cereal in times of food scarcity. In Niger (Africa), a sweet drink is prepared from sap of the stem; a kind of sugar can also be extracted from this sap.

Ecology Barnyard millet has a C4-cycle photosynthetic pathway. In general, Indian barnyard millet is more tropical and Japanese barnyard millet more temperate, but both may occur up to 1000 m altitude in the tropics. Japanese barnyard millet is more tolerant of low temperatures than Indian barnyard millet. The optimum climatic requirements of the barnyard millets are similar to those of paddy rice, although in practice they are mostly grown in dry and less fertile locations where rice will not grow well.

Propagation and planting Propagation is usually by seed, but is also possible by planting rooted tillers. If stored dry, seed can remain viable for several years. At the beginning of the rainy season, seed is broadcast or drilled in rows 20–25 cm apart and 10–15 cm within the rows, at a seed rate of 7–10 kg/ha. A density of at least 15 000 plants/ha is required. It is usually grown as a rainfed crop, but can be grown under irrigation and in waterlogged areas as well.

Husbandry The crop responds well to weeding and ample fertilization (farmyard manure, 40 kg/ha N and 9 kg/ha P), but normally it receives little attention and is not manured. In southern India, where Indian barnyard millet is grown as a cereal, it is often intercropped with finger millet or foxtail millet. A rotation of Indian barnyard millet with pea, wheat or chickpea was found to be advantageous both for total yields and total returns in India.

Diseases and pests The crop may suffer from shoot smut caused by *Ustilago crus-galli* and from head smut caused by *Ustilago panici-frumentacei*. Shoot smut causes gall-like swellings on the stem and deformed inflorescences; the disease is seedborne and can be controlled with organomercurial fungicides. Head smut causes swelling of the ovaries; it is seedborne and can be controlled by several fungicides (e.g. ceresan, bovistin). Shoot fly (*Atherigona* spp.) is a major pest of small millets.

Harvesting Indian barnyard millet can be harvested from about 6 weeks after sowing onwards depending on cultivar.
Japanese barnyard millet is harvested 30–40 days after flowering when the racemes have turned brown. Plants are cut off at their base with a hand sickle, bundled and dried in the field for 20 days. The infructescences are soaked or heated with steam, dried and subsequently threshed.

Yield Yields of Indian barnyard millet amount to 700–800 kg/ha of grain and 1000–1500 kg/ha of straw. It is believed that it can reach a grain yield of more than 2 t/ha. As a forage crop in the United States it can produce as many as eight crops per year.
Average yield of Japanese barnyard millet is 1.65 t/ha.

Handling after harvest The milling process may include husking, debranning and grinding. The husked grains are polished. Polished grain may be ground to flour. The grain can also be cooked like rice or processed for flaking.

Genetic resources and breeding Germplasm collections of barnyard millet are present in India (Bangalore, 800 accessions) and in Japan (National Northeast Agricultural Experiment Station Tohoku, 120 accessions). Breeding programmes (mainly for higher yield and disease resistance) are in progress in India.

Prospects In the regions where barnyard millet is at present most widely grown, it is mainly restricted to marginal lands where rice and other crops will not grow well. In South-East Asia, it will remain an emergency crop, giving at least some produce in a short time when rice has failed. In the near future, the position of barnyard millet is unlikely to improve.

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S. Partohardjono & P.C.M. Jansen

Eleusine coracana (L.) Gaertner cv. group Finger Millet

Fruct. sem. pl. 1: 8 (1788). Cv. group Finger Millet: name is proposed here.

GRAMINEAE

$2n = 36$ (tetraploid)

Synonyms *Cynosurus coracan* L. (1759), *Eleusine indica* (L.) Gaertner f. *coracana* (L.) Hook.f. ex Backer (1927), *E. coracana* (L.) Gaertner subsp. *coracana* sensu Hilu & de Wet (1976).

Vernacular names Finger millet, African millet, koracan (En). Eleusine, coracan (Fr). Indonesia: jaba (Batak Karo), suket lulangan (Javanese), jampang carulang (Sundanese). Malaysia: rumput sambau, ragi. Cambodia: chë:ng kra:hs, si:ng söng. Laos: pha:k kh'wa:y. Thailand: khao-pang-samngam. Vietnam: m[aaf]n tr[aaf]u, c[or] m[aaf]n tr[aaf]u voi, c[or] k[ee].

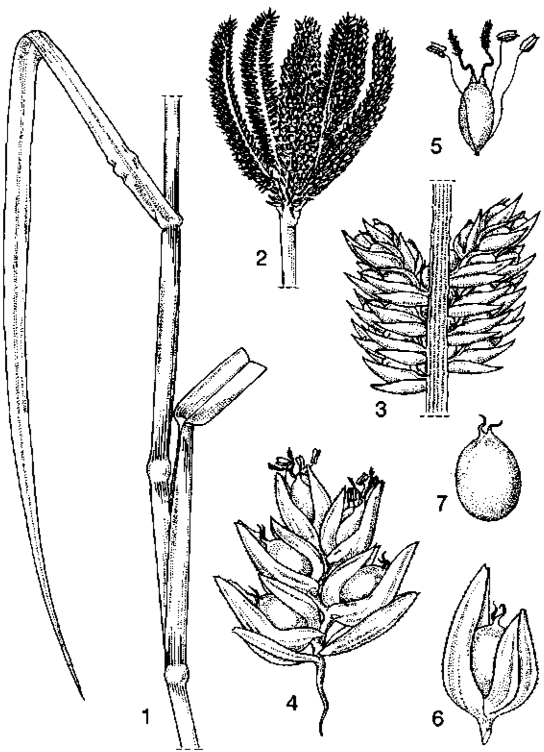
Origin and geographic distribution Finger millet most probably originated about 5000 years ago in the highlands of eastern Africa (from western Uganda to Ethiopia) by domestication of wild weedy forms and is the oldest known domesticated tropical African cereal. From eastern Africa, it was taken elsewhere: to India about 3000 years ago, to southern Africa about 800 years ago. As a cultivated crop, it is at present most important in eastern and southern Africa and in the Indian subcontinent, and is occasionally cultivated elsewhere in the tropics. In South-East Asia, it is grown on a small scale but nowhere reaches commercial importance.

Uses Finger millet grain is used for food, for malting and brewing, and for animal feed. For use as food, the grain is ground and the resulting flour cooked to prepare a thin or thick porridge or baked into a flat (unleavened) kind of bread or pancake. In some parts of eastern Africa and India, it is an important traditional staple food and in many regions it is an important famine food because the grain stores extremely well. The flour is sometimes mixed with other flours (e.g. from cassava, teff, sweet potato), enriched with spices, and the porridge eaten together with meat, pulses, or vegetables. White grain is preferred for use as malt; it is soaked in water for up to 48 hours, germinated, dried, roasted and ground. Home or industrially brewed beer (alcoholic or non-alcoholic) is made by germinating the grain, drying, grinding, mixing with water and adding yeast. Other alcoholic drinks can be distilled from the resulting liquid (e.g. 'areki' in Ethiopia). In West Java (Indonesia), young plants are eaten raw or steamed as a vegetable. Finger millet is also used medicinally as a prophylaxis for dysentery. The straw or stover is usually used as forage for cattle, sheep and goats. Old stems have a silky lustre and are used as material for plaiting. Because finger millet tillers strongly it is also a suitable crop to prevent soil erosion.

Production and international trade The average annual world production of finger millet is about 3.8 million t of grain from 4 million ha. Asia is the largest producer, with 2.9 million t from 3 million ha (mostly from India), followed by Africa with 0.9 million t from 1 million ha (mostly from Uganda, Ethiopia, Zimbabwe and Malawi). Finger millet is usually consumed locally and only surpluses are locally traded. There is hardly any international trade.

Properties Per 100 g edible portion, finger millet grain contains approximately: water 13 g, protein 8 g, fat 1.3 g, carbohydrates 72 g, fibre 3 g, ash 2.7 g. The energy value is 1400 kJ/100 g. The protein content may vary considerably between cultivars, i.e. from 6–14%; it is rich in the amino acids cystine, tyrosine, tryptophane and methionine, but poor in lysine. Finger millet is rich in Ca (up to 0.3%), which may be why it is often recommended as a healthy food for pregnant women, children and sick people. P and Fe contents can also be high. The organic matter in finger millet straw has an in vitro digestibility of about 40–60%. The weight of 1000 grains is about 2.8 g.

Description A robust, tillering, tufted, annual grass, up to 170 cm tall with a shallow, branched,



Eleusine coracana (L.) Gaertner cv. group Finger Millet – 1, stem part with leaves; 2, inflorescence; 3, part of inflorescence branch; 4, spikelet; 5, floret without lemma and palea; 6, fruit within lemma and palea; 7, fruit.

fibrous, adventitious root system. Stem erect to ascending, compressed, robust, glabrous, shiny light green, sometimes branching at the upper nodes. Leaves numerous, distichous, sheath flattened, overlapping, split along the entire length, glabrous except for some hairs along the edges; ligule short, fimbriate; blade linear, 30–75 cm × 1–2 cm, often folded, recurved, scabrous above, dark green. Inflorescence a terminal cluster of 3–6(–26) dense sessile spikes ('fingers'), the cluster consisting of a terminal digitate whorl, often with 1–2(–7) additional spikes 2–4 cm below this whorl; spikes 3.5–15 cm long, up to 1 cm in diameter, straight and spreading or variously incurved and compact, unbranched or branched; spikelets ovoid-elliptical, up to about 1 cm long, awnless, flattened, containing 6–12 florets arranged alternately in two parallel rows on a zigzag rachilla; florets hermaphrodite but terminal ones may be sterile or male; lemma deeply boat-shaped, 2–5 mm long; palea about three-quarters of the length of the lemma; stamens 3; ovary with 2 free styles with plumose stigmas. Fruit a utricle, 4–7 per spikelet, globose, 1–2 mm in diameter, smooth or rugose, varying from orange to red, red-brown, dark brown to black or white; pericarp remains distinct during development and at maturity appears as a papery structure surrounding the seed.

Growth and development Seed of finger millet has no dormancy and its viability drops to about 50% after 2 years of appropriate storage. Young seedlings are very susceptible to drought and competition. It takes finger millet 3.5–6 months to mature, depending on cultivar, photoperiod and temperature. On average, cultivars need about 80 days to 50% flowering but variation is great. An inflorescence flowers about 8–10 days with a maximum number of florets opening on the third day. Flowering proceeds from the top to the bottom of the inflorescence, from the bottom to the top in the spikelet. Self pollination is normal; about 1% cross pollination by wind may occur. Heavy rain at flowering reduces grain setting.

Other botanical information Botanically, finger millet is part of a complex formed by *Eleusine indica* (L.) Gaertner (fowl-foot grass), *E. africana* Kennedy-O'Byrne and *E. coracana*. *E. indica* is a diploid ($2n = 18$) wild grass of Old World origin but at present widespread throughout the tropics and warm temperate regions of the world. It is often a troublesome weed, but sometimes it is used as fodder, the grain as famine food and dried culms for plaiting. *E. africana* is a tetraploid ($2n = 36$) wild grass confined to the eastern and southern African highlands, with similar uses as *E. indica*. Although in older literature finger millet is thought to have been derived from *E. indica* and considered a form or variety of it, more evidence exists for a closer relationship with *E. africana* which in turn could have been derived from *E. indica* (cf. the synonymous name *E. indica* (L.) Gaertner subsp. *africana* (Kennedy-O'Byrne) S.M. Phillips). *E. coracana* and *E. africana* cross readily and produce fertile hybrids, and are quite similar vegetatively. Therefore they are also considered as being one species, *E. coracana*, with wild (subsp. *africana* (Kennedy-O'Byrne) Hilu & de Wet) and cultivated (subsp. *coracana*) representatives. This view is followed here but it is proposed to classify the cultivated forms not as subspecies but as the cultivar group Finger Millet. Finger millet differs from its wild progenitor primarily in having spikelets that do not shatter at maturity.

Many cultivars and landraces of finger millet exist, with different ecological requirements (e.g. highland or lowland, rainfed or irrigated land) and many varying characteristics like height, colour, degree of tillering, type of inflorescence, length of spikes and number of spikelets per spike, site of glumes, colour and yield of grains, susceptibility to diseases). Well-known cultivars include 'Engenyi' from Uganda, 'EC593' from India, '25C' from Zimbabwe and 'Lima' from Zambia. The cultivars have been grouped into 5 major cultivar subgroups based on the inflorescence morphology (especially the branches or 'fingers'):

- cv. subgroup Compacta (other names: race Compacta, cockscomb finger millet): Main inflorescence branches 4–14, incurved, larger than in subgroup Vulgaris and always branched again, forming a large fist-like inflorescence. Indian cultivars have one branch inserted lower than the other branches (not in African cultivars). Grown in north-eastern India, Kenya, Ethiopia and Uganda.
- cv. subgroup Coracana (other name: race Coracana): Inflorescence branches 5–19, slender, straight, 6–11 cm long, all cultivars with a well-developed central inflorescence branch. Cultivars resemble the wild subsp. *africana*. Grown throughout the finger millet range in Africa and India.
- cv. subgroup Elongata (other name: race Elongata): Inflorescence branches long and slender, 10–15(–24) cm long, reflexed at maturity This group is the most distinct of the 5 subgroups. Grown in the eastern African highlands and in the eastern Ghats of India. Sometimes again

subdivided into 3 subgroups: Laxa (longest open fingers with spikelets arranged in narrow rows), Reclusa (short open fingers, not curving outwards) and Sparsa (open fingers but spikelets arranged in clusters with bare space in between).

- cv. subgroup Plana (other name: race Plana): Inflorescence branches have a flat ribbon-like appearance with large spikelets (8–15 mm long) that are arranged in two more or less even rows along the rachis. In some cultivars the florets are congested and surround the rachis at maturity. Grown in the western and eastern Ghats of India and in Ethiopia, Malawi and Uganda. Sometimes again subdivided into 3 subgroups: Confundere (fertile florets numerous, almost surrounding the rachis at maturity, thus giving a compact appearance to the inflorescence), Grandigluma (glumes large, pointed, and several times longer than the spikelets) and Seriata.
- cv. subgroup Vulgaris (other name: race Vulgaris): Inflorescence branches straight, reflexed or incurved – both forms can usually be found in the same field. This subgroup comprises the most common cultivars in Africa and India and is also grown in Indonesia. Sometimes again subdivided into 4 subgroups: Digitata (inflorescence branches only curved at the top), Incurvata (inflorescence branches incurved), Liliacea (inflorescence branches reflexed) and Stellata (inflorescence branches twisted).

Ecology Finger millet is mainly grown in the tropics, from sea-level up to 2400 m altitude (in Nepal up to 3150 m), preferably in areas with the optimum daylength of about 12 hours. It has a C4-cycle photosynthetic pathway. Optimum temperatures are an average maximum of above 27°C and an average minimum not below 18°C. It needs about 750 mm rainfall during growth (average annual rainfall usually 900–1200 mm), well distributed during the growing season and without prolonged spells of drought. It is not as drought tolerant as sorghum and pearl millet and, unlike rice and maize, does not grow well with heavy rainfall. At harvesting, a dry period is required. It grows on a wide range of soils, but reasonably fertile, well-drained sandy loams are preferred, with pH 6.5–8. It does not tolerate waterlogging. In South-East Asia, finger millet is grown in semi-arid to subhumid areas.

Propagation and planting Finger millet is propagated by seed. When irrigated, seedlings are raised in nurseries and transplanted when 3–4 weeks old. This usually gives better results than direct seeding, although transplanting is labour intensive. Under rainfed conditions seed is often broadcast, preferably 1–2 weeks before the onset of the rains. Planting or sowing (2.5 cm deep) in rows facilitates weeding; the usual spacing is about 25 cm between rows, and plants are thinned to 10–12.5 cm apart. Finger millet is planted or sown on ridges where there is a risk of waterlogging. Seed rate depends on the cultivation method and varies from 6–20 kg/ha. Finger millet is mainly a smallholder's crop and is often intercropped, for example, with other cereals (sorghum, maize), legumes (pigeon pea, cowpea, green gram, lupin) or rape seed. Land is prepared by hand or by ox-drawn plough. In Africa, finger millet is often grown in shifting cultivation systems. The 'chitemene' system in Zambia is well known: branches from 2.5–4 ha of woodland are piled and burned on about 0.4 ha of land, with finger millet broadcast in the ash, giving a reasonable yield without any further cultivation but requiring a regeneration time of 20–40 years for the woodland.

Husbandry Finger millet does not tolerate competition in its early stages of growth, so weeding and thinning are important and are usually effected when plants are about 5 cm tall. *E. indica* and wild forms of finger millet that are difficult to distinguish vegetatively from the crop, are serious weeds. In Ethiopia, *Guizotia scabra* (Vis.) Chiov. and *Setaria* species are major weeds and sometimes 7–8 ploughings are needed to eradicate them. When rainfall is insufficient, only irrigation can save the crop, but this can hardly be afforded by smallholders. In India, finger millet is usually manured with cattle or sheep dung, applied at sowing or later. In shifting cultivation systems in Africa, finger millet is fertilized with ash and a mulch of the surrounding vegetation. Finger millet responds well to chemical fertilizers. In Zimbabwe, for example, 40–60 kg N, 26–40 kg P and 35–50 kg K are recommended per ha for poor soils; in Kenya, good results were obtained with an application of N and P of 20 kg/ha each; in India, recommendations are 20–60 kg N, 15–25 kg P, and 50 kg K. In practice, however, fertilizers are seldom applied and finger millet should profit from residual soil fertility from previous crops. In shifting cultivation, finger millet is often the first crop in the rotation, often followed by pulses and cassava. In other cropping systems, finger millet is usually intercropped or grown as a sole crop between two major crops (e.g. in Bangladesh between 2 rice crops). Sometimes two crops of finger millet can be grown per year.

Diseases and pests In general, finger millet suffers from relatively few diseases and pests. Blast (*Magnaporthe grisea*, syn. *Piricularia grisea*) can be a serious disease. It provokes brownish lesions on young leaves, black lesions on the inflorescence, and the premature drying of old leaves. Other lesser diseases include leaf blight caused by *Helminthosporium nodulosum* and *Gloeocercospora* sp., leaf spot (*Cercospora* sp.), tar spot (*Phyllachora eleusinis*) and footrot (*Sclerotium rolfsii*).
The only serious pest in India is the hairy caterpillar of *Amsacta albistriga*, but army worms and grasshoppers may cause damage too. In Africa, the phytophagous ladybird *Epilachna similis* sometimes causes serious damage. Bird damage may occur but is nowhere reported to be serious. Stored grains are hardly attacked by insects and can be kept up to 10 years with little damage.

Harvesting Harvesting time varies per cultivar from 3.5–6 months after sowing, but may start when grains contain about 10% moisture. Because mixtures of cultivars are often grown, ripening is uneven, making several pickings necessary. Local cultivars are liable to shatter. Harvest is usually by hand and, therefore, very laborious. In Africa, infructescences are cut with a knife with 5–8 cm of the culm attached, then dried, stored, and threshed by beating with sticks when required. In India, usually the entire aboveground plants are cut, stacked for about 2 months and then threshed, either by beating with sticks, trampling with bullocks or using stone rollers. Unthreshed infructescences produce 80–85% of grain. Mechanical threshing is possible with hammer mills.

Yield Grain yields of finger millet are very variable, ranging from 400–2000 kg/ha, averaging 950 kg/ha. In India, the average yield of rainfed crops increased from 700 kg/ha in the 1950s to about 1000 kg/ha in the 1980s. Irrigated finger millet usually reaches double the yield of rainfed crops. Under optimal conditions including fertilizer applications yields can reach about 5 t/ha.

Handling after harvest Smallholders grind grain to flour between two stones as required. To obtain larger quantities of flour, grain can be ground in grinding mills. The straw is fed to animals, burned, or used as mulch and incorporated in the soil.

Genetic resources Ethiopia, where the largest diversity exists, is considered to be the centre of origin of finger millet. The Plant Genetic Resource Centre of Ethiopia keeps about 1300 accessions. Large germplasm collections are also available in other African countries: Uganda more than 1000, Kenya about 1100, Malawi 1000, Zimbabwe 600 accessions. India is considered as a centre of diversity, and 2500 accessions are available at the International Crops Research Institute for the Semi-Arid Tropics (ICRISAT).

Breeding Numerous cultivars adapted to local circumstances have been developed in countries where finger millet is grown on a larger scale. The potential for finger millet improvement is promising because enough valuable germplasm is available. In general, the major breeding objectives are: higher and stable yield, short growing cycle and resistance to lodging and to blast disease. For grain, white-seeded forms are preferred. New breeding techniques, including mutation breeding and breeding of high-yielding hybrid cultivars with male sterile lines, show promising results.

Prospects In Africa and India, finger millet is growing in popularity, unlike other lesser millets. Because of its good storage capacity, finger millet will remain an important crop to overcome periods of famine in areas with unreliable rainfall or other natural calamities. It seems unlikely that it will become a major cereal because labour, capital and research will be diverted to other crops. In South-East Asia, finger millet can be potentially useful, for example, as a short-term off-season catch crop on paddy fields which have been drained and harvested.

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P.C.M. Jansen & H.C. Ong

Fagopyrum esculentum Moench

Methodus pl.: 290 (1794).

POLYGONACEAE

$2n = 16$

Synonyms *Polygonum fagopyrum* L. (1753), *Fagopyrum vulgare* Hill (1756, nom. illeg.), *F. sagittatum* Gilib. (1792, nom. illeg.).

Vernacular names Buckwheat (En). Blé noir, sarrazin (Fr). Laos: khauz sa:m hlièmx. Thailand: phakbung-som (northern). Vietnam: m[aj]ch ba g[os]c, m[aj]ch hoa.

Origin and geographic distribution Buckwheat is not an ancient crop. It was described for the first time in China in the 5th Century. It was probably domesticated in China from the shattering, wild species *Fagopyrum acutatum* (Lehm.) Mansf. ex K. Hammer (synonym: *F. cymosum* (Trevir.) Meissner), perennial buckwheat. For over a thousand years buckwheat has been an important subsistence and cash crop in the Himalayan area from northern India, Nepal, Burma (Myanmar), Mongolia and China to Korea and Japan. Although the total area may have declined, buckwheat is still very important in these areas. It is a popular food crop in some former Soviet Union republics. It is cultivated sporadically in the northernmost parts of South-East Asia, in northern Vietnam and northern Thailand. In the early Middle Ages it was introduced into Europe, probably through Siberia with the Mongols, to become a leading grain crop on poor soils and an important staple food. After its introduction by European emigrants, it became an important food crop in the United States and in Canada. It is occasionally cultivated elsewhere in the world. However, the increased use of chemical fertilizer in the beginning of the 20th Century led to the buckwheat area in Europe and North America decreasing enormously, to be replaced by higher yielding crops such as rye, oats, maize, wheat, and Irish potato. At present, it is regaining some importance in western countries because of its excellent nutritional qualities.

Uses Buckwheat is commonly used for the preparation of noodles, pancakes, porridge, cakes and biscuits, comparable to those made from wheat. It is an ingredient in breakfast cereals. Groats is the part of the seed left after hulling. Buckwheat is often ground or milled coarsely, to produce broken groats. Many consumers like the coarsely milled flour (meal) which is brownish because of the high content of hull particles. At present, a high fibre content is considered a favourable character. When sieving for almost white buckwheat flour, the extraction rate is quite low, only 60–70%, the waste being used for fodder.

Although pure buckwheat flour is sometimes used for baking bread, it lacks the gluten to provoke rising of the dough. It is popular for use in mixtures with wheat, barley or rye flour to improve the taste and nutritional value of bread and other foodstuffs. Up to 30% of buckwheat may be mixed in wheat dough for baking bread.

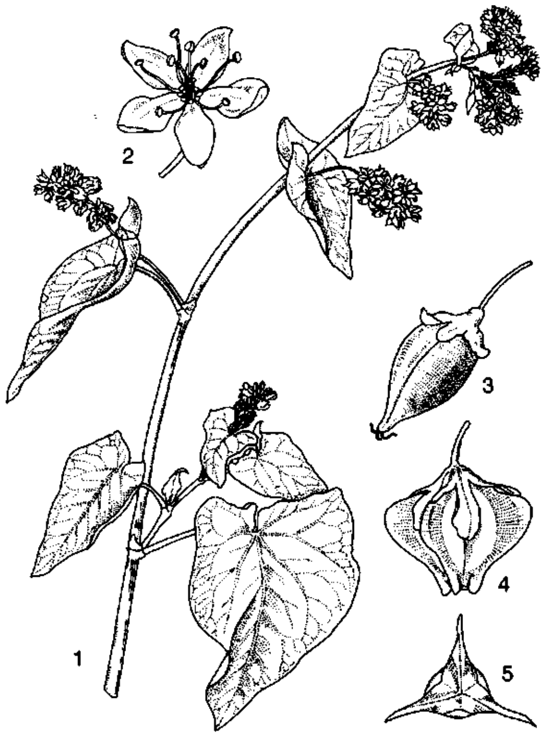
The tender shoots make a palatable green leaf vegetable. The flavonoid rutin, a traditional medicine, is present in all aboveground plant parts (leaves, stems, inflorescence, grain). Fresh leaves and inflorescences are used for industrial rutin extraction. In the Himalayas, buckwheat is processed into alcoholic drinks. In that area, people believe that buckwheat consumption reduces hazards of exposure to excessive solar radiation. Honeybees in buckwheat fields produce a dark coloured fragrant honey; a honey yield of 120 kg/ha may be attained. The grain is also fed to animals, especially pigs and chickens. The plants are occasionally used for silage, but must be mixed with other fodder because pure buckwheat silage may cause a cattle disease called fagopyrism. Buckwheat forms a good green manure. The seed hulls are used as litter in poultry houses, for stuffing pillows, as fuel or for compost.

Production and international trade At present, buckwheat is still grown in many countries, and is mainly commercialized locally. Annual world production is about 1 million t from 2 million ha. The Russian Federation is the largest producer, followed by China (90 000 t), India (60 000 ha; 35 000 t), Canada, the United States, Brazil, Nepal, Japan (28 000 ha; 21 000 t). In Brazil, Canada, the United States and South Africa it is grown as an export crop in a highly mechanized way, like wheat. The farmgate prices are high, about double the price of wheat, but crops often fail, and average yields are low when compared with true cereals. Buckwheat noodles ('soba-uchi') are very popular in Japan, and the country imports 80% of its domestic demand, mostly from Brazil.

Properties The seed has a cereal-like composition. The approximate composition of hulled buckwheat seed per 100 g edible portion is: water 10–15 g, protein 12–15 g, fat 2–3 g, carbohydrates 70–80 g, fibre 1.5 g, ash 1.5 g. Like small-seeded cereals, unhulled buckwheat grain is rich in fibre, containing up to 10%, the seed hull providing most of it. This may be partly or even almost completely sieved out from the flour. Stored flour may become rancid because of the high fat content. Buckwheat differs from true cereals in the high biological value of the protein, caused by the high content of essential amino acids, in particular lysine (6%). The high rutin content is also remarkable; it is about 1.2 mg per 100 g in boiled flour. Rutin is a vitamin that cures hypertension, reduces cholesterol count, protects the blood vessels from rupturing, and blood from forming clots. The flour is also rich in vitamins B_1, B_2 and P. The straw has a reasonable good composition as a fodder, with 1.2% digestible protein, whereas buckwheat as green fodder contains about 2.9% digestible protein.
The 1000-kernel weight varies from 12–35 g, averaging about 22 g.

Description Erect annual herb, 40–120 cm tall. Stem angular, hollow. Leaves alternate, upper ones almost sessile, lower ones with petiole up to 10 cm long; ocrea tubular, short, truncate; blade triangular, hastate or cordate, acute, 2–10 cm × 2–10 cm. Inflorescence compound, consisting of axillary or terminal clusters of flowers combined into corymbose pseudo-spikes; flowers small, shortly pedicelled, rose-red to white; tepals 5, 3–4 mm long, persistent; stamens 8, alternating at the base with 8 honey glands; ovary 1-celled, trigonous, style tripartite with capitate stigmas; flowers show heterostylic dimorphy: some have 8 long stamens and 3 short styles, others have 8 short stamens and 3 long styles. Fruit a 3-sided achene or nutlet, 6 mm × 3 mm, sometimes winged, grey-brown, dark brown to almost black. Seed light green turning reddish-brown, slightly smaller than fruit.

Growth and development At soil temperatures above 10°C the seed germinates fast, and seedlings emerge after about 7 days. The crop grows fast, reaching the full height of 60–100 cm in 4–6 weeks. Growth is indeterminate. Flower formation starts 20 days after emergence, anthesis starts a week later and continues until complete senescence and death of the whole plant. After the onset of flowering, the vegetative organs (leaves and stems) continue to grow while the grain is forming, hence seed ripening is very uneven. From the middle of the flowering period onwards, when the leaf area has reached its maximum, further growth of vegetative organs is slow, and the seed has become the main sink for assimilates. Buckwheat is self-incompatible. Cross pollination occurs by insects, mostly bees and flies. The grain is ready for harvesting 70–130 days after emergence, depending on cultivar and ecological conditions.



Fagopyrum esculentum Moench – 1, flowering branch; 2, flower; 3, unwinged fruit; 4, winged fruit; 5, top view winged fruit.

Buckwheat has the reputation of producing an acceptable yield on marginal, infertile land, where other cereals or pseudo-cereals fail. On wet soils or soils rich in nitrogen, luxuriant growth leads to lodging, a low grain/straw ratio (down to 0.7), poor fruit setting, considerable losses during harvest, and thus modest yields. When used for silage or as green manure, a low grain yield is unimportant, and more biomass will be produced on wetter, heavier soils.

Other botanical information The name 'buckwheat' is the English translation of the genus name *Fagopyrum* which is derived from the latin word 'fagus' (the beech or buck tree) and the greek word 'pyron' (wheat). Its three-angled fruit resembles the beechnut.

Numerous landraces and cultivars are known in the main production areas, adapted to local ecological conditions, and with morphological and physiological differences, e.g. cultivars with well-filled roundish seed or very sharp-sided seed, cultivars for the summer or for the winter season, and special-purpose types for grain, fodder, vegetable or medicine.

A classification into 3 cultivar groups is possible, based mainly on the form of the fruit:

- cv. group Emarginatum (synonyms: *Polygonum emarginatum* Roth, *Fagopyrum emarginatum* (Roth) Moench, *F. esculentum* Moench var. *emarginatum* (Roth) Alef.); this is Japanese buckwheat with winged fruits, mainly cultivated in China, Japan and India;
- cv. group Esculentum (synonym: *Fagopyrum esculentum* Moench var. *vulgare* Alef.) with fruits triangular in cross-section;
- cv. group Pyramidatum (synonyms: *Polygonum pyramidatum* Loisel., *Fagopyrum esculentum* Moench var. *pyramidatum* (Loisel.) Meissner) with pyramidal fruits.

F. tataricum (L.) Gaertner is a related species, called tartary buckwheat or bitter buckwheat, grown in India and China under cooler and harsher conditions than normal buckwheat, and occurring as a weed in Europe. In Europe it used to be cultivated on the poorest soils, and used for feed or silage more than as cereal food. It produces more biomass for silage than normal buckwheat. It is distinguished from buckwheat by green flowers and dented seed sides. It is self-compatible, not heterostylic dimorphic and is assumed to have evolved from *F. acutatum* too. The wild perennial *F. acutatum* is said to be cultivated in Assam (India).

Ecology Buckwheat is a crop of temperate and subtropical areas, but may be grown successfully at higher elevations in the tropics. It is photosynthetically active between 10°C and 40°C, the optimum being between 15°C and 25°C. Exact data on optimal temperatures are scarce, but climate descriptions indicate a range of 18–30°C for day temperatures, and night temperatures 5–10°C lower. Because the leaf mass dries slowly, a dry period is required at maturity and harvest. Buckwheat is very sensitive to frost. Strong winds cause lodging during crop growth and shattering of the seed at maturity. The crop is rather sensitive to drought because of its poorly developed root system. During flowering, drought combined with high temperatures will cause poor seed setting. Much rain during the crop cycle stimulates vegetative growth, but inhibits seed setting, also because it hampers pollination by insects.

Buckwheat cultivars are either indifferent to daylength (day-neutral) or show a short-day photosensitivity. Typical autumn-cropping cultivars are short-day sensitive.

Buckwheat performs best on nitrogen-poor light sandy soils, from neutral to rather acid (pH value 4.5–7.0). It is suitable for newly cleared infertile land, drained marshland, rough land or acid soils with a high content of decomposing organic matter.

Propagation and planting Buckwheat is propagated by seed. The seed has no dormancy. The seed-bed should be finely crumbed. A firm soil at about 5 cm depth reduces drought injury and lodging. Very crusted land and heavy clay soil will result in poor field emergence. Most growers use farm-saved seed. There are numerous landraces, but few improved cultivars are available. For seed production of improved cultivars the fields must be at least 200 m apart, because of the risk of outcrossing.

In mechanized cultivation, seed is drilled in rows about 30 cm apart, at a depth of 2–4 cm, requiring 40–60 kg of seed per ha, depending on seed quality, seed weight and density. The crop compensates for a thin stand by branching more. Thin stands produce more inflorescences and seeds per plant. In manual cultivation, seed is broadcast, followed by harrowing to cover the kernels with topsoil. Broadcasting requires 10–20 kg seed more per ha than row drilling. With a seed rate of 40 kg/ha and a 1000-seed weight of 20 g, about 200 seeds/m^2 are sown, and with an establishment rate of 50%, a density of 100 plants/m^2 will be obtained. A higher plant density has the advantage of better weed suppression, but the heavy leaf canopy may cause rotting of the inflorescence and lodging, and hampers harvest.

Husbandry Buckwheat is a crop with a short growing season, easily fitting in cropping patterns with cereals, root crops, legumes, and forages. It is sometimes intercropped with vegetables.

No serious losses from soilborne diseases have been reported. Any crop is suitable as preceding crop provided that it does not leave much nitrogen or weed seeds. Although buckwheat competes well with most weeds, some fast-growing weeds are a problem. Some growers sow more densely on purpose, and then weed mechanically by harrowing about 4 weeks after emergence, killing most weed plants together with a number of buckwheat seedlings.

The uptake of minerals per ha for a yield of 2 t/ha grain is about 45 kg N, 10 kg P and 50 kg K. Growers usually apply no organic manure and no or little chemical fertilizer, e.g. 10–30 kg N, 0–15 kg P and 15–30 kg K. Only P and K fertilizers should be applied if there is a risk of lodging. Growers in western countries apply about 40 kg N, 15 kg P and 30 kg K, but recommendations for subtropical areas are lower: about 20 kg N, 15 kg P and 10 kg K. In some places, foliar application of the micronutrient boron has considerably increased the yield.

Diseases and pests Although many fungal diseases have been reported on buckwheat, they only occasionally cause serious damage. The following diseases are to be noted: smut (*Sphacelotheca fagopyri*), leaf spot (*Septoria polygonicola*), root and basal rot (*Phytophthora fagopyri*), powdery mildew (*Erysiphe polygoni*), brown leaf spot (*Ascochyta italica*), rust (*Puccinia fagopyri*), root and collar rot (*Sclerotinia libertiana*), stem rot (*Botrytis cinerea*), root rot (*Fusarium* sp., *Botrytis* sp., *Rhizoctonia* sp.), chlorotic leaf spot (*Alternaria alternata*), stipple spot (*Bipolaris sorokiniana*), and downy mildew (*Peronospora* sp.). Cultivars differ markedly in susceptibility. Several viral diseases have been reported, but they do not cause much damage. Bean weevil (*Acanthoscelides obtectus*), cutworm (*Cirphis* sp.), green peach aphid (*Myzus persicae*), grain moth (*Cephitinea* sp.) and storage beetles (*Mycetophagus* sp.) may cause some damage. Sometimes insecticide is sprayed, although it is doubtful whether this is economically justified.

The worst problem for buckwheat production is damage by birds at maturity and after harvest, when the crop is left to dry in the field. Rats are also sometimes destructive.

Harvesting When most (at least 75%) seed is mature and most leaves have yellowed and dropped, the crop is harvested by mowing, after which the stems are bundled and put in heaps to dry. Farmers prefer to harvest early in the morning or late in the afternoon, or even at night, when the plants are slightly damp from dew, to reduce grain shattering. The bundles are stacked alternately head-to-tail in the heaps, to reduce bird damage. If the leaves are not dry enough, they may stick together, causing problems for threshing. Combine-harvesting is practised in more advanced countries.

Yield A good crop yields about 2 t/ha of grain and 2.5 t/ha of straw. Grain yields normally vary from 0.6–2.5 t/ha, but 3.0 t/ha has been obtained from experimental plots in Korea. In Germany, average yields amount to 1.2 t/ha, in Japan to 750 kg/ha, and in India to 600 kg/ha. Buckwheat research has not succeeded in raising yields; they remain about the same as a century ago.

Handling after harvest Thorough drying to a moisture content below 16% facilitates the removal of straw fragments and immature seed. Small farmers usually thresh manually, as in other small grain crops. Mechanical threshing requires careful regulation of the threshing cylinder to avoid damaging the seed. In Japan, standard quality grain should have less than 15% moisture, at least 85% healthy kernels, not more than 20% damaged or immature seed and no alien material.

Processing starts with hulling and separation of the hulls from the groats, followed by milling. Formerly, the grain was processed by individual households or in small village workshops. At present, most buckwheat is processed in factories that apply advanced food technology to make specific foodstuffs.

Genetic resources There are numerous landraces and many have already been collected for selection and testing, and for storage in genebanks. Germplasm is available in national collections in the United States, Canada, South Africa, Japan, Korea, China, India, Pakistan, Nepal, Russia, Slovenia, Poland, and Germany. These countries are part of a network under the International Plant Genetic Resources Institute (IPGRI), responsible for characterization and documentation. IPGRI plans to analyse and assess breeding and production constraints and to conserve genetic diversity for the Asia, Pacific and Oceania region.

Breeding Buckwheat has received relatively little attention from international and national research institutes. The important problems of the crop are lodging, seed shattering and low yields. These handicaps might partly be solved by improved cropping techniques and a proper breeding programme. Breeding has been carried out in, for example, the United States, Russia, Japan, India and former Yugoslavia. The mechanism of pollination and fertilization has been studied. Homomorphic, highly self-compatible diploid lines have been isolated. They revealed a severe inbreeding depression, and heterosis in F_1 generations. Breeders have selected improved cultivars with higher yields, e.g. by improving the plant habit.

Autotetraploid buckwheat selections show superior characters in many aspects (self-fertile, higher rutin content, increased dry matter production, improved nitrogen uptake, no seed shedding). Tetraploid cultivars developed in Japan and China show a yield increase of about 20%.

Prospects Internationally, the interest in buckwheat as a health food is increasing. With a higher price compensating for the lower yield level compared to cereals, the acreage under buckwheat may increase. Buckwheat is fairly heat tolerant. It is potentially an interesting crop for marginal land in highland areas in South-East Asia, or as a winter crop in the northern part of the region, especially as a low-input subsistence or cash crop in rotation with other crops. An interesting feature is that at the moment buckwheat is hardly affected by diseases and pests. Giving the existing genetic variability, it is likely that breeding will result in cultivars better adapted to more tropical conditions, with less lodging and seed shattering, and improved seedset, hence with higher yield levels.

The International Buckwheat Research Association (IBRA) issues a newsletter 'Fagopyrum' and organizes international meetings.

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Hordeum vulgare L.

Sp. pl.: 84 (1753).
GRAMINEAE
$2n = 2x = 14$

Synonyms *Hordeum distichon* L. (1753), *H. hexastichon* L. (1753), *H. sativum* Jessen (1863).

Vernacular names Barley (En). Orge (Fr). Cebada (Sp). Malaysia: barli. Indo-China: ta mé (Chinese), tai mak (Cantonese). Thailand: khao-ba-le. Vietnam: l[us]a m[aj]ch, l[us]a m[aj]ch nha, d[aj]i m[aj]ch.

Origin and geographic distribution Barley was domesticated in the Fertile Crescent of the Middle East from wild barley populations (sometimes considered as a separate species *H. spontaneum* C. Koch) before 7000 BC. It was the most abundant and cheapest grain of the ancient Near East. It spread over the Old World between 5000–2000 BC, reaching India 3000 BC and China in 2000 BC; it was taken to the New World by Columbus. At present it is grown over a broader environmental range than any other cereal, from 70°N in Norway to 44°S in New Zealand. In Tibet, Ethiopia and the Andes it is cultivated higher on the mountain slopes than other cereals. In many areas of northern Africa, the Near East, Afghanistan, Pakistan, Eritrea, and Yemen it is often the only possible rainfed crop. In South-East Asia it is grown to a limited extent in central Burma (Myanmar), Thailand and, very rarely, in Indonesia in the mountainous areas of East Java.

Uses In the tropics and subtropics barley is cultivated for food, e.g. in India, Nepal, Tibet, Afghanistan, Russia, Ethiopia, North Africa, and the Andean region of South America.

The straw is used as animal feed in the Near East, northern Africa, Ethiopia, Eritrea, Yemen, in the Andes and the Far East; it is also used for animal bedding and to cover roofs. Barley is often grazed during tillering or cut before maturity and fed directly to livestock or used for silage.

In temperate regions, the crop is used as feed and for the production of malt to prepare beer; the brewing process varies with the type of beer being produced.

Production and international trade In 1993, world barley grain production was about 170 million t from 74 million ha. Major producing countries are Russia (26 million t), Germany (13 million t) and Canada (12 million t). Over 60% of the world production is in Europe. The main producing countries in East Asia are China (3.1 million t, 1.2 million ha) and India (2.5 million ha). In South-East Asia, Thailand produced 1400 t from 2000 ha. World production is about 36% of that of maize and 30% of that of wheat. Europe, Canada and the United States are the largest exporters. The largest importers in South-East Asia are Thailand, the Philippines, Malaysia, Papua New Guinea and Indonesia.

Properties Barley grain contains approximately per 100 g edible portion: water 13 g, protein 12 g, fat 2 g, carbohydrates 68 g, fibre 3.5 g, ash 1.5 g. Hordeins are the major storage proteins in the endosperm and have a low lysine content. The major constituent of the kernel is starch, which consists of a mixture of amylopectin (about 75%) and amylose (about 25%). The fat content in barley is low compared to that of maize. The grain is an excellent source of vitamins of the B-complex (B_1, B_2, B_6) and panthotenic acid. Barley cannot be used to make leavened bread because of its low gluten content. The 1000-kernel weight is 25–50 g.

Description Annual, erect grass, 80–120 cm tall, tillering freely. Root system consisting of 3–9 primary (seminal) roots and of adventitious (nodal) roots; only seminal roots develop under severe drought. Stem usually hairy, with solid nodes and 5–7 hollow internodes. Leaves 5–10, borne alternately on either side of the stem at the nodes; sheath glabrous; auricles overlapping and much larger than in wheat or rye; ligule membranaceous, 1–3 mm long, hyaline, ciliolate; blade linear-lanceolate, 5–40 cm × 0.5–1.5 cm, scaberulous. Inflorescence a terminal cylindrical spike, 5–12 cm long, excluding the awns; rachis non-disarticulating, with 1-flowered spikelets alternating in distichous groups of 3 at each node; in 2-rowed barley, only the central spikelet of each group is fertile (hetero-spiculate barley), in 6-rowed barley, the lateral spikelets are also fertile (iso-spiculate barley); glumes 2, narrow, about half the length of the lemma, with fine bristles at the tip; lemma ovate, 9–11 mm × 3 mm, 5-nerved, usually terminated by a long barbed awn up to 15 cm long, but some cultivars are awnless; palea 2-keeled, as long as the lemma but awnless; floret with 2 lodicules, 3 stamens and ovary with 2 plumose stigmas. Fruit a caryopsis, 20–60 per spike, elliptical in frontal view, convex on the embryo side, varying in size according to cultivar, hairy at the tip, grooved on the hilum side, usually invested by lemma and palea but 'naked' forms, in which the husks do not adhere to the grain, occur as well.

Hordeum vulgare L. – 1, habit; 2, 6-rowed spike; 3, triad of spikelets of 6-rowed spike.

Growth and development The coleoptile emerges from the soil 5–6 days after germination. Tillers are produced on the main shoot and the process continues until flower initiation. Time to flower initiation varies with cultivar, but barley flowers earlier than wheat. Barley is predominantly self-pollinating but cross pollination can be as high as 10%. It can mature in a short season of 3–4 months.

Other botanical information The large variability in barley led to many 'species' being distinguished in the past. At present, the most accepted view is that in barley evolution only a single species is involved, *H. vulgare*, forming a crop-weed complex, in which the cultivated barleys have been developed from original wild populations and the modern cultivars are the result of breeding and selection. 'Hybrids' between wild and cultivated forms are easily obtained and are fully fertile. In wild forms (formerly classified as *H. spontaneum* C. Koch) the spikes are 2-rowed and fragment at maturity, and the grains fall. In domesticated forms 6-rowed spikes were developed as well as 2-rowed ones, and the spikes are tough and the grains do not fall. Crossings of barley with other *Hordeum* species result in sterile hybrids. No other species are known to be involved in barley evolution.

Hundreds of barley cultivars exist; they have been grouped into 3 cultivar groups (there is no generally accepted classification system):

- cv. group Vulgare, including iso-spiculate, 6-rowed, tough-rachis barley cultivars, which again can be grouped into several cv. subgroups based on lemma characteristics (long-awned, hooded or awnless);
- cv. group Distichon, including hetero-spiculate, 2-rowed, tough-rachis cultivars, which can also be grouped into several cv. subgroups based on characteristics of the spikes (normal, compressed and flabellate, or bearing spikelets with much reduced parts);
- cv. group Irregulare, including cultivars in which the spikes are composed of an irregular mixture of iso-spiculate and hetero-spiculate spikelets.

Based on vernalization requirements, barley can also be classified as winter or spring barley.

Ecology Barley can grow at low temperatures during its vegetative phase, but can endure high temperatures during and after heading, provided the relative humidity is low. In temperate countries it can be grown as a winter or as a spring crop, just like wheat. In India, it is planted in October–November at the close of the monsoon. In Kenya, it grows in areas of light rainfall between 1500–3000 m altitude.

Barley is best adapted to temperate climates with cool and moderately dry seasons. The crop withstands high temperatures in dry climates, but is ill-adapted to hot, humid climates. It is adapted to areas with annual rainfall ranging from 200 mm to more than 1000 mm; it is very sensitive to waterlogging, but very drought tolerant. It is less cold tolerant than wheat or rye. Barley does not tolerate acid soils, but is more salt tolerant than other cereals.

Propagation and planting Barley is propagated by direct seeding. On smallholdings the land is prepared by animal traction. The depth of ploughing is 10–15 cm. Preferably, the seed should be treated with a fungicide to protect the crop against seed and soilborne diseases. On smallholdings and in adverse environments sowing is done by hand; normally, the seed is drilled 2–6 cm deep in rows 15–35 cm apart. Seeding rate is 50–150 kg/ha. Average plant density is 200–250 plants/m^2.

Husbandry Weeding is essential to procure a reasonable yield. Resource-poor farmers weed manually and use the weeds as animal feed. Post-emergence spraying of 2,4-D is widely used to control broad-leaved weeds. Barley requires about 25 kg/ha of nitrogen to produce 1 t of grain. Nitrogen can be applied before sowing or by top dressing after germination. Under dry conditions high rates of N-application can reduce yields, whereas under favourable conditions high rates of nitrogen increase the occurrence of lodging and diseases. N-fertilization of malting barley may increase the protein level in the grain above the permitted level. As a barley crop removes 15–20 kg/ha of phosphorus, this amount should be applied to maintain soil reserves.

Diseases and pests Barley is affected by several viral and fungal diseases. The most important viral diseases are barley yellow dwarf virus (BYDV) and barley stripe mosaic virus (BSMV). Major fungal diseases are powdery mildew (*Erysiphe graminis*), spot blotch (*Helminthosporium sativum*), scald (*Rhynchosporium secalis*), scab (*Giberella zeae*), rusts (*Puccinia* spp.), net blotch (*Pyrenophora teres*), barley stripe (*Helminthosporium gramineum*), and smuts (*Ustilago* spp.). Several nematodes can parasitize barley: e.g. root-knot nematode (*Meloidogyne* sp.), cyst nematode (*Heterodera* sp.) and root-lesion nematode (*Pratylenchus* sp.).

Major pests are aphids.

Harvesting Barley can be harvested when the grains reach 35% moisture content. It is harvested by hand or by combine. Hand-harvesting is done by sickle or by pulling the plants. Special care must be taken when threshing malting or naked barley, to minimize the amount of broken seed.

Yield Barley yields vary from 0.3 t/ha in dry years and under marginal conditions to 10 t/ha in high-input agriculture. Average yields vary from 1.5–1.7 t/ha in Asia and South America to 2.9 t/ha in North America and 4 t/ha in Europe. Straw yields are equally important in many developing countries but no data are available.

Handling after harvest The major problem for harvested grain is damage and losses caused by insects and rodents. A high moisture content at harvest favours the development of mycotoxins dangerous to humans and certain animals (e.g. cattle, pigs, poultry). In developing countries it is common practice to keep selected spikes to pro-

duce the seed for the next cropping season. Barley seeds having 14% moisture content can be safely stored.
For the brewing of beer, 2-rowed barleys with a low protein content, a soft mealy endosperm and a thin hull are preferred. The grain is germinated and when the radicle appears the very young seedlings are dried to produce malt. The malt is mixed with water and heated; the malt enzyme diastase hydrolyses the starch to fermentable maltose and glucose and the bitter flavour is imparted by boiling with the flower buds of hops (*Humulus lupulus* L.). The resulting wort is then cooled and fermented by brewers' yeast (*Saccharomyces cerevisiae*), which produces alcohol (3–8%), carbon dioxide and flavouring substances. The yeast is removed by settling and filtration; further carbonation is usually provided before the beer is bottled or canned.

Genetic resources The primary centre of diversity for barley is the Fertile Crescent in the Middle East, with Ethiopia being an important centre of diversity. The International Centre for Agricultural Research in the Dry Areas (ICARDA, Syria) plays a major role in collecting, maintaining and distributing barley germplasm. The Centre collaborates with several national programmes in collecting and evaluating germplasm. Many national programmes maintain their own working collections.

Breeding Landraces are still cultivated today in many countries and are composed of many different homozygotes. These landraces are maintained by the farmers themselves. Before 1950, the main breeding method was either mass selection or pure-line selection within landraces. New variability has been created by crossing or by mutation. ICARDA has the mandate for barley improvement in developing countries. The major emphasis is on producing cultivars resistant to diseases and pests and with adaptation to specific agro-ecological environments. Ethiopian barleys often show good disease resistance.

Prospects Barley has received less attention in crop improvement than wheat, rice and maize. As breeding has mostly addressed favourable environments, the potential of the crop in low-input agriculture is largely underexploited. Considerable improvement is expected in breeding cultivars resistant to lodging and diseases. However, since barley is primarily a cereal for temperate climates, it will most probably remain unimportant in South-East Asia.

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S. Ceccarelli & S. Grando

Oryza L.

Sp. pl.: 54 (1753), Gen. pl. ed. 5: 29 (1754).
GRAMINEAE

$x = 12$; $2n = 24$ (*O. australiensis*, EE group; *O. granulata*; *O. meridionalis*, AA group; *O. meyeriana*; *O. nivara*, AA group; *O. officinalis*, CC group; *O. rufipogon*, AA group; *O. sativa*, AA group); $2n = 48$ (*O. longiglumis*; *O. minuta*, BBCC group; *O. ridleyi*, *O. schlechteri*).

Major species and synonyms
- *Oryza australiensis* Domin, Bibl. bot. 85(1): 333 (1915).
- *Oryza granulata* Nees & Arnott ex Watt, Dict. econ. prod. ind. 5: 500 (1891), synonyms: *O. meyeriana* (Zoll. & Mor.) Baillon subsp. *granulata* (Nees & Arnott ex Watt) Tateoka (1962) and var. *granulata* (Nees & Arnott ex Watt) Duistermaat (1987).
- *Oryza longiglumis* Jansen, Reinwardtia 2: 312 (1953).
- *Oryza meridionalis* Ng, Bot. J. Linn. Soc. 82: 328 (1981).
- *Oryza meyeriana* (Zoll. & Mor.) Baillon, Hist. pl. 12: 166 (1894), synonyms: *O. abromeitiana* Prodoehl (1922), *O. meyeriana* (Zoll. & Mor.) Baillon subsp. *abromeitiana* (Prodoehl) Tateoka (1962), subsp. *meyeriana* [Tateoka] (1962) and var. *meyeriana* [(Tateoka) Duistermaat] (1987).
- *Oryza minuta* J.S. Presl, Rel. Haenk. 1: 208 (1830), synonyms: *O. manilensis* Merrill (1908), *O. latifolia* auct., non Desv.

- *Oryza nivara* Sharma & Shastry, Ind. J. Gen. Pl. Br. 25: 157 (1965).
- *Oryza officinalis* Wallich ex Watt, Dict. econ. prod. 5: 501 (1891), synonyms: *O. latifolia* Desv. var. *silvatica* Camus, *O. malampuzhaensis* Krishn. & Chandr. (1958).
- *Oryza ridleyi* Hook.f., Fl. Br. Ind. 7: 93 (1896), synonym: *O. stenothyrsus* K. Schum. (1905).
- *Oryza rufipogon* Griffith, Notul. pl. Asia 3: 5 (1851), synonyms: *O. fatua* Koenig ex Trin. (1839), *O. sativa* L. f. *spontanea* Backer (1928) & f. *spontanea* Rosh. (1931), *O. aquatica* Rosh. (1937).
- *Oryza sativa* L. – see separate article.
- *Oryza schlechteri* Pilger, Bot. Jahrb. 52: 168 (1915).

Vernacular names For general rice names, see *Oryza sativa* L. article.
- *O. granulata*: Jungle oryza (En). Indonesia: rumput lorodan, lorodan pari (Javanese). Thailand: khao-nok (south-western). Vietnam: l[us]a con cong.
- *O. meyeriana*: Indonesia: hehawa (Sulawesi), padi-padian (Kalimantan). Philippines: paray-agway.
- *O. minuta*: Indonesia: padi monyet (North Sumatra), paparean (Sundanese), suket paren (Javanese). Malaysia: padi burung. Philippines: palay-maya (Sulu), bayli-gadja (Tausug), palai-palai (Subanun). Vietnam: l[us]a ma.
- *O. ridleyi*: Malaysia: paroi tasur (Sabah). Thailand: ya-khaotham (south-eastern). Vietnam: l[us]a r[uwf]ng.
- *O. rufipogon*: Indonesia: padi burung (Sumatra), paparean (Java), waiwi (Irian Jaya). Malaysia: padi hantu (Peninsular). Vietnam: l[us]a hoang.

Origin and geographic distribution There are strong indications that the genus *Oryza* originated in the Gondwana supercontinent, which began to fracture and drift apart in the early Cretaceous period, and that wild species differentiated out of a common ancestor and became widely distributed in the humid tropics of Africa, South America, South and South-East Asia (including south-western and southern China), Oceania and Australia. However, there is no agreement as to what the common ancestor might have been or whether it still exists. Of the wild species in Asia, *O. nivara* and *O. rufipogon* are found mainly in the Asian mainland, *O. granulata*, *O. meyeriana*, *O. officinalis*, and *O. ridleyi* span both mainland and islands, *O. longiglumis*, *O. minuta* and *O. schlechteri* are confined to the islands. Australia has *O. australiensis*, *O. meridionalis* and *O. rufipogon*. In addition to the cultivated *O. glaberrima* Steudel, Africa has the wild species *O. barthii* A. Chev., *O. brachyantha* A. Chev. & Roehr., *O. eichingeri* A. Peter, *O. longistaminata* A. Chev. & Roehr. and *O. punctata* Kotschy ex Steudel. South America has *O. alta* Swallen, *O. glumaepatula* Steudel, *O. grandiglumis* (Doell) Prod. and *O. latifolia* Desv.

Parallel and independent evolutionary processes occurred in Asia and Africa following the sequence of wild perennial to wild annual to cultivated annual. The corresponding members for Asia are *O. rufipogon* (wild perennial), *O. nivara* (wild annual) and *O. sativa* (cultivated annual), for Africa they are *O. longistaminata* (wild perennial), *O. barthii* (wild annual) and *O. glaberrima* (cultivated annual). *O. sativa* is now cultivated pantropically, *O. glaberrima* only in West Africa. In Australia, Oceania and South America no cultivated annual has been developed from the wild species.

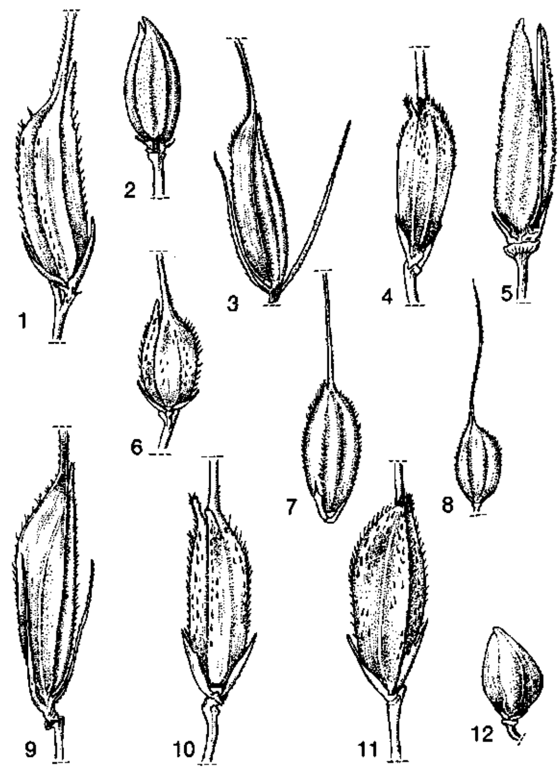
Uses The most important use of wild rices is in breeding programmes to improve cultivated rice because they are a source of resistance to or tolerance of biotic and abiotic stresses. They are also valuable as food supplement (e.g. *O. nivara* in India and Sri Lanka) and as famine food when other crops fail, as a raw material for special liquors (China) and they often provide a good fodder. In many parts of South Asia, wild rice grain is used as an offering to deities in the temples and can command a high price in the market where it is sold during religious festivals. In Burma (Myanmar), *O. officinalis* is a kind of holy plant and is protected within sanctuaries of Buddhist temples. Some wild rices are also used medicinally (e.g. *O. officinalis* in China).

Production and international trade Wild rices are only used locally. None of the species is found in large enough patches to be traded.

Properties The chemical composition of the starch fractions of wild rices is essentially the same as in the cultigen *O. sativa*. The protein and amino acid contents are very variable but not outstanding.

The red pericarp present in nearly all wild species is favoured by ethnic tribes and some urban people as having nutritional increments or is used for decorative purpose during festivities. On the other hand, if found in commercial lots, the red seedcoat carried by primitive cultivars lowers the grade of milled rice.

Description Annual or perennial plants with erect or ascending culms. Leaves herbaceous, sheath terete with more or less distinct transverse



Oryza L. (spikelets) – 1, O. australiensis; 2, O. granulata; 3, O. longiglumis; 4, O. meridionalis; 5, O. meyeriana; 6, O. minuta; 7, O. nivara; 8, O. officinalis; 9, O. ridleyi; 10, O. rufipogon; 11, O. sativa; 12, O. schlechteri.

veinlets, blade flat, linear to lanceolate. Inflorescence a panicle; spikelets laterally compressed, usually articulating above the glumes, 3-flowered, lower two florets sterile, upper one bisexual; glumes 2, reduced; sterile lemmas 2, subequal, 1-nerved; fertile lemma boat-shaped, 5-nerved, usually with apical awn; palea 3-nerved, usually mucronate; lodicules 2, anthers 6; ovary with 2 styles. Caryopsis laterally compressed, 2-ribbed, or cylindrical, tightly enveloped by lemma and palea.

- *O. australiensis*. Perennial, growing in tufts, stoloniferous; culm erect, 80–240 cm tall; ligule ovate-triangular to lanceolate, 4–8 mm × 2.5 mm; nodes glabrous; blade linear, 25–35 cm × 0.4–1.4 cm; panicle 18–50 cm long, axis increasingly hispid scabrous toward the tip, primary branches with slightly woolly pubescence at their base; pedicel covered with long glossy hairs; spikelet 6.5–8.4 mm × 2.25–3.1 mm; awn of fertile lemma 5–55 mm long; caryopsis 4.7–6.4 mm × 2–2.5 mm, brown to red-brown.
- *O. granulata*. Perennial, loosely tufted or stoloniferous; culm erect to ascending, 23–78 cm long; ligule collar-shaped, 0.5–2 mm long; nodes glabrous; blade lanceolate, 8–27 cm × 0.7–2 cm, dark green; panicle 4–15 cm long; spikelet 4.9–6.5 mm × 1.5–2.6 mm; glume surface granulate; sterile lemma up to 1.4 mm long; fertile lemma awnless; caryopsis 3.4–4.1 mm × 0.8–2 mm, brown.
- *O. longiglumis*. Perennial, forming tufts, not stoloniferous; culm erect, 85–120 cm long; sheath tight, ligule collar-shaped, 1 mm long; nodes glabrous; blade linear, 25–40 cm × 1 cm; panicle 28–30 cm long; spikelet obliquely to horizontally inserted on the pedicel, 7–8 mm × 1.8–2.3 mm; sterile lemma 0.8–1.6 times as long as the spikelet; awn of fertile lemma 12–25 mm long; caryopsis about 4 mm × 1 mm, brown.
- *O. meridionalis*. Annual or perennial, sometimes forming small tufts, not stoloniferous; culm erect to geniculate, 1–2 m long; sheath tight but lower ones slightly inflated, ligule ovate to linear-lanceolate, 13–25 mm × 4 mm; nodes glabrous; blade linear, 18–30 cm × 0.9–1.2 cm, scabrous above; panicle 11–24 cm long; spikelet 6.5–8.9 mm × 2.1–2.5 mm; sterile lemma 0.2–0.3 times as long as the spikelet; awn of fertile lemma 70–120 mm long; caryopsis 6–6.4 mm × 1.7–2 mm, red-brown.
- *O. meyeriana*. Perennial, loosely tufted or stoloniferous; culm erect to ascending, 23–78 cm long; ligule collar-shaped, 1–5 mm long; nodes glabrous; blade ovate-lanceolate to linear, 8–27 cm × 0.8–3.2 cm; panicle 4–15 cm long; spikelet 6.1–10.5 mm long, about 3–6.5 times as long as wide; glume surface granulate; sterile lemma up to 2.5 mm long; fertile lemma awnless; caryopsis 4.1–7.3 mm × 0.8–2 mm, brown.
- *O. minuta*. Perennial, tufted, stoloniferous; culm erect, 0.5–2.3 m long; sheath tight, lower ones slightly inflated; ligule collar-shaped to triangular 1–8 mm × 2–5 mm, glabrous or hairy; nodes glabrous; blade linear, 15–80 cm × 1–2 cm, glabrous or hairy; panicle 9–20 cm long with spreading branches; spikelet 3.7–4.7 mm long, narrower than 2 mm; sterile lemma up to 3.4 mm long; fertile lemma without or with up to 23 mm long awn; caryopsis 2.3–4.4 mm × 1.3–2.3 mm, orange-brown.
- *O. nivara*. Difficult to distinguish from *O. sativa*. Annual, not stoloniferous; culm semi-erect to decumbent; ligule 14–45 mm long; nodes glabrous; panicle less branched than in *O. sativa*; spikelet 6–8.4 mm × 1.9–3.0 mm; fertile lemma with

thick, 4–10 cm long awn; caryopsis deciduous at maturity and with strong seed dormancy.

- *O. officinalis*. Perennial, tufted, stoloniferous; culm erect to semi-erect, up to 2.3 m long; sheath tight, lower ones slightly inflated; ligule collar-shaped to triangular, 1–8 mm × 2–5 mm, glabrous or hairy; nodes glabrous; blade linear, 15–80 cm × 1–2 cm, glabrous or hairy; panicle up to 42 cm long, whorled at base; spikelet 4–6.4 mm long, wider than 2 mm; sterile lemma up to 3.4 mm long; fertile lemma without or with up to 23 mm long awn; caryopsis 2.3–4.4 mm × 1.3–2.3 mm, orange-brown.
- *O. ridleyi*. Perennial, tufted, stoloniferous; culm erect, up to 3 m long; sheath tight; auricles often present; ligule collar-shaped, deltoid to triangular, 2–5 mm × 2–4 mm, glabrous; nodes glabrous; blade linear, 21–42 cm × 1.2–2.4 cm, glabrous; panicle 15–40 cm long; spikelet 7.6–12.7 mm × 1.7–2.9 mm; sterile lemma up to 10.5 mm long; fertile lemma with 3–12 mm long awn; caryopsis 5.9–7 mm × 0.7–1 mm, brown.
- *O. rufipogon*. Perennial, tufted or stoloniferous, with adventitious roots; culm decumbent and floating or ascending to erect, 1–3 m long, with extravaginal branching at higher nodes; sheath tight, lower ones slightly inflated; ligule triangular, 9–38 mm × 5–8 mm, glabrous; nodes glabrous; blade linear, 27–60 cm × 0.7–2.5 cm, glabrous; panicle 12–30 cm long; spikelet 7.3–11.4 mm × 2–4.4 mm; sterile lemma up to 7.5 mm long; awn of fertile lemma very variable, up to 11 cm long; anthers long; caryopsis 5.2–6.7 mm × 1.4–2 mm, red-brown.
- *O. schlechteri*. Perennial, tufted, stoloniferous; culm erect, 25–85 cm long; sheath tight; ligule collar-shaped, 1 mm long; nodes hairy; blade linear, 10–30 cm × 0.6–1.2 cm, with white hairs; panicle 4–6.5 cm long; spikelet 1.7–2.1 mm × 0.9–1.3 mm; sterile lemma 0.1–0.5 mm long; fertile lemma up to 2.1 mm long, awnless; caryopsis 1.1–1.3 mm × 0.7–0.9 mm, dark brown.

Growth and development Little is known about growth and development. Growth is slow at the seedling stage. *Oryza* species form a group of C3-cycle plants. Flowering occurs near the end of the prevailing rainy season. Grains are usually deciduous and often have a strong dormancy.

Other botanical information *Oryza* is generally considered to belong to the tribe *Oryzeae* of the subfamily *Bambusoideae* and sometimes considered as a separate subfamily, the *Oryzoideae*. Related genera of *Oryza* in South-East Asia are *Hygroryza* Nees, *Leersia* Sw., *Porteresia* Tateoka, *Potamophila* R. Br. and *Zizania* L. Opinions differ about the number of species in the genus *Oryza*; it ranges from 18–22. Several species complexes exist, in which the taxa are difficult to distinguish from each other: e.g. *O. meyeriana* and *O. granulata*, which some consider to be one species *O. meyeriana*; *O. officinalis* and *O. minuta*, which some consider to be one species *O. minuta*; *O. sativa* and *O. nivara*, which some consider to be one species *O. sativa*.

Ecology The wild rice species cover a wide range of habitats, ranging from open and often flooded areas, to partially or heavily shaded mesophytic niches, up to 1500 m altitude in the tropics. Tropical populations are largely perennial, subtropical taxa tend to be annual. *O. nivara* and *O. rufipogon* thrive under full sun, while all others are found under partial or full shade. Soil types vary from heavy clay to forest soils high in organic matter. Because seedlings usually grow slowly, populations are only found under stable conditions, away from fast-flowing streams and cliffs.

Agronomy Deliberate cultivation only takes place for research purposes. Field-collected seed needs to be slowly dried and stored cold and dry. It should be sown at the beginning of the rainy season. Prior to seeding, strong grain dormancy should be broken by dry heat treatment (50°C, 5–10 days), hulling, surface disinfection, and for unusually strong dormancy, the pericarp should be scratched near the embryo with a sterile needle. Treated seed is best germinated in Petri dishes and the sprouted seed transferred to a tray of fine soil. Healthy seedlings beyond the 3-leaf stage are transplanted into large clay pots, with several plants per pot. Seedlings and young plants need partial shading, careful watering, and light fertilization.

To multiply germplasm, plants are best kept in pots in a screenhouse for isolation and protection. Vigorously growing plants should be staked and tied, exserting panicles must be bagged with a porous bag or net to collect shattering seed. The identity of individual plants has to be checked, to ensure the nomenclature is correct. Herbarium specimens should be taken after first planting. Some species can be maintained by ratooning and repeatedly harvested for seed. Rhizomes or seed should not be allowed to escape into drainage canals or fields and become noxious weeds.

Genetic resources A few decades ago the wild rice species were widespread and readily found in their native habitats. Development projects, deforestation and habitat disturbance have rapidly reduced population number and size. Neglect in maintaining drainage and irrigation canals has led to *O. nivara* and *O. rufipogon* being rapidly ousted by tall grasses and aquatic weeds. The future existence of nearly all wild taxa is threatened. Ex situ conservation in genebanks is both insufficient and inefficient: the wild populations are heterozygous and heterogeneous, requiring several plants to represent each, and seed production is meagre. Staff of the International Rice Research Institute (IRRI) have actively collected and assembled approximately 1400 samples, but further exploration and collection is needed in many inaccessible areas. In situ conservation with collaboration from local communities offers an alternative and more effective conservation approach, though its implementation is even more challenging. Field botanists should promote and expand in situ activities.

Breeding Most wild rice species play an important role in breeding programmes to improve the cultivated rices *O. sativa* and *O. glaberrima*. Multidisciplinary evaluation at IRRI has revealed the enormous potential of wild species as sources of resistance to or tolerance of biotic and abiotic stresses. *O. nivara* has furnished the sole resistance to grassy stunt virus; *O. officinalis* is resistant to yellow stem borers, tungro virus and several planthoppers; *O. minuta* is resistant to blast and bacterial blight; *O. rufipogon* has the ability to elongate internodes (important for deep-water areas) and salinity tolerance. A weedy sterile plant found on Hainan island of China has provided the cytoplasmic male-sterility for 18 million ha of hybrid rices in China.

Prospects With the advent of biotechnological innovations, the wild rices will quickly grow in economic potential for further enhancing rice production.

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T.T. Chang & Z. Harahap

Oryza sativa L.

Sp. pl.: 333 (1753).
GRAMINEAE
$2n = 24$

Synonyms *Oryza glutinosa* Lour. (1790), *O. montana* Lour. (1790), *O. praecox* Lour. (1790), *O. aristata* Blanco (1837).

Vernacular names Rice (En). Riz (Fr). Indonesia: padi (general), pari (Javanese), pare (Sundanese). Malaysia: padi. Papua New Guinea: rais. Philippines: palay. Burma (Myanmar): sabar-bin. Cambodia: srö:w. Laos: khauz. Thailand: khao. Vietnam: l[us]a.
There are specific vernacular names for the rice grain, unhulled grain, polished rice, cooked rice (also depending on how it is cooked), left-over rice and even rice stuck to the bottom of the pot. The crop and the unhusked grain are known as paddy.

Origin and geographic distribution *O. sativa* evolved along the foothills of the Himalayas and was probably first cultivated in ancient India. Rice has been cultivated for about 9000 years. In Indonesia, Malaysia and the Philippines rice cultivation began some time after 1500 BC. The earliest evidence of cultivated rice was found in the Ban Chian excavation in Thailand, dating cultivated rice at 500–900 BC. Rice is planted throughout the humid tropics and in many subtropical and temperate areas with a frost-free period longer than 130 days.

Uses Rice is the main staple food of 40% of the world population and the main food throughout South-East Asia. The rice grain is cooked by boiling in water or by steaming, and is eaten mostly with pulses, vegetables, fish or meat. It is often the main source of energy. Flour from rice is used for breakfast foods, meat products, baby foods, bread and cake mixes, and cosmetics. The waxy rice flour has superior qualities as a thickening agent for white sauces, puddings and oriental snackfoods. Glutinous rice is used for making sweetmeats. Starch is made from broken rice, and used as laundry starch, in foods, and textile manufacture. Beers, wines and spirits are manufactured from rice.

The husk or hull is used as fuel, bedding, absorbent, building board, and carrier for vitamins, drugs, toxicants, etc. The charred rice hull is used for filtration of impurities in water, medium for hydroponics and manufacture of charcoal briquettes.

The rice bran or meal obtained in pearling and polishing is a valuable livestock and poultry food. It consists of the pericarp, the aleurone layer, the embryo and some of the endosperm. The bran contains 14–17% oil. Crude rice bran oils are used for producing solidified oil, stearic and oleic acids, glycerine and soap. Processed bran oil is used for cooking, antirust and anticorrosive agents, textile and leather finishers, and in medicine. China, India, Japan, Vietnam and Thailand are the main producers of rice-bran oil.

Rice straw is used for animal feed and bedding, but is nutritionally inferior to other cereal straws unless ensiled. It is used for the manufacture of straw boards and pulp for paper, for mushroom growing medium, for the production of organic manure, for mulching crops such as onions, garlic and cucurbits, and only rarely for rope and roof thatch.

Production and international trade The yearly fluctuation in rice production resulting from government policies, environmental aberrations such as drought and flood, availability of inputs, and other factors is reflected in the international trade. Some importing countries become exporting in certain years (e.g. the Philippines). Other countries where rice is a main staple food are perennial importers (e.g. Malaysia) or exporters (e.g. Thailand).

Probably half the world production is consumed on the farms where it is grown while only 5% enters into international trade. Approximately 3–4% of the rice crop is required annually for planting.

The 1994 world rice area was 146 million ha with a production of 530 million t. Asia accounts for 90% of the world production and area. China, India and Indonesia are the largest producers. Malaysia was one of the largest importers, while Thailand continues to be the world's largest exporter of rice (34% of world trade) followed by the United States, Pakistan, Vietnam and China. Cambodia and Sri Lanka generally import rice although Cambodia used to export rice.

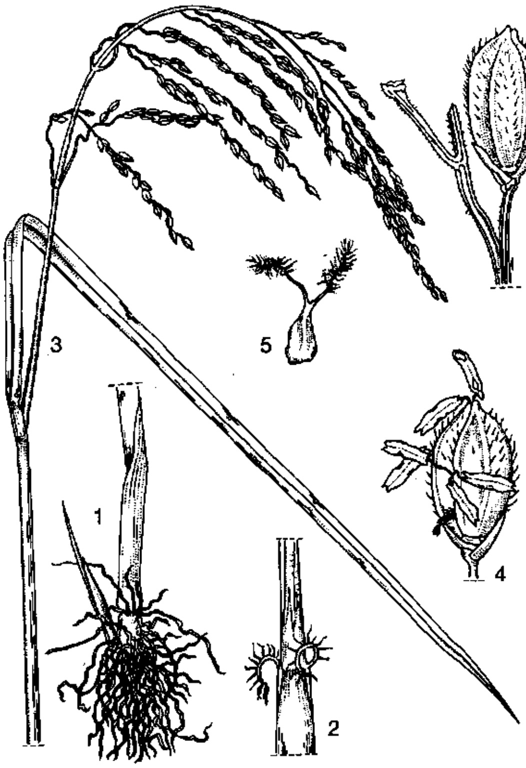
Per capita annual consumption in South-East Asia is about 142 kg. The trend is for per capita intake to decline with rising income.

Properties The grain is the important economic yield component of the rice plant and its endosperm is the final product consumed. The endosperm consists mainly of starch granules embedded in a proteinaceous matrix. The endosperm may be waxy (glutinous) or non-waxy (non-glutinous) depending on the content of amylose and amylopectin. The higher the amylopectin content, the more glutinous the product is. The endosperm also contains sugar, fat, crude fibre, vitamins, and inorganic matter.

The composition of rice depends upon the method and degree of milling, polishing and whether or not it has been parboiled. It is also influenced by genetic and environmental factors to some extent. Analyses of brown (and white) rice give the following composition per 100 g edible portion: water 12 g, protein (6.7–)7.5 g, fat (0.4–)1.9 g, carbohydrates 77.4(–80.4) g, fibre (0.3–)0.9 g and ash (0.5–)1.2 g. Milling and polishing result in a substantial loss of protein, fat, minerals (phosphorus and potassium) and vitamins (thiamin, riboflavin and niacin). Parboiling results in the retention of more minerals, particularly phosphorus, and vitamins.

The 1000-kernel weight of paddy rice is 20–35 g; about 20% of this weight is the husk. The extracted bran is rich in proteins and carbohydrates. The husk is very rich in silica. Rice straw contains approximately: water 7.0%, protein 3.4%, fat 0.9%, carbohydrates 47.8%, fibre 33.4% and ash 7.5%.

Description Annual grass, 50–130 cm tall, up to 5 m long in deep-water rices, forming small tufts. Roots fibrous, arising from the base of the shoots. Stem (culm) erect to ascending, glabrous, composed of a series of nodes and internodes, the number depending on cultivar and growing season; each node with a single leaf, and sometimes also with a tiller or adventitious roots; internodes usually short at base of plant, progressively increasing towards top. Leaves in two ranks; sheaths initially enclosing each other, forming a pseudostem, later enclosing the internodes; ligule triangular to linear-lanceolate, 1–1.5 cm long, of-



Oryza sativa L. – 1, plant base with roots; 2, ligule and auricles; 3, panicle with leaf; 4, flowering spikelet; 5, pistil; 6, inflorescence branch with mature spikelet.

ten split; auricles often present, falcate, 1–5 mm long, hairy; blade linear, 24–60 cm × 0.6–2.2 cm, glabrous, smooth to scabrous, often with spiny hairs on margin. Inflorescence a terminal panicle, 9–40 cm long, with 50–500 spikelets depending on the cultivar; spikelets single, borne on a short pedicel, oblong to lanceolate, 7–11 mm long, about 2–3 times longer than wide, containing a single bisexual flower, with 2 small glumes, a large, 6–10 mm long, boat-shaped lemma sometimes with an awn up to 15 cm long, and likewise palea with very short awn, 6 stamens, a broad ovary, and 2 plumose stigmas. Fruit (caryopsis, grain) varying in size, shape and colour, ovoid, ellipsoid or cylindrical, 5–7.5 mm × 2–3.5 mm, often whitish-yellow or brown to fuscous.

Growth and development Growth and development depend on cultivar and environmental conditions. Seed soaked in water germinates in 24–48 hours. Seed dormancy may last up to 4 months but most cultivars have a short dormancy or none at all. Ten days after germination the plant becomes independent as the seed reserve is exhausted. Tillering begins thereafter, although it may be set back for a week in transplanted seedlings. Roots can grow under low oxygen concentrations. During early growth the roots are positively geotrophic, but by the time of panicle initiation, they are growing horizontally to produce a dense surface mat. The roots are not typically aquatic as they are much branched and have a profusion of root hairs; later, aerenchyma develops in the cortex. The type of root development is largely dependent upon the nature of the soil, the method of cultivation and differences between cultivars. Upland rice cultivars usually have fewer tillers and larger panicles. Floating rices have a long maturation period of 7 months or more. In modern cultivars with an average maturation period, maximum tillering stage is attained around 45 days after transplanting and coincides with panicle initiation. The duration of the vegetative stage varies greatly among cultivars and depends on the photoperiod sensitivity of the cultivar and the season of planting.

In photoperiod-sensitive cultivars, panicle initiation occurs only when daylength is less than the critical. Panicle initiation is delayed by long daylength and occurs several days after maximum tillering stage. Thus, the vegetative stage might range from 7 to more than 120 days. The reproductive stage starts at panicle initiation, and the period from panicle initiation to flowering or anthesis is around 35 days. Rice is mainly self-pollinating, but varying small amounts of cross pollination by wind do occur. Anthesis occurs during the day between 10 a.m. and 2 p.m. depending on temperature and humidity. The higher the temperature and the lower the humidity, the earlier the anthesis. It takes around 7 days to complete the anthesis of all spikelets on a panicle, starting from the top and progressing downwards. The period from flowering to full ripening of all the grains in a clump is usually about 30 days. Low temperature can delay maturity and high temperature accelerates it.

Other botanical information *O. sativa* has a polyphyletic origin and developed from hybrids of wild species. There is disagreement about the identity of the wild relatives of rice. Some consider them to be one species (*O. rufipogon* Griffith), others contend they are two species (*O. rufipogon* and *O. nivara* Sharma & Shastry). The evolution of the cultivated rice *O. sativa* is supposed to extend from perennial forms (*O. rufipogon*) to annual forms (*O. nivara*). *O. sativa*, *O. rufipogon* and *O.*

nivara form a large species complex together with weedy forms of rice (popularly called 'red rice' because of the red endosperm). Cultivars are developed through hybridization, selection, introgression and inter-cultivar recombination. There are believed to be around 100 000 different cultivars and selections of rice. The widespread dispersal of the Asian cultivated forms led to the formation of two major eco-geographical cultivar groups: the indicas, which are mostly from the tropics, and the japonicas, from temperate areas. Traditional indica cultivars are tall, leafy, high tillering, and prone to lodging; they respond poorly to fertilization, particularly to nitrogen, and are sensitive to photoperiod; they are hardy, resistant to disease and tolerate unfavourable growing conditions; they will produce fair yields under conditions of low management. Modern japonica rices have short stiff straw, and are less tillering, less leafy, resistant to lodging, insensitive to photoperiod and are early maturing. Modern indicas have similar characteristics to the japonicas. The characteristics of the two cultivar groups have become less distinct because of the interbreeding programmes in recent years. On the basis of chemotaxonomy a third group previously known as javanicas has now been assigned to the tropical japonicas.

Rice may also be classified according to the conditions under which it is grown, namely:

- upland rice (also called hill rice), grown as a rainfed crop, generally low tillering with large tillers and panicles;
- lowland rice (also called swamp rice), grown on irrigated or flooded land;
- deep-water rice (also known as floating rice), grown in areas of deep flooding, up to 5 m or more, in which the rapid growth of the internodes keeps pace with the rising water.

Rice cultivars can also be classified according to the size, shape and texture of the grain, or according to the period needed to mature.

O. glaberrima Steudel cultivars are grown in Africa only.

Ecology Rice is grown as far north as 53°N in Moho, northern China and as far south as 35°S in New South Wales, Australia. It grows on dry or flooded soil. Tolerant cultivars can withstand varying degrees of low temperature. Traditional cultivars are generally photoperiod sensitive, and flower when daylengths are short (critical daylength of 12.5–14 hours). Many modern cultivars are photoperiod insensitive and flower at any latitude, provided temperature is not limiting.

Rice yields are higher when solar radiation during the reproductive and ripening phases is high, so that generally grain yields are higher during the dry season than during the wet season. Low temperature limits the range of the rice crop. The average temperature during the growing season varies from 20–38°C. Rice is most susceptible to low temperature at the stage of panicle initiation, when temperatures below 15°C at night can cause spikelet sterility. Low temperature can also result in poor germination or death of seedlings, yellowing of leaves, low tiller number, degeneration of spikelets, high sterility, stunting, and poor panicle exsertion causing low grain yields. Low soil and floodwater temperatures also affect the nutrition, growth and grain yield of rice. Temperatures above 21°C at flowering are needed for anthesis and pollination.

The chief factor limiting the growth of rice is the water supply. However, the water regime in which rice is growing and the water requirements are variable. Upland rice, grown as a rainfed crop, requires an assured rainfall of at least 750 mm over a period of 3–4 months and does not tolerate desiccation. Lowland rice tends to be concentrated in flat lowlands, river basins and deltas. In South-East Asian countries the average water requirement for irrigated rice is 1200 mm per crop or 200 mm of rainfall per month.

Relative humidity within the crop canopy is high, since there is standing water in most rice crops. A low relative humidity above the canopy during the dry season aggravated by strong winds can cause spikelet sterility.

Rice is generally grown at sea-level but also in mountainous areas of South-East Asian countries. Cold-tolerant cultivars are grown up to 1230 m in the Mountain Province of the Philippines and up to 2300 m in the northwestern Himalayas. No direct effect of altitude is evident. Cold-tolerant cultivars do not differ morphologically from other cultivars. However, such cultivars can withstand 12°C water temperature at seedling stage, 15–17°C night temperature during panicle initiation and 21°C day temperature during anthesis.

Rice does best in fertile heavy soils. Rice can be planted in dry soil or puddled soil and grown like an upland crop, or in inundated soils. The soils on which rice grows vary greatly: texture ranges from sand to clay, organic matter content from 1–50%, pH from 3–10, salt content from almost 0–1%, and nutrient availability from acute deficiencies to surplus. The optimum pH for flooded soil is 6.5–7.0. Because land management depends on soil, climate, water supply, and socio-economic conditions of the area, there is a considerable range in the pedogenetic and morphological characteristics of rice-growing soils. Rice is grown primarily in submerged soil, and the physical properties of the soil are relatively unimportant as long as sufficient water is available. Pore spaces are important physical properties as they influence the retention and movement of water and air. The soil pH before and after lowland fields have been flooded is an important determinant of soil fertility and of the management of rice soils. In submerged soil the pH tends to be neutral, i.e. the pH of acid soils increases whereas the pH of calcareous and sodic soils decreases; ions of Fe, N and S are reduced; the supply and availability of the elements N, P, Si and Mo is improved, whereas the concentration of water-soluble Zn and Cu decreases; toxic reduction products such as methane, organic acids and hydrogen sulphide are formed. The chemical composition of the soil varies among regions, countries, and areas. The flooding of rice soils creates a favourable environment for anaerobic microbes and the accompanying biochemical changes. As a result, the decomposition rate of organic matter decreases. However, a thin surface layer generally remains oxidized and sustains aerobic microbes. The main biochemical processes in flooded soil are a series of successive oxidation-reduction reactions mediated by different types of bacteria. Nitrogen fixation takes place in paddy soils by *Azotobacter* and blue-green algae.

Lowland rice and deep-water rice may be subjected to drought or complete submergence. There is varietal tolerance of such adverse conditions.

Propagation and planting Different systems of growing rice have evolved to suit specific environments and socio-economic conditions. Rice culture can be classified according to the water source as rainfed, floodfed, or irrigated. Based on land management practices, rice lands can be grouped as: lowland (wetland preparation of fields) or upland (dryland preparation of fields). Using water regime as the criterion, rice lands can be classified as: upland (without standing water), lowland (with 5–50 cm of standing water), or deep-water (with 50–600 cm of standing water). There is a lack of accurate data on the extent of different rice cultures. In Asia, lowland rice culture is the most prevalent system. The upland rice ecosystem accounts for 19% of the total rice area in Asia, but only for 4.5% of the production. Land is prepared either wet or dry and water is generally retained in the field by bunds. Systems of lowland rice cultivation are usually traditional, based on centuries of experience. Most rice is grown on smallholdings, usually of 0.4–2 ha. In Africa and Latin America, upland rice culture is the major system and rice is grown on level and sloping fields that are not bunded.

The rice crop is propagated by seed, which may either be broadcast or drilled directly in the field, or the seedlings may be grown in nurseries and transplanted. Direct seeding is done in dry or puddled soil. In puddled soil the (pre-germinated) seeds are broadcast. The water level is kept at 0–5 cm under tropical conditions, but higher in temperate areas. This type of sowing is possible in combination with the use of herbicides, and is becoming an important method of rice culture in Thailand, Malaysia and the Philippines, due to rising labour costs. In dry soil the seeds are sown after land preparation and are then covered lightly with soil by a tooth harrow. Germination occurs after heavy continuous rains. In upland rice cultivation the land is prepared in the dry weather and the rice is broadcast or dibbled in when the rains start. It may be grown in rotation or intercropped with other crops such as cassava, maize, groundnut and other pulse crops. Floating rice is cultivated in areas subject to deep flooding, and the seed is sown either dry or wet.

The three major methods of raising seedlings common in lowland rice cultivation are the dry bed, wet bed and dapog:

- Dry seed-bed: The nursery bed is prepared near the water source before land preparation. The bed is about 1.5 m wide and the seeds are sown at 1 kg per 10 m^2 and then covered with a thin layer of soil and watered until saturation for uniform germination. Further watering is applied as needed. The seedlings are ready for transplanting 20–35 days after sowing.
- Wet seed-bed: The raised nursery bed is made in the puddled or wet field, and is about 1.5 m wide. About 400 m^2 will accommodate 45 kg of rice, which is sufficient to plant one ha. Seeds are pre-germinated and spread on the seed-bed which is kept constantly wet. When seedlings are 2–3 cm tall, continuous shallow irrigation is practised. Water depth is increased to 5 cm as the seedlings grow taller. The seedlings are ready for transplanting 20–35 days after sowing.
- Dapog: Pre-germinated seeds are sown on cement or puddled soil covered with banana leaves or plastic sheets. Seeding density is much higher, 60 kg seeds per 40 m^2, which is sufficient to plant one ha. The pre-germinated seeds are

pressed in lightly and continuously watered. The resulting mat is rolled up and taken to the field for transplanting after 11 days. This method is used in some provinces of the Philippines, and has been adopted by other countries.

Although intercropping is practised in upland rice, rice is generally a sole crop under lowland conditions. In many parts of the tropics 2 or even 3 crops of rice can be grown per year, provided water, fertilizer and day-neutral cultivars are available for 1 or 2 of the crops. Near harvest, relay planting is rarely practised.

Land preparation varies, even within the lowland rainfed-rice areas:

- Wetland tillage: This method is common in most tropical Asian countries. It consists of soaking the land, which entails water being absorbed until the soil is saturated; ploughing, which is the initial breaking and turning over of the soil, to a depth of 10–20 cm, using a wooden or light iron plough drawn by 1–2 buffaloes or oxen, preferably when there is 7.5–10 cm of water on the land; and harrowing, during which big clods of soil are broken and puddled with water. The important benefits of puddling include the apparent reduction of moisture loss by percolation, better weed control, and easy transplanting. The low redox potential of submerged puddled soil helps to conserve water-soluble nutrients, favours accumulation of ammonium, increases biological nitrogen fixation and increases the availability of phosphorus, silicon, iron, and manganese.
- Dryland tillage: The land is prepared in dry weather and the rice is sown just before the rains begin. This method makes it possible to have initial crop growth from early monsoon rains. Less labour is required for seed-bed preparation, land preparation and transplanting, and the soil structure is better for the stand establishment of the following non-rice crop. This method has its disadvantages: weed control is a major problem; percolation losses are high, increasing the risk of drought stress; also, fertilizer requirements are often higher. Bunding and levelling are essential in order to hold the water on the land and maintain it at the required depth. The land is divided into fields by contour bunds; field size and shape vary with the topography. The bunds are usually made of clay, mud and weeds, with controlled openings to allow water in and out.

Husbandry The agronomy of the rice crop is rather diverse. Rice is mostly hand-transplanted in puddled soil. This is a labour-intensive operation. About a third of the transplanted seedling should be above the water. The spacing is 15–25 cm (160 000–400 000 plants/ha). Transplanting in rows facilitates hand weeding. The operations required after the crop has become established are weeding, application of manure and fertilizers, and the regulation of the water supply. Weeding is not necessary in the first 2 weeks. Weeding up to 40 days after transplanting increases grain yields. Manual weeding is common practice, although rotary weeders are also commonly used in some areas. Chemical weed control, either pre- or post-emergence, is also becoming popular in the tropics, especially in areas where pre-germinated seed is broadcast in puddled soil. Broadcasting of seed will increase with rising cost of labour. The water level in the fields is kept at a height of 5–15 cm to suppress weed growth and to ensure water availability. Weeds are worse in a broadcast crop than in transplanted rice. In many countries the most serious weed of rice is wild red rice (*Oryza rufipogon*). Other serious weeds include grasses, such as barnyard grass (*Echinochloa crus-galli* (L.) P. Beauvois), several *Cyperaceae* and water hyacinth (*Eichhornia crassipes* (Martius) Solms).

In the cultivation of lowland rice, the land is inundated from the time of planting until the approach of harvest. The water is supplied either by flooding during the rainy season, by growing the crop in naturally swampy land or by controlled irrigation where water is guided through irrigation canals or lifted from wells by human or animal power. Continuous flooding at a static 2.5–7.5 cm depth provides the potential to produce optimum rice yields. The fields may be drained temporarily to facilitate weeding and fertilizing. At flowering the water is gradually reduced until the field is almost dry at harvest. Generally speaking 1.5–2 m of water, rainfall plus irrigation, are required to produce a good crop. The period in which rice is most sensitive to water shortage is 20 days before to 10 days after the beginning of flowering.

Fish often occur in paddy fields and help to supplement the rice diet. In some cases they are deliberately introduced and trenches are provided to give deeper water. The most commonly used species are carp (*Cyprinus*) and *Tilapia*. Pesticides often prove to be toxic to fish in rice fields.

Fertilizer application is recommended at final harrowing, but farmers generally fertilize later, including topdressing of nitrogen. The amount of fertilizer used depends on cultivar, season, soil, and availability. Modern cultivars produce higher yields with higher nitrogen levels. At high rates of nitrogen the traditional cultivars become too vegetative, tall, and are prone to lodging. A rice crop producing about 3500 kg/ha of grain and an equal quantity of straw removes approximately 56 kg N, 12 kg P and 48 kg K from the soil. The most common mineral deficiencies in rice cultivation are of nitrogen and phosphorus, with potassium and sulphur in limited areas and sometimes zinc and silicon on peaty soils. Deficiency of potassium is often associated with iron toxicity, which is common on acid, sandy, latosolic (ultisols and oxisols), sulphate and peat soils (histosols). Upland rice often suffers from sulphur deficiency. Zinc deficiency occurs regularly in rice areas because of the high pH and strong reduction of the soil.

In Indonesia and elsewhere, phosphorus is often limiting, and must be added to achieve a significant response to nitrogen. Higher nitrogen rates are used during the dry season when solar radiation is higher and increase in grain yields is larger. In many areas of the tropics, the availability of commercial inorganic fertilizer to farmers is still a problem. Generally, only nitrogen fertilizer is top-dressed, mostly before or at panicle initiation. Fertilizer is broadcast by hand.

Physiological diseases occur in the rice plant when the uptake of nutrients is disturbed. Influenced by reduction and poor internal drainage, several toxic elements such as iron which inhibit the uptake of phosphorus in the plant may accumulate in the environment of the root. Often an excess of harmful elements such as calcium is accompanied by a lack of other elements such as phosphorus, iron, and zinc. Double cropping is inadvisable where physiological diseases occur.

Green manure and *Azolla* are seldom used in the tropics although the technology to apply them is available. *Sesbania rostrata* (Bremek. & Oberm.) Gillet is a promising green manure crop. Organic fertilizer is not commonly applied to rice crops, although it used to be popular in China and Vietnam. Although soil conditions are improved by incorporating such fertilizer, the result is not immediately apparent. The cost and labour involved also discourages its use.

The degree of mechanization varies; in some countries the land preparation, seeding or transplanting, fertilizer application, herbicide application, harvesting, threshing and drying are fully mechanized. Hand tractors are becoming popular, and large deep-water rice areas in Thailand are ploughed with large tractors. It takes 105 hours to plough one hectare with animal traction compared to 35 hours with hand tractors. Threshing machines are the most popular machines in the rice farms of South-East Asia.

For various reasons many rice fields are left fallow in the dry season. In areas with suitable climatic and soil conditions for dry-season cultivation, rice may be rotated with crops such as cereals, pulses and vegetables.

Diseases and pests The most serious diseases of rice are blast (*Magnaporthe grisea*, anamorph *Piricularia grisea*), bacterial leaf blight (*Xanthomonas campestris* pv *oryzae*), and tungro (virus disease). The blast fungus can infect rice plants at any growth stage. Typical leaf lesions are spindle-shaped (wide in the centre and pointed toward each end). Large lesions usually develop grey centres. Leaves of susceptible cultivars may be killed. At heading, the peduncle may be affected and the whole bent panicle rendered useless. Blast disease is more severe under humid conditions.

Bacterial leaf blight causes yellow to white lesions which begin as water-soaked stripes at the margins of a leaf blade. Lesions may start on one or both edges of a leaf or at any point on injured blades, and advance to cover the entire leaf blade. They may reach the lower end of the leaf sheath in susceptible cultivars. Bacteria invade the vascular system of the rice plant when roots are broken or when leaves are damaged during transplanting. High nitrogen fertilizer rates favour blight epidemics where suspectible cultivars are grown.

Tungro virus is the most important virus disease of rice in tropical Asia. Tungro virus vectors are *Nephotettix malayanus*, *N. nigropictus*, *N. parvus*, *N. virescens*, and the zigzag leafhopper (*Recilia dorsalis*). Outbreaks destroy plants in a large area in a short time. Infected plants are stunted and the number of tillers is reduced. Leaf colour changes from green to light-yellow to orange-yellow to brown-yellow, starting from the tips of olders leaves. Young leaves are often mottled or have pale green to white stripes of different lengths running parallel to the veins. Infected plants usually live until maturity but panicles are often small, sterile, and incompletely exserted. Low yields mainly result from fewer filled spikelets per plant.

Chemical control for blast and blight is expensive and is hardly used in the tropics. The insect vectors of the tungro virus can be controlled by insecticides, but this does not prevent the virus disease to occur on susceptible cultivars.

Insects cause extensive damage to the rice crop in the field and to the grain during storage. The brown planthopper (*Nilaparvata lugens*) can cause rice plants to die by feeding intensely on them. Brown planthoppers can attack susceptible cultivars in large numbers, causing hopperburn. Infested plants turn yellow and die. Hoppers also transmit grassy stunt, ragged stunt, and wilted stunt virus diseases. Different species of stem borers can cause serious damage to the rice crop; the most important species are striped borer (*Chilo suppressalis*) and yellow borer (*Scirpophaga incertulas*). Damage results from larvae feeding within the stem, severing the vascular system. Deadheart is the damage to the tiller before flowering. Whitehead is the damage after flowering which causes the entire panicle to dry. The most serious pests of stored rice are the rice weevil (*Sitophilus oryzae*) and the lesser grain-borer (*Rhyzopertha dominica*). These insects bore into the sound kernels and can completely destroy the whole grain.

The high-yielding cultivars developed in the 1960s caused major shifts in the insect pest complex. Insecticide use has become a part of crop management recommendations in many developing countries. However, the indiscriminate use of insecticides has led to major outbreaks of insect pests such as brown planthopper and green leafhopper because of the destruction of indigenous predators and parasites that had kept pest populations in check. Considerable progress has been made on various methods of pest control. It is important to use all of these measures in developing an integrated pest management (IPM) programme that is sustainable, inexpensive, and environmentally safe. This means using non-pesticidal methods of pest control, and resorting to pesticides only when the pest causes economic loss. The various components of IPM are host plant resistance, cultural methods, biological control and, finally, chemical control when pest damage threatens to exceed the economic injury threshold. Resistant rice cultivars provide an inherent control which does not involve any expense or result in environmental pollution, and are generally compatible with other insect control methods. Cultural methods include sanitation (the destruction of crop residue and of alternative hosts including weeds and of habitats for aestivation), tillage and flooding of fields to destroy insect pests in stubbles, crop rotation, intercropping, timing of planting and harvest to avoid pest infestation, use of trap crops, and proper fertilizer and water management. One of the most important approaches to biological control in the rice ecosystem is conservation of the natural enemy complex. The IPM strategy emphasizes the need-based use of insecticides rather than prophylactic treatment.

In some countries, specific diseases and pests are serious threats to rice growing: ufra (caused by the nematode *Ditylenchus angustus*) in Vietnam and Bangladesh, gall midge (*Orseolia oryzae*) in India, Cambodia, Vietnam, Indonesia, Sri Lanka and Thailand.

The most effective control of most diseases and pests of rice is breeding for tolerant or resistant cultivars.

Harvesting Grains should be harvested before fully mature (around 21–24% moisture), usually about 30 days after flowering, or when 90% of the grains are firm and do not have a greenish tint. Wetting and drying cause grain cracking, cracks being formed more readily when the grain is quite hard. So, delayed harvesting results in a lower percentage recovery of whole grains. The rice plants are cut halfway up the stem and either allowed to dry in the field or bundled for processing in a selected area. Harvesting by hand, the commonest method, is very labour-intensive. In some areas a small knife is used, but the common method is to use a sickle which cuts the heads plus some of the straw. Mechanical harvesters are beginning to be used in many areas of South-East Asia. Drying to 14% moisture is necessary to prevent fungal and bacterial growth and to lessen the generation of heat and the decrease in dry matter caused by respiration.

Yield Grain yields in South-East Asia are generally lower than in temperate areas. Average yields in t/ha in 1994 were 4.3 in Indonesia, 3.1 in Malaysia, 3.0 in the Philippines, 2.2 in Thailand, 3.5 in Vietnam, versus 5.8 in Korea, 6.0 in China, and 6.2 in the United States. The average world yield is 3.7 t/ha, higher than the yields in most tropical Asian countries. Yields are generally higher during the dry season than during the wet season and in irrigated than in upland rice. The grain yield of upland rice is around 0.5–2.0 t/ha in Asia but may reach 4 t/ha in Latin America. Upland rice yield in Indonesia is only one third of the yield of irrigated rice. Rainfed lowland rice is also higher yielding than upland rice but may suffer a drastic reduction in years with drought or floods. Although yields in the deep-water rice areas are generally low, they are more stable than in the upland rice areas of South-East Asia.

Handling after harvest Threshing to separate the grain and its enclosing husks from the stalk may be done by hand, by beating the rice stalk bundles on a stone or slatted bamboo platform, or using animals to trample on the panicles, or using threshing machines of various sizes. Threshing machines are becoming popular as there is a need to process the harvest as soon as possible to reduce grain yield losses. Because of the shortage of cemented drying floors, roadsides are often used as drying floors. Winnowing is usually done by shaking and tossing the paddy on a basket-work tray with a narrow rim. The grain falls on the mat and the husk, chaff and dust are carried away by the wind. Hand-winnowing machines are also available. After winnowing the paddy is dried in the sun and is then ready for hulling or transport to the mill.

Proper drying of the rice grains is important to prevent germination and rapid loss of quality. Optimum moisture content for storage is 12.5%. Rice grains are mostly stored in sacks after drying. Storage losses are often high because of poor facilities. Moulds, insects, rodents and birds affect both the quantity and quality of the grains. Increase in fat acidity during improper storage reduces the eating quality. Temperature and humidity during storage affect rice quality and these have to be taken into consideration in the proper storage of rice grains. Rice for home consumption is stored unhusked, as it is less susceptible to deterioration. It is then husked in small quantities to supply current domestic needs.

When milling maize or wheat the kernels are broken into small particles, but in rice milling the aim is to avoid breaking the kernels because whole kernels command a higher price. The percentage of head rice (whole kernels) depends on the drying process, cultivar, environment during maturity and the milling machine used. There are different methods of milling. On milling, paddy gives approximately: husk 20%, whole rice 50%, broken rice 16%, bran and meal 14%. The husked or hulled rice is usually called brown rice, and this is then milled to remove the outer layers, including the aleurone layer and the germ, after which it is polished to produce white rice. Inevitably some of the grains are broken during husking and milling, giving rise to broken rice. During milling and polishing, some of the protein, fat, minerals and vitamins are removed, reducing the nutritional value but increasing eye-appeal and storability. Much of the vitamin B_1 (thiamine) may be lost and this may cause beriberi in consumers.

In Bangladesh and India, parboiling is common. This involves soaking, boiling and drying the rice grains before milling. The nutrient value of the kernels is improved with parboiling but the practice is not popular in South-East Asia.

Genetic resources Most national programmes have their own collections of rice cultivars. Indonesia has about 1300 accessions, Malaysia 5500 and Thailand 16 000. Most of these accessions are also available at the International Rice Research Institute (IRRI), where the largest collection is found, with about 83 000 accessions which are characterized on the basis of about 80 traits. These traits not only include morphological characteristics but also susceptibility to diseases and pests, and reaction to environmental stresses, mineral deficiencies or toxicities. Other countries have only a working collection but are starting to build up their own germplasm bank consisting of the landraces in their country. Collection of wild rices is being emphasized for possible new sources of important genes.

Breeding Potential rice grain yields in the tropics have increased dramatically since the mid 1960s with the introduction of IR8 and similar plant types. The green revolution started with the development of semi-dwarf, stiff-straw plant types which prevented lodging, a serious problem in rice cultivation, and allowed high nitrogen fertilizer doses. The 'miracle cultivars' also had upright short leaves which resulted in better light distribution and photosynthesis. Carbohydrate partitioning was also greatly improved with reduction in height. Grain yields reached a plateau in the late 1960s. Subsequent breeding objectives have been to increase disease and pest resistance, early maturity and tolerance of adverse environments. Biotechnology is helping in these objectives and also in the further increase of grain yields.

Improvements in biotechnology opened up new methods (e.g. embryo rescue) of crossing wild relatives of rice and finding new sources of important genes. Resistance to grassy stunt virus was found only in the wild species *O. nivara*. Fortunately it was compatible with *O. sativa*. Other wild species with important resistance to diseases and environmental stresses have been found. *O. rufipogon* is a source of cytoplasmic male sterility and flood tolerance; *O. glaberrima*, cultivated in Africa, is resistant to green leafhopper; *O. barthii* A. Chev. to bacterial blight; *O. punctata* Kotschy ex Steudel, *O. officinalis* Wallich ex Watt, *O. eichingeri* A. Peter, *O. minuta* J.S. Presl to brown planthopper; *O. brachyantha* A. Chev. & Roehr. to rice whorl maggot; and *Porteresia coarctata* (Roxb.) Tateoka (synonym: *O. coarctata* Roxb.) is tolerant of salinity.

Prospects Some of the prospects for rice are:

- continued emphasis on stability of yields under tropical conditions;
- greater resistance to diseases and pests; this is more likely to be found in the hardier indica cultivars;
- tolerance of and adaptation to local and environmental stresses;
- better utilization of available nutrients and greater production of endogenous available nitrogen;
- mechanization of rice farming, especially land preparation, direct seeding/transplanting, harvesting, and processing;
- application of integrated pest management (IPM) by more farmers through adequate dissemination of information.

Any new types recommended should be well adapted to the local environment and methods of cultivation, but steps should be taken to improve the latter. This requires adequate research adjusted to the local conditions, a well-functioning extension service, and government support. For instance, hybrid rice is used in China and lately in Vietnam. However, the high cost of seed production and the quality of rice produced have discouraged other countries from pursuing this option of increasing grain yields.

Some of the above topics are actively being researched on. Rice-based cropping systems including the integration of livestock and fish are also being actively pursued and are likely to be an integral part of rice farming in South-East Asian countries. Research on saline and sodic soils, which form a vast area for potential expansion of rice production is receiving priority.

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B.S. Vergara & S.K. De Datta

Panicum miliaceum L. cv. group Proso Millet

Sp. pl.: 58 (1753); cv. group Proso Millet: name is proposed here.

GRAMINEAE

$2n = 36$

Synonyms *Panicum miliaceum* L. subsp. *miliaceum* sensu Tsvelev (1968).

Vernacular names Proso millet, common millet, Russian millet (En). Brown-corn millet (Am). Grand millet, millet commun (Fr). Indonesia: sekoi sejati (Javanese). Philippines: kabug (Bisaya). Vietnam: k[ee], c[or] k[ee].

Origin and geographic distribution Proso millet is of ancient cultivation (5000 years in China, 3000 years in Europe); it is mentioned in the Bible and was the 'milium' (millet) of the Romans. It was domesticated in central China and spread as a cereal and as a weed to many, mainly temperate, regions all over the world. As a cereal it is most important in northern China, Mongolia, Korea, Russia, Afghanistan, Pakistan, India and southern Europe. In the Bronze Age it spread widely in Europe, including to northern regions where the cold-susceptible foxtail millet (*Setaria italica* (L.) P. Beauvois) could not be grown. In Europe and the United States its popularity as a cereal declined after the large-scale introduction of potato and maize, and it is now mainly cultivated as a feed for cage birds. In Africa it is cultivated in Malawi, Zimbabwe and Ethiopia. In South-East Asia it is occasionally cultivated in the drier areas.

Uses The husked grain of proso millet has a slightly nutty flavour and can be eaten whole after roasting or after cooking or boiling like rice. Millet flour is used for making mush, porridge, flat bread or chupatty. If mixed with wheat flour it may be used to make leavened bread, but some cultivars have glutinous endosperm. The flour is also used for making wine or beer. The grain is a feed for animals, fowls and cage birds. The green plant is used as a forage, but the quality of the straw is poor. Brooms are made from the straw. Starch from the grains is used for sizing textiles.

Production and international trade Proso millet is usually used locally and, since it is quick-maturing, may fill periods of scarcity before the main crops of other cereals are harvested. The crop is of some importance locally, but statistics are scarce and data on proso millet are usually lumped with data on other millets. Estimated annual world production of proso millet is 5 million t (Russia 2–3 million t, China 1.5 million t, India 0.5 million t) from about 5.5 million ha. However, when irrigation facilities are available, the area under proso millet declines in favour of other crops such as rice, wheat or sesame.

Properties The whole grain of proso millet contains per 100 g edible portion approximately: water 10 g, protein 11 g, fat 4 g, carbohydrates 61 g, fibre 8 g and ash 4 g. The energy value is about 1580 kJ/100 g. The approximate composition of flour per 100 g edible portion (dry matter basis) is: protein 12.3 g, fat 1.7 g, carbohydrates 83.7 g, fibre 0.9 g and ash 1.4 g. The energy value is about 1720 kJ/100 g. Proso grain is rich in minerals such as phosphorus, calcium and iron, with traces of manganese, copper and zinc. It contains some of the B vitamins and is rich in choline, but as in most cereals, the limiting amino acid is lysine. The 1000-grain weight is 5.5 g for husked grain, 7.1 g for unhusked grain.

Description An erect annual grass, up to 1 m tall, usually free-tillering and tufted, with a rather shallow root system. Stem cylindrical, internodes hollow, glabrous to variously hairy. Leaf blade linear-lanceolate, 15–30 cm × 0.6–2 cm, variously hairy as is the cylindrical sheath; ligule membranous, about 1 mm tall, with cilia about 2 mm long. Inflorescence a slender panicle up to 45 cm long, open or compact, erect or drooping;

Panicum miliaceum L. cv. group Proso Millet. cv. subgroup Contractum: – 1, habit flowering stem; 2, detail inflorescence branch; 3, grains; cv. subgroup Miliaceum: – 4, habit flowering stem; 5, detail inflorescence branch.

pedicels of all spikelets without joints; spikelet ovoid-elliptical, 4–5 mm long, 2-flowered, glabrous; glumes unequal, upper glume as long as spikelet; lower floret sterile; upper floret hermaphrodite with coriaceous broad (1.7–2.2 mm) lemma and palea, 2 lodicules, 3 stamens and 2 styles with plumose stigmas. Caryopsis broadly ovoid, up to 3 mm × 2 mm, smooth, variously coloured but often white, enclosed by the persistent lemma and palea but shedding easily.

Growth and development Proso millet has a short growing cycle and is adapted to areas of low rainfall. On average, after sowing it needs 1–2 months to reach the 50% flowering stage and it matures in 2–4 months after sowing. Proso millet is partly self- and partly cross-pollinated.

Other botanical information *P. miliaceum* is a complex species with wild and cultivated taxa. In the literature those two groups have been classified as subspecies (for the wild taxa: subsp. *ruderale* (Kitag.) Tsvelev (synonyms: var. *ruderale*

Kitag., *P. spontaneum* Lyssov ex Zhukovsky); for the cultivated taxa: subsp. *miliaceum*), but here it is proposed to classify the cultivated forms into cultivar group Proso Millet. The wild taxa have broadly lax panicles, usually jointed pedicels and narrow lemmas, while the culta have either lax or compressed panicles, unjointed pedicels and wider lemmas.

The true wild form of subsp. *ruderale* is native to central China and is considered to be the ancestor of the cultivated forms. In temperate Europe, temperate Asia and in the United States, however, wild forms occur that differ from the wild form in China and are most probably derivatives of cultivated forms which have regained the ability of natural seed dispersal and spread as weeds.

Cv. group Proso Millet comprises many cultivars and landraces, and 5 cv. subgroups can be distinguished:

- cv. subgroup Compactum (synonyms: convar. *compactum* Koernicke, race Compactum): Inflorescence small to large, more or less elliptical in outline, drooping at maturity, with spikelets crowded along the panicle branches. Grown in Japan, the former Soviet Union, Iran and Iraq. Together with subgroup Ovatum it comprises the highest evolved Proso Millet cultivars.
- cv. subgroup Contractum (synonyms: convar. *contractum* Alefeld, race Contractum): Inflorescence large, semi-compact, drooping at maturity, with spikelets crowded along the length of the panicle branches. Grown in Europe, Transcaucasian Russia, and China. The cultivars grade morphologically into the subgroups Compactum and Patentissimum.
- cv. subgroup Miliaceum (synonyms: convar. *effusum* Alefeld, race Miliaceum): Plants with numerous decumbent culms, each producing several racemes. Inflorescence large with spreading branches bearing relatively widely spaced spikelets and lacking spikelets at the base. This subgroup closely resembles the wild subsp. *ruderale*, and the other subgroups were derived from this subgroup under cultivation. It is grown across the whole range of proso millet cultivation and comprises the most primitive cultivars.
- cv. subgroup Ovatum (synonym: race Ovatum): Difficult to distinguish from subgroup Compactum (its inflorescences are usually smaller) with which it comprises the most advanced cultivars. Its cultivars are grown in the former Soviet Union, Turkey and Afghanistan.
- cv. subgroup Patentissimum (synonym: race Patentissimum): Resembles subgroup Miliaceum in its lax inflorescences with spreading branches having a sterile zone at the base and becoming curved at maturity. It is grown in India, Bangladesh, Pakistan, Afghanistan, Turkey, Hungary, the former Soviet Union and China. Just like subgroup Miliaceum, it comprises primitive cultivars.

Within the subgroups, the cultivars are mainly distinghuised on the basis of grain colour (varying largely from white, yellow, brown, red, to almost black) and on ecological adaptation.

Ecology Proso millet is mostly grown in temperate and subtropical regions. Although it has a C4-cycle photosynthetic pathway, it is cultivated further north than any other millet, the limit being the June isotherm of 17°C and the July isotherm of 20°C. It is adapted to conditions which are too hot and too dry, and to soils too shallow and poor for successful cultivation of other cereals. It is tolerant of a very wide temperature range but susceptible to frost. Cultivation occurs up to 3000 m altitude in the Himalayas. Proso millet has one of the lowest water requirements of all cereals. An average annual rainfall of 200–450 mm is sufficient, of which 35–40% should fall during the growing period. Most soils are suitable for its cultivation, except coarse sand.

Propagation and planting Proso millet is commonly propagated by seed, either broadcast or drilled in rows 20–25 cm apart and at a distance of 7.5 cm in the row. This corresponds with a seed rate of 10–12 kg/ha. For optimal germination seed should be soaked in water for 24 hours and planted no deeper than 4 cm. In the Bombay area in India, the crop is grown from transplanted seedlings. In Russia grains are often dressed with fungicides to combat soilborne diseases.

Husbandry In Russia, weeds are eradicated mechanically with a cultivator. When necessary, herbicides are applied at the 3–5-leaf-stage. Per t proso grain, the crop extracts about 30 kg N, 8 kg P and 34 kg K from the soil. Usually, per ha 30–60 kg N, 15–25 kg P, and 25–35 kg K is applied in autumn, with an additional 10 kg N during the growing season. In Russia, proso millet is usually grown in rotation with a forage grass, winter wheat, spring wheat or barley. In Bangladesh, the rotation may comprise a pulse, wheat, jute, rice, potato or a *Brassica* crop.

Diseases and pests Proso millet is relatively little affected by diseases and pests and none of them is serious. Smuts (*Sphacelotheca destruens* and *Ustilago* spp.), ergot (*Claviceps* spp.), rusts

(*Puccinia* and *Uromyces* spp.), downy mildew (*Sclerospora graminicola*), leaf blight (*Helminthosporium* sp.) and foot rot (*Sclerotium rolfsii*) may cause some damage. The bacterium *Xanthomonas holcicola* can cause melanopathy, a darkening of the endosperm.
Insect pests like stem borers (*Chilo partellus*, *C. suppressalis* and *Sesamia inferens*), midges, bugs, army worms and shoot flies (*Atherigona miliaceae*) are sometimes troublesome. Rats and birds may destroy a considerable part of the harvest.

Harvesting Harvest takes place 2–4 months after sowing, when the grain has a moisture content of 14–15%. Delayed harvesting should be avoided, as the seed shatters easily. If proso millet is harvested during the rainy season with high relative humidity, the grain must be dried to 14% moisture content. Households usually do this above the domestic fire.

Yield Under rainfed conditions, average yield of proso millet is 400–600 kg/ha. With sufficient rain or under irrigation and with application of fertilizers, a yield of 1–2 t/ha can be reached. The milling recovery is 70–80%.

Handling after harvest Proso millet is threshed immediately after harvest. The grain stores well for up to five years. In India, storage is in granaries with clay walls, or in clay jars; sometimes the grain is mixed with ash or slightly baked before storage. Because of its small size, the grain is barely susceptible to insect attack.

Genetic resources China, India and Russia hold the largest proso millet germplasm collections. In China there are 5500 accessions in the National Gene Bank (Institute of Germplasm Resources, CAAS, Beijing), 4200 of which have been described (53% are non-glutinous and the remaining 47% are glutinous). The International Crops Research Institute for the Semi-Arid Tropics (ICRISAT), India, has a collection of 1200 accessions (from 26 countries) and the All India Coordinated Minor Millets Improvement Programme possesses 1100 samples. Smaller collections are available in the Czech Republic, Germany, Hungary, Japan and the United States.

Breeding Since ancient times man has selected proso millet on drought tolerance and short growing cycle. Russian cultivars are said to be much earlier than those from China or India. Breeding programmes in Russia and India aim at a high productivity (drought resistance and early or late maturity), disease resistance (especially to smut) and grain quality (uniform size and shape, yellow endosperm with high carotenoid content). High-yielding cultivars in Russia generally mature 14 days later than standard cultivars. Several improved cultivars, including some hybrids, have been released recently in Russia ('Sartovskoye 8') and China ('Jinsu No 1' and 'Jinsu No 2').

Prospects The production of proso millet is declining and the crop is being replaced in the human diet by other cereals, especially rice, wheat and maize. However, it will continue to be an important staple in some areas of the semi-arid tropics where hardly any other cereal can be grown. Its use as a food might be important in rural areas, as consumption in urban centres appears to be constrained by a lack of regular supply and by changing food habits.
Proso millet could gain in importance by being incorporated in crop rotations in more humid regions, e.g. in South-East Asia. Because of its low water requirement and short duration, it can be cultivated during the dry season and grow mainly on residual soil moisture.

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H.N. van der Hoek & P.C.M. Jansen

Pennisetum glaucum (L.) R. Br.

Prodr. Fl. Nov. Holl. 1: 95 (1810).

GRAMINEAE

$2n = 14$

Synonyms *Pennisetum americanum* (L.) Leeke (1907), *P. typhoides* (Burm.f.) Stapf & Hubbard (1933).

Vernacular names Pearl millet, bulrush millet, cattail millet (En). Mil à chandelle, mil pénicillaire (Fr). Bajra (Hindi). Vietnam: c[or] du[oo]i voi, k[ee] voi, l[us]a mi[ee]u.

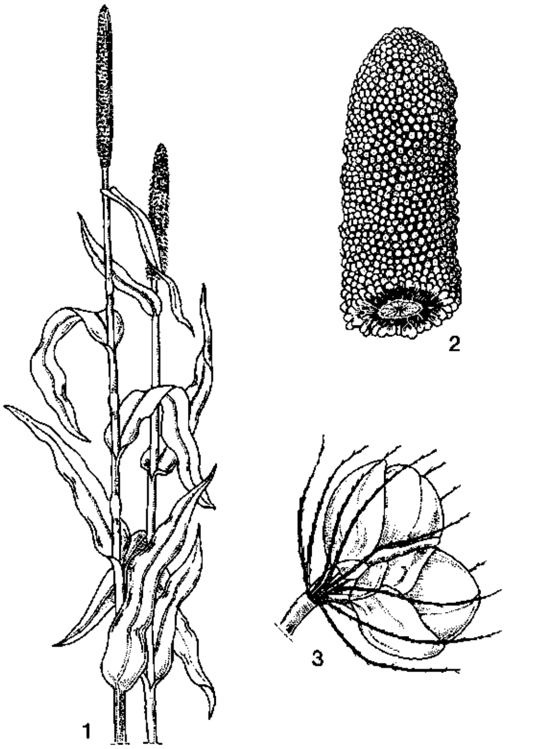
Origin and geographic distribution After Africa's most recent humid era from 5000–3000 BC, pearl millet originated in the period 3000–2000 BC in the African Sahel zone by domestication from its wild ancestor *P. violaceum* (Lamk) Richard. From there it spread to East Africa, India, Spain and the United States. It is commonly grown as a grain crop in the semi-arid regions of West Africa and the driest parts of East Africa and the Indian subcontinent. In Australia, South Africa and the United States, it is grown as a fodder crop.

Uses Pearl millet is the staple food for about 90 million people in parts of tropical Africa and India, which are too hot, dry and sandy for sorghum production. Decorticated and pounded into flour it is mostly consumed as a stiff porridge (tô) or gruel in Africa, or as flat unleavened bread (chupatty) in India. There are various other preparations such as couscous, rice-like products, snacks of blends with pulses, and fermented and non-fermented beverages in Africa. In several Indian preparations parched seeds are used. The stalks are used for thatching and building, as fuel and as a poor quality fodder. Outside India and Africa it is mostly grown as a green fodder crop.

Production and international trade Production statistics on millet often combine data on all millet species. Estimates based on total millet production and relative importance of pearl millet indicate an annual production of 13 million t from a planted area of 25 million ha. The largest acreages occur in India and the dry regions of Africa. Production figures over the past 25 years show considerable fluctuations; in Africa, area and yield have remained constant; in India, the cultivated area has declined steadily, but yields have increased proportionately. Negligible quantities are traded internationally.

Properties Average composition of the seed per 100 g edible portion is: water 12 g, protein 10–12 g, fat 3–5 g, carbohydrates 60–70 g, fibre 1.5–3 g, ash 1.5–2 g. The energy value is about 1525 kJ/100 g. The protein is rich in tryptophane and cystine, poor in lysine and methionine. Its nutritional value is somewhat superior to maize, rice, sorghum and wheat. 1000-seed weight is 3.5–16 g.

Description A robust, strongly tillering, annual grass, usually 1–4 m tall, with basal and nodal tillering. Root system extremely profuse; sometimes the nodes near ground level produce thick, strong prop roots. Stem slender, 1–3 cm in diameter, solid, often densely villous below the panicle,



Pennisetum glaucum (L.) R. Br. – 1, habit flowering and fruiting stem; 2, part of infructescence; 3, pair of spikelets surrounded by involucre of bristles.

nodes prominent. Leaf sheath open and often hairy; ligule short, membranous, with a fringe of hairs; leaf blade linear to linear-lanceolate, up to 1.5 m × 5–8 cm, margins with small teeth, scaberulous and often pubescent. Inflorescence a cylindrical or ellipsoidal, contracted, stiff and compact panicle, suggesting a spike, 15–200 cm long; rachis cylindrical, bearing densely packed clusters of spikelets; spikelets usually borne in pairs, sometimes 1–4 or more per cluster, subtended by a tuft (involucre) of 25–90 bristles, that are about as long as the spikelets, but in some cultivars a terminal bristle is elongated; spikelet 3–7 mm long, consisting of 2 glumes and usually 2 florets, the lower one staminate or sterile, the upper one bisexual; lemma and palea not clasping the grain; lodicules absent; ovary obovoid, smooth, with 2 styles, connate at the base; stamens 3; anthers 2–5 mm long, tipped with brush-like bristles. Caryopsis globose to subcylindrical or conical, 2.5–6.5 mm long, colour variable, from white, pearl-coloured or yellow to grey-blueish and brown, occasionally purple; hilum marked by a distinct black dot at maturity.

Growth and development Cultivars vary in time to maturity from 55–280 days, but mostly from 75–180 days. Time to flower initiation is the main factor determining the life cycle of a cultivar. Photo-sensitive cultivars require shorthening days of less than 12 hours. In short-duration cultivars the developmental stages (from germination to flower initiation, to flowering and to maturity) are of approximately equal duration.

Field establishment of pearl millet is affected by its relatively small seed size, especially in crusting soils. During early development the roots grow more than the above-ground parts. Pearl millet produces an extensive and dense root system, which may reach a depth of 1.2–1.6 m, sometimes even of 3.5 m. Basal tillering occurs between 2–6 weeks after sowing, and up to 40 tillers may be produced. Tillering from the upper nodes of the stems is common and occurs in response to drought, or damage to the main stem. These secondary tillers produce 2–3 leaves and an inflorescence within 10–20 days; they may contribute 15% and occasionally up to 50% of grain yield. Its asynchronous tillering habit compensates for the effects of drought before anthesis by an increased yield from tillers.

It takes 15–20 days from inflorescence differentiation to flowering. Pearl millet is protogynous and normally cross-fertilized, but about 10% or more selfing may occur, depending on overlap in flowering of tillers. Heavy rainfall, low temperature and moisture stress reduce seedset. The length of the grain-filling period varies greatly with genotype and is temperature dependent, but normally takes 22–25 days. The harvest index is very low (0.15–0.20), attaining 0.35 in improved cultivars.

Other botanical information *P. glaucum* belongs to a complex of 3 taxa which hybridize freely and which are sometimes considered as belonging to one species. However, as long as the complicated taxonomy of pearl millet has not been fully cleared up, it is preferable to keep those taxa separate:

- *P. glaucum* (synonym: *P. americanum* (L.) Leeke subsp. *americanum*). The crop plant, with persistent, stipitate involucral bristles usually subtending 2 spikelets.
- *P. sieberanum* (Schlecht.) Stapf & Hubbard (synonyms: *P. stenostachyum* (A. Br. & Bouché) Stapf & Hubbard, *P. dalzielii* Stapf & Hubbard, *P. americanum* (L.) Leeke subsp. *stenostachyum* (A. Br. & Bouché) Brunken). These plants (also collectively called 'shibras') are weeds in pearl millet fields in West Africa and northern Namibia (not in Asia). They commonly mimic the companion pearl millet in inflorescence size and shape, vegetative morphology and time of flowering. They differ from pearl millet in having deciduous, stipitate involucral bristles. They are obligate weeds of cultivation and do not persist more than one generation in abandoned fields. They are derived from introgression between wild *P. violaceum* and cultivated *P. glaucum*.
- *P. violaceum* (Lamk) Richard (synonyms: *P. fallax* (Fig. & De Not.) Stapf & Hubbard, *P. americanum* (L.) Leeke subsp. *monodii* (Maire) Brunken). This is a polymorphic weed of disturbed places, commonly occurring around villages from Senegal to the Sudan, and is harvested as a wild cereal in times of scarcity. It differs from *P. glaucum* in having deciduous, sessile involucral bristles which always contain a single spikelet. Some authors restrict *P. violaceum* to only the true wild pearl millet, limited in its distribution to very dry areas in the northern Sahel and consider the weedy forms of disturbed places as belonging to *P. sieberanum*, together with the shibras.

Mainly based on differences in grain shape, four cultivar groups have been distinguished in *P. glaucum*:

- cv. group Globosum (synonym: race Globosum). Caryopsis globose, more than 2.4 mm in diameter. The inflorescence is cylindrical, often longer than 1 m. It is most common in the Sahel west of Nigeria.

- cv. group Leonis (synonym: race Leonis). Caryopsis oblanceolate in outline, 3.8–6.3 mm × 1.9–2.5 mm × 1.9–2.5 mm, apex acute. The inflorescence is cylindrical. At maturity about one-third of the grain protrudes beyond the floral bracts. This is the smallest cv. group and is grown in Sierra Leone, Senegal and Mauritania.
- cv. group Nigritarum (synonym: race Nigritarum). Caryopsis obovoid but extremely angular in cross-section, 3–5 mm × 1.7–2.5 mm × 1.5–2.2 mm. The inflorescence is cylindrical. The mature grain generally protrudes beyond the floral bracts. It is most common in semi-arid regions from Nigeria to Sudan.
- cv. group Typhoides (synonym: race Typhoides). Caryopsis obovoid but terete in cross-section, 2.5–5.5 mm × 1.5–3 mm × 1.2–2.4 mm. The inflorescence is cylindrical or ellipsoidal, usually less than 0.5 m long. Occasionally the grains remain enclosed by the floral bracts. It is the most primitive, the most variable and most widely distributed cv. group, occurring all over the pearl millet range in Africa and also in India. Probably the other cv. groups were derived from this group.

Based on growth duration, agronomically two main groups of cultivars are recognized in West Africa: short duration Gero or Souna cultivars and long duration Maiwa or Sanio cultivars. Gero cultivars are less photo-sensitive and, being early maturing, are adapted to regions with a short rainy season. They are more widely grown than Maiwa cultivars. Flowering in Maiwa cultivars is strongly controlled by daylength and they are grown in regions where the rainy season is longer and where sorghum is the major cereal, but on poorer, more drought-prone soils than sorghum. Certain Maiwa millets are transplanted from seed-bed into the field and are known as Dauro millet.

In India, both improved cultivars and single-cross hybrids are grown on about 40% of the area sown to pearl millet. Most are early (80 days) to very early (65 days) maturing and less photo-sensitive than African cultivars.

Pearl millet is not closely related to other millet species, although foxtail millet (*Setaria italica* (L.) P. Beauvois) was once classified as a *Pennisetum*.

Ecology Pearl millet is characterized by the C4-cycle photosynthetic pathway and has a very high rate of biomass production, despite being a crop adapted to the drier parts of the semi-arid tropics. Its northern limit in West Africa is the zone with about 250 mm annual rainfall, where cultivars requiring only 55–65 days to mature are grown. In the 250–400 mm rainfall zone, where very high temperatures are common especially at planting time, it is the dominant cereal. Further south it is found with sorghum. Optimum temperature for germination is 33–35°C; no germination occurs below 12°C. Optimum temperature for tiller production and development is 21–24°C, and for spikelet initiation and development about 25°C. Extreme high temperatures before anthesis reduce panicle size and spikelet density, thus reducing yield. Pearl millet is tolerant of various soil conditions, especially of light and acid soils. Its large and dense root system allows it to grow on soils with a low nutrient status. On light soils it is less affected by nematodes than sorghum. Soil crusting is a major cause of poor seedling establishment. It does not tolerate waterlogging. Once established, the crop is tolerant of salinity.

Propagation and planting Propagation is by seed, usually sown directly in the field. Transplanting is carried out on a very limited scale in India and West Africa (Dauro millet).

In Africa, short-duration cultivars are sown as early as possible after the onset of the rains and land preparation is limited to a light hoeing. Land preparation for long-duration cultivars, which are sown later, is done more thoroughly. Pearl millet is mostly sown in pockets on hills or ridges; in drier areas and on light soils it is also sown in furrows. Plant density depends on rainfall and amounts to 20 000–50 000 plants/ha in pure stands.

In India the usual method of land preparation is to make 2–3 passes with a traditional plough. The seed is broadcast with the first rains and is then covered with a brush harrow. Occasionally, traditional seed drills are used. Row spacing varies between 45–60 cm. Seed rates vary with desired stand and soil type from 3–11 kg/ha.

In Africa pearl millet is often intercropped with sorghum (*Sorghum bicolor* (L.) Moench), cowpea (*Vigna unguiculata* (L.) Walp.) or groundnut (*Arachis hypogaea* L.), its place and importance in the system being dependent on rainfall. In India pearl millet is often intercropped with a great variety of pulses, e.g. hyacinth bean (*Lablab purpureus* (L.) Sweet), mung bean (*Vigna radiata* (L.) Wilczek), horse gram (*Macrotyloma uniflorum* (Lamk) Verdc.), and less commonly with castor (*Ricinus communis* L.) or cotton (*Gossypium* spp.).

Husbandry The weeding of short-duration cul-

tivars in Africa coincides with land preparation and planting of later crops and therefore shortage of labour often leads to weeding being neglected.
In India pearl millet is weeded using a bullock-drawn peg-tooth harrow, followed by hand weeding. Usually, 1–2 harrowings and 1–2 hand weedings are needed. Broadcast crops can only be hand weeded. Pearl millet is grown in rotation with sorghum, cotton, groundnut, other millets and occasionally rice. In northern India, if the rainfall pattern allows, it is often double-cropped with wheat and sometimes finger millet.
Under traditional, rainfed conditions the application of manure and chemical fertilizers is limited. Vigorous early growth, promoted by nitrogen, may consume water required for later crop development and grain growth. Response to phosphorus is not uncommon, but the requirement under rainfed conditions does not appear to be high. The requirement for potassium is relatively high. A new cultivar yielding about 3.1 t/ha in the West African savanna is reported to have removed N 132 kg, P 28 kg, K 65 kg and Ca 31 kg per ha.

Diseases and pests Green ear caused by downy mildew (*Sclerospora graminicola*), smut (*Tolyposporium penicillariae*), rust (*Puccinia penniseti*) and ergot (*Claviceps microcephala*) are important diseases in both Asia and Africa. Sources of resistance against all four have been identified and are being incorporated into new cultivars (except for resistance to ergot which is polygenic and recessive).
Birds are the major pest in pearl millet: *Quelea* spp. in Africa and sparrows, parakeets, crows and migrating rosy pastors in India. Bird scaring for several weeks before the harvest is essential. Farmers in West Africa often do not expect to harvest a larger area than they can protect from birds. Cultivars with long, hard bristles are attacked less severely than awnless ones.
Insect pests are of more importance in West Africa than in India. Stem borer (*Coniesta ignefusalis*) and earworm (*Heliocheilus albipunctella*) are locally important. Other pests are millet midge (*Geromiya penniseti*), white grubs, grasshoppers, locusts, and various Lepidoptera.
Pearl millet is attacked by *Striga hermontica* (Del.) Benth. in West Africa, sometimes seriously, and by white-flowered *S. asiatica* (L.) Kuntze in parts of northern India. In southern Africa, red-flowered *S. asiatica* that parasitizes sorghum does not affect pearl millet, not even cultivars that are attacked in West Africa. Apparently, *S. asiatica* has not yet evolved a pearl millet biotype in southern Africa.

Harvesting Pearl millet is harvested by hand, either by picking the panicles or by harvesting whole plants. In strongly tillering cultivars, where spikes (heads) ripen unevenly, several pickings are required.

Yield Yields vary considerably with amount and distribution of rainfall and range from 250 kg/ha in the driest areas, to 500–1500 kg/ha in the main production areas. Average yields in West Africa and India are about 600 kg/ha. Under optimal growth conditions maximum yields from improved cultivars are 3–3.5 t/ha. Hybrids can reach 5 t/ha in 85 days and yields of 8 t/ha have been reported.

Handling after harvest The harvested crop is dried in the sun for a few days. In Africa it is commonly stored on the panicle in elevated granaries, built of mud or plant materials and covered with thatch. Sometimes it is stored in pits. Threshing is normally done manually when grain is needed. In India the grain is threshed soon after harvesting and drying. Threshing is carried out by beating with sticks or trampling with cattle. Threshing recovery is about 55%. The grain may then be stored in containers which are kept in granaries or store rooms, or sometimes in pits in the ground. Seed may be covered with sand or mixed with leaves of the neem tree (*Azadirachta indica* Juss.) to reduce insect attack. Pearl millet grain can be stored more easily and longer than maize or sorghum. Grain kept for seed can be stored adequately at room temperature for several years.

Genetic resources Landraces of pearl millet have been selected by farmers for yield, adaptability to unfertilized soil, resistance to drought and diseases, and for grain type. Frequent cross pollination with wild relatives in West Africa further contributes to the crop's genetic diversity. Genetic variation is conserved and evaluated at the Coastal Plains Experiment Station, Tifton (Georgia, United States) and the International Crops Research Institute for the Semi-Arid Tropics (ICRISAT) in Hyderabad (India), where the world collection of 21 000 entries is housed. The International Plant Genetic Resources Institute (IPGRI) supports a programme, started in Burkina Faso, to improve the description and evaluation of material at the time and location of collection.
One particular germplasm source, the Iniadi cultivar from northern Togo and Ghana has had a profound effect on pearl millet breeding. Selections from it have been successful as cultivars in northern India, Namibia and Botswana, and it has been extensively used in breeding programmes.

Breeding Although genetic manipulation is facilitated by its profuse tillering, protogynous flowering habit and high fertility, breeding of pearl millet only started in the 1950s and traditional cultivars are still commonly used. Breeding work by the Indian Council of Agricultural Research and ICRISAT has been most successful in developing cultivars rapidly adopted by farmers. The discovery of cytoplasmic male sterility in 1958 in the forage breeding programme at Tifton (Georgia, United States), led to the production of grain hybrids in India, which covered 3 million ha by 1970. Despite disease epidemics, now overcome, some 40% of the Indian millet crop on peasant farms now consists of hybrids and improved cultivars, and yields have increased by 30% since 1965. Early breeding work in West Africa by the 'Institut de Recherches Agronomiques Tropicales et de Cultures Vivrières' and the East African Agriculture and Forestry Organization, produced improved cultivars, but adoption has been negligible. The International Crops Research Institute for the Semi-Arid Tropics (ICRISAT), working in Niger and Zimbabwe since the early 1980s, have produced improved cultivars which, prompted by increasing food shortages, are being grown in 8 countries in West Africa and 5 countries in southern Africa. Work at ICRISAT is focused on the identification of stable stress tolerance, wide adaptability and high yield potential. Sources of tolerance of the major diseases have been identified and are being incorporated into new cultivars. Breeding work on fodder millets is done mainly in the United States, Australia and South Africa and has produced pearl millet hybrids and interspecific hybrids between pearl millet and elephant grass (*Pennisetum purpureum* Schumach.). The latter hybrid is a sterile perennial, usually propagated by cuttings. It is well adapted to use by small farmers in Asia, East Africa and parts of South America. Pearl millet has been bred as a new feed grain crop in the United States and commercial production for poultry feed has commenced in Georgia.

Prospects Compared to other major cereals, little research effort has been invested in pearl millet. However, genetic yield gains have been good, 1–2% per year as measured in India over the last 30 years. It has one of the highest rates of dry matter gain among the C4-cycle cereals. Only a small proportion of the available genetic variability has been used from the primary pearl millet gene pool. Thus the potential for further improvement is high, both as a staple cereal for low to medium productivity agriculture in drought-stress and nutrient-deficient conditions in developing countries, and as a high yield nutritious food or feed grain crop in tropical or warm temperate intensive agriculture.

Some testing has been carried out in all South-East Asian countries with variable results, but its potential under limited rainfall and poor light soils merits further study.

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L.P.A. Oyen & D.J. Andrews

Secale cereale L.

Sp. pl.: 84 (1753).

GRAMINEAE

$2n = 14$

Vernacular names Rye (En). Seigle (Fr). Indonesia: gandum hitam.

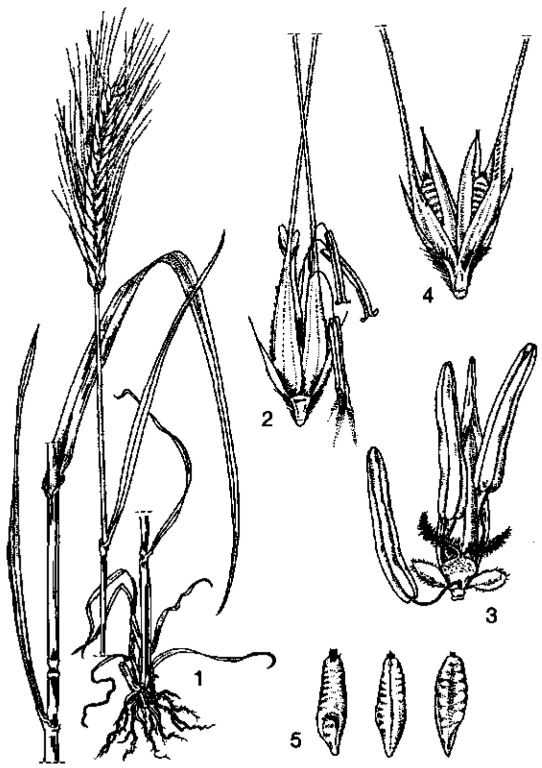
Origin and geographic distribution Rye is known only from cultivation. The gene centre of rye is located in the mountainous areas of Afghanistan, Iran and the Middle East, from which other small-grain crops like wheat, barley and oats also originated. From there, rye was spread to the surrounding areas in Asia (Iraq, Turkey), northern Africa and later, just like wheat, to Russia, Central and West Europe, where it is cultivated under temperate climatic conditions. Due to its hardiness to drought and frost, rye was spread well beyond 60°N. It has been spread to all continents, especially to areas with temperate growing conditions. Occasionally it is cultivated at high elevations in the tropics and subtropics, e.g. in East and South Africa.

Uses Rye kernels are used as a foodstuff for humans, but are more important as animal feed. Rye is processed for making bread and cakes. Whole or broken kernels are used for bread-making; for cake-making, the kernels need to be milled. Rye flour is often mixed with wheat flour. Several alcoholic beverages are prepared by distilling malted rye grain. Rye is used as a component in fodder, especially in pig husbandry. The straw is harvested for feed (cattle), litter (in livestock sheds), mulching material, industrial use (paper/cardboard) and even for fuel.
On a small scale, immature rye is harvested as a whole crop for animal feed or it is grown as a green manure crop.

Production and international trade In 1993, more than 13 million ha of rye was grown worldwide, with a total production of about 26 million t. Cultivation of rye is mainly concentrated in the Russian Federation (6 million ha/9 million t) and Europe (3.7 million ha/10 million t), of which 50% in Poland. In Asia, 0.65 million ha are cultivated, with a production of 0.9 million t. No data are available on area and production in South-East Asia.
Rye enters world trade on a small scale; it is commonly grown for domestic consumption and to feed livestock on the farm.

Properties The chemical composition of 100 g edible portion is approximately: water 14 g, protein 11 g, fat 2 g, carbohydrates 69 g, fibre 2 g and ash 2 g. The protein content varies from 8–12%. The protein fraction contains relatively high contents of lysine and threonine. Due to the lack of gluten, bread made from rye has a compact structure. 1000-kernel weight ranges from 30–40 g.

Description Annual (spring rye) or biennial (winter rye) tufted herb, 1–1.5(–3) m tall, often blueish-green in colour. Root system extensive, penetrating to 1–2 m depth. Culm erect, slender, glabrous except pubescent near the spike, with 6–7 (spring rye) and 10–12 (winter rye) nodes of which the 5–6 basal ones are very close, with hollow internodes; one leaf is produced at each node, the basic nodes also producing shoots or tillers and crown roots. Leaf sheath long and loose; ligule short, jagged; auricles short and small; blade linear-lanceolate, 10–20 cm × 1–2 cm, smooth or slightly scabrous. Inflorescence a terminal spike, 7–15 cm long, curved, much awned, narrow but close-flowered; spikelet with 2 fertile florets, alternating on a long zigzag rachis; glumes subulate, 1-veined, up to 1 cm long; lemma up to 18 mm long, narrow, tapering into a 2–8 cm long awn, 3(–5)-veined, keel prominently set with stiff teeth; palea scabrid on the keel; stamens 3, pistil 1 with 2 plumose stigmas. Caryopsis oblongoid, 5–9 mm long, light brown, narrowly grooved, short-pointed, glabrous.



Secale cereale L. – 1, habit base of plant, stem part with leaves, spike; 2, flowering spikelet; 3, floret without lemma and palea; 4, fruiting spikelet; 5, grains.

Growth and development First, the coleoptile emerges from the soil and leaves are formed. At the appearance of the fourth leaf, tillers and crown roots are formed to anchor the plant. Initiation and formation of shoots (tillering) enables the crop to compensate for low plant densities. Shoot initiation ceases as the plant enters the reproductive stage. Then, stem elongation starts and initiation and differentiation of the inflorescence take place. In each spike 40–45 spikelets are initiated, 30–35 of which bear 1–2 kernels, resulting in 45–55 kernels per spike. Flowering lasts 3–5 days for a spike and 8–12 days for a rye crop. The post-floral period for grain-filling is 4–5 weeks. The period from sowing to harvesting varies from 7–10 months for winter rye and from 4–6 months for spring rye. The duration of growth is largely dependent on temperature during reproductive development. Winter rye is planted in autumn to receive sufficient cold and short days to induce vernalization and reproductive growth.

Other botanical information There are many landraces (usually with longer culms and smaller grains) and cultivars. Well-known cultivars include 'Petkus', 'Pearl', 'Steel' and 'King II'.

Cultivated rye is assumed to have developed from *Secale montanum* Guss., a perennial, wild, outbreeding species of mountainous regions in the Mediterranean and Central Asia.

Triticale (*Triticosecale* Wittmack) is a cereal derived from hybridization of rye and wheat. After several cycles of selection, the resulting triticale cultivars show characteristics in between wheat and rye. Breeders strive to combine the hardiness of rye with the high yield and quality of wheat. Tetraploid ($2n = 28$), hexaploid ($2n = 42$) and octoploid ($2n = 56$) forms exist, but the hexaploid forms are most successful. As a new food crop, triticale fell short of expectations, but it is becoming increasingly popular as a forage crop. Only where wheat does not grow well because of adverse conditions, triticale is a promising human food crop. It is estimated that it is grown annually on 1.5 million ha with Poland, France, Russia and Australia as the main producers.

Ecology Rye is the most tolerant among the small-grain cereals of variations in (low) temperature, water supply and soil type. It germinates at a soil temperature of 4–5°C within 4 days and the seedlings can endure frost during winter down to −25°C. Vernalization occurs naturally. Tillering, shoot growth and flower initiation require rather low temperatures (10–15°C); for adequate growth during reproductive development the mean daily temperature must not exceed 20°C. The demand for water is relatively low; rye is more tolerant of water stress than other small-grain cereals. Flowering is favoured by dry and sunny weather. Continuous rain, high humidity and low temperatures hamper pollination, causing incomplete grain set. Rye is a cross-pollinated crop, depending on wind for the spread of pollen. It is suited for growth under temperate and continental climatic conditions. Winter rye is a long-day plant; the reproductive development is stimulated by daylength increasing from 14 to 20 hours. Therefore, winter rye is mainly grown between 40–65°N. Cultivars of spring rye are occasionally grown at high elevations in subtropical and tropical areas. They are less sensitive to long daylength and do not need vernalization. Their flowering and seedset are satisfactory at a daylength of 12–13 hours.

Rye can be grown on most well-aerated soil types with a pH from 5–7.5. It is mainly grown on light, sandy and peaty soils. Fertile clay soils are usually reserved for more productive crops, such as wheat.

Propagation and planting Seed for sowing must be of good quality to ensure optimal germination and favourable crop growth. It is advisable to treat the seed with a fungicide. At the onset of the winter frosts the rye needs to have reached the tillering stage, to ensure good winter hardiness and productivity. Therefore, the optimal planting time for winter rye depends on growing conditions in autumn, but usually ranges from mid-September until mid-October in Europe. Seed can be broadcast by hand but needs to be covered to achieve adequate germination. Better conditions are created by drilling seed mechanically at a uniform depth of 2–4 cm in rows 10–25 cm apart. Depending on sowing time and soil conditions, the seed rate ranges from 100–150 kg/ha to obtain an optimal density of 200–300 plants/m². Spring rye needs to be planted as early as possible, if necessary even during winter, when soil conditions are suitable for preparing a seed-bed. Spring rye tillers poorly, so requires a higher seed rate (150–200 kg/ha).

Husbandry Rye competes strongly with weeds. In spite of small yield reductions, weeds can cause problems at harvesting. They can be controlled mechanically by harrowing or hoeing, but most effectively by herbicides during the tillering stage. Considerable damage can be caused by lodging, which is common in dense and leafy crop stands.

The amount of fertilizer required is largely related to the expected yield; about 20 kg N, 4 kg P and 13 kg K are removed from the soil per t kernel yield. Nitrogen is often the most yield-limiting nutrient. Fertilizers can be best given at the onset of crop

growth in early spring. Nitrogen is taken up slowly during vegetative growth, but quickly during stem elongation. For yields over 5 t/ha a split N-application is preferred. The demand for micronutrients is small; shortages can be remedied by liquid application, but this may not be feasible for smallholders.
Rye fits well into crop rotation systems as an anterior crop as well as a posterior crop. Even continuous cropping is often possible.

Diseases and pests Rye is considered to be a relatively tolerant cereal. Nevertheless, after germination snow mould (*Fusarium nivale*) can cause considerable plant losses and brown rust (*Puccinia recondita*) can severely damage leaves and stem. But the most conspicuous disease is ergot (*Claviceps purpurea*), which infects the kernel especially when grain set is poor. Ergot kernels are toxic and can make a rye stock unsuitable for human and animal consumption. Other diseases are e.g. eyespot (*Pseudocercosporella herpotrichoides*), sharp eyespot (*Rhizoctonia solani*), powdery mildew (*Erysiphe graminis*), stem rust (*Puccinia graminis*), glume blotch (*Septoria nodorum*) and leaf blotch (*Rynchosporium secalis*). Most fungal diseases can be controlled by fungicides, but damage by snow mould, sharp eyespot and ergot can only be restricted by using healthy and disinfected seed.
Damage by insects and viruses is of minor importance. Only the nematode *Ditylenchus dipsaci* can damage rye, but it is not common.

Harvesting Time of harvest is mid-summer in Europe when leaves are dead, stems yellowish-brown and the moisture content of the kernel is below 15%. Kernels at this moisture content can be stored for a long time. For combine harvesting, it is best to wait until the moisture content has dropped below 16%. However, to prevent loss of quality due to pre-sprouting, the crop may be harvested at a higher moisture content (18–20%), especially if wet weather conditions prevail and are delaying ripening. Then subsequent drying will be required, in sheaves in the field or mechanically during storage.
The crop can also be harvested by hand; the method of harvesting, threshing, collecting and storing is similar to that used for small-grain cereals like sorghum and millets.

Yield Kernel yields vary widely, from less than 1 t/ha (Africa, Latin America) to well over 5 t/ha (some West European countries). Growing conditions and cultivation techniques largely determine the yield; poor management hampers crop growth and severely reduces yield. In West Europe, kernel yields of 8–9 t/ha are attainable in farmers' fields.

Handling after harvest Low moisture content of the grain and low storage temperatures are desirable for long-term storage. The moisture content of the kernel should be less than 13% if rye is to be stored for six months (without ventilation) at 15°C. If the stock is regularly ventilated, a moisture content of 14–15% may be acceptable. In temperate regions, such low moisture contents are often not reached at harvesting, and kernels need to be dried by warm air. Cleaning is commonly done before or during storage.
After drying in the field, straw is usually baled and stored in barns or stacks for later use.

Genetic resources In countries with substantial areas under rye germplasm collections are maintained at research institutes and at private breeding stations, and used in national and international breeding programmes. International institutes such as the International Maize and Wheat Improvement Center (CIMMYT) in Mexico, play a major role for breeding programmes in tropical regions, as conservators and suppliers of germplasm.

Breeding There is a great variety of rye cultivars, most of which are adapted to or bred for particular geographical areas. Rye breeding programmes have given priority to winter types, and aspects as winter hardiness, straw stiffness, disease resistance and pre-sprouting resistance have received much attention. Breeding for (baking) quality has been restricted to reducing the pre-sprouting. These breeding efforts have resulted in a considerable increase in grain yield and yield stability, shorter plants, reduced lodging and enhanced grain/straw ratio. Efforts to exploit heterosis for enhancing grain yield have resulted in hybrids that have entered commercial production with high-input management in recent years. Hybrids outyield conventional cultivars by 10–20%, but they demand more inputs (seed, crop protection).

Prospects Winter rye is the most hardy and least susceptible to drought, diseases and pests of all cereals. Consequently, rye will remain an important cereal crop in continental climatic zones on light soils of moderate fertility and water-retaining capacity. Under such suboptimal growing conditions, rye has proved to be a productive and reliable cereal crop. There is considerable scope for improving yields, especially in areas with a low productivity. The application of high quality seed,

new (hybrid) cultivars and advanced management practices can increase yield levels in the short term.
Since rye is potentially an interesting cereal crop for South-East Asia (especially for highland areas well over 1500 m altitude), its prospects merit further investigation.

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A. Darwinkel

Setaria italica (L.) P. Beauvois cv. group Foxtail Millet

Ess. Agrostogr.: 51 (1812); cv. group Foxtail Millet: name is proposed here.

GRAMINEAE

$2n = 18$

Synonyms *Panicum italicum* L. (1753), *P. viride* L. [var.] *italica* L. (1759), *Setaria viridis* (L.) P. Beauvois subsp. *italica* (L.) Briquet (1910).

Vernacular names Foxtail millet, Italian millet, German millet (En). Petit mil, millet des oiseaux, miliade (Fr). Indonesia: juwawut (Javanese), jawawut (Sundanese). Malaysia: sekoi, sekui, rumput ekor kuching. Philippines: dawa (Tagalog), bukakaw (Iloko), turai (Sulu). Cambodia: kuö thpu:. Laos: khauz fa:ngz. Thailand: khao-fang (central), fanghangma (southern). Vietnam: k[ee].

Origin and geographic distribution Foxtail millet has been known as a cultivated cereal since ancient times (since 5000 BC in China and 3000 BC in Europe). It probably evolved from its wild weedy form (green foxtail millet) and its domestication could have taken place anywhere across its natural range extending from Europe to Japan, perhaps even independently several times, e.g. in Europe and in China; most probably, however, it was first domesticated in the highlands of central China and spread to India and Europe soon thereafter. At present, foxtail millet is cultivated all over the world, being most important in China, India and south-eastern Europe. In South-East Asia it is only occasionally grown, on a small scale.

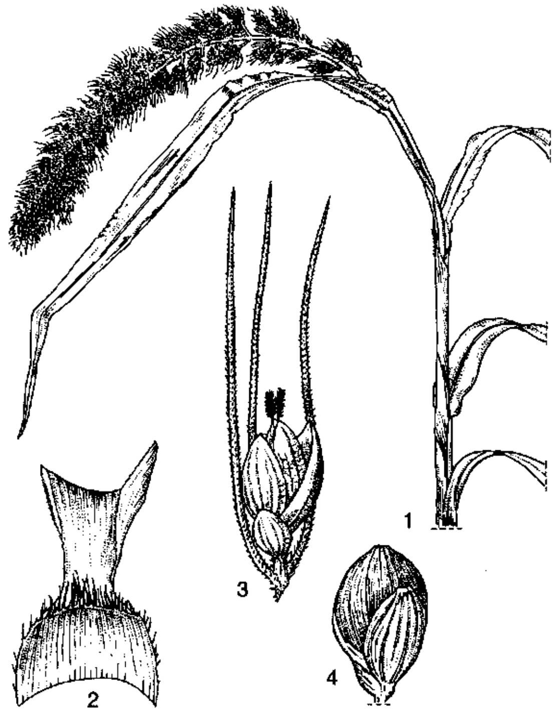
Uses The grain of foxtail millet is used for human food in Asia, south-eastern Europe and northern Africa. It may be cooked and eaten like rice, either entire or broken. It can also be ground and the flour made into unleavened bread or, when mixed with wheat flour, made into leavened bread. The flour is also used to make porridge and puddings. In northern China it is part of the staple diet and usually mixed with pulses and cooked, or the flour is mixed with flour of other cereals in the preparation of dough for bread and noodles. In India, foxtail millet grain is prized as a food and considered as a 'holy' dish in religious ceremonies. In China it is considered as a nutritious food, often recommended for the elderly and pregnant women. Since the 1990s foxtail millet has also been used in China for the industrial preparation of mini crisp chips, millet crisp rolls and flour for babyfood. Sprouted foxtail millet is used as a vegetable and, especially in Russia and

Burma (Myanmar), for the preparation of beer and alcohol, and in China also for vinegar and wine. In Europe, foxtail millet and other *Setaria* species are primarily grown as feed for domesticated fowl and cage birds. The same holds true in Indonesia. Foxtail millet is an important fodder crop and in the United States it is grown for hay and silage. Wild *S. italica* can be a troublesome weed in cereal and pulse crops, especially in temperate regions.
Medicinally, foxtail millet is thought to have diuretic, astringent and emollient properties and is also used against rheumatism.

Production and international trade Foxtail millet is mainly produced and traded locally. In China about 90% is consumed locally, 10% is traded locally and internationally. No reliable statistics are available; usually the data presented are combined for all millets. In China, the largest foxtail millet producer in the world, 4.5 million t was produced on 2.5 million ha in 1988. The market price for hulled grain in China is approximately US$ 0.20–0.30 per kg.
World production has declined substantially since the 1950s and the crop has been replaced by wheat and maize in Europe and Russia, and by rice in Asia. Foxtail millet only remains an important crop in parts of India, Afghanistan, Central Asia, Manchuria, Korea and Georgia.

Properties Per 100 g edible portion foxtail millet grain contains approximately: water 10.5–11.9 g, protein 9.7–10.8 g, fat 1.7–3.5 g, carbohydrates 72.4–76.6 g, fibre 1 g, ash 1.5 g, P 311 mg, Ca 28 mg, Fe 5 mg. The energy value averages 1400–1500 kJ/100 g. The weight of 1000 grains is 2–4 g. Green foxtail millet, used as fodder, has a dry matter content of about 87%. Its digestibility varies widely; due to oxalate accumulation in its green parts, foxtail millet can be problematic as feed for animals, which may develop a pathological condition, such as big-head in horses.

Description Annual grass, 60–120(–175) cm tall, tufted, often variously tinged with purple. Root system dense, with thin wiry adventitious roots from the lowest nodes. Culm erect, slender, tillering from lower buds, sometimes branched. Leaf-sheath cylindrical, open above, 10–15(–26) cm long, glabrous or slightly hairy; ligule short, fimbriate; blade linear-acuminate, 16–32(–50) cm × 1.5–2.5(–4) cm, midrib prominent, scaberulous. Inflorescence a spike-like panicle, 8–18(–30) cm × 1–2(–5) cm, peduncle 25–30(–50) cm long, erect or pendulous; rachis ribbed and ciliate; lateral branches much reduced, ciliate, bearing 6–12 two-



Setaria italica (L.) P. Beauvois cv. group Foxtail Millet – 1, habit flowering stem; 2, sheath mouth with ligule; 3, flowering spikelet with bristles; 4, fruiting spikelet.

flowered subsessile spikelets, each subtended by 1–3 bristles; bristles 3–14 mm long, scabrid hairy; spikelet elliptical, usually about half as long as subtending bristles, lower glume small and 3-veined, upper glume large and 5-veined; lower floret sterile; upper floret hermaphrodite with 5-veined lemma and palea, 2 lodicules, 3 stamens, 2 styles with plumose stigmas. Caryopsis broadly ovoid, up to 2 mm long, tightly enclosed by lemma and palea, pale yellow to orange, red, brown or black.

Growth and development Most foxtail millet cultivars have a growth cycle of 3–4 months but some cultivars (e.g. in Hungary) only need 2 months to mature. On average, cultivars of the subgroup Indica start flowering 57 days after sowing, those of Maxima need 41 days and those of Moharia 40 days; flowering extends over a period of 10–15 days. The flowers open late at night and early in the morning. Foxtail millet is highly autogamous, but natural hybrids between wild and cultivated taxa do occur.

Other botanical information *S. italica* is a 'crop–weed' complex, i.e. with wild taxa (green foxtail) and cultivated culta (foxtail millet). These groups show no crossing barriers. In the literature the two groups have often been described as different species or subspecies (e.g. for the wild green foxtail: *S. viridis* (L.) P. Beauvois, *S. italica* (L.) P. Beauvois subsp. *viridis* (L.) Thell.; for the cultivated foxtail millet: *S. italica* (L.) P. Beauvois, *S. italica* (L.) P. Beauvois subsp. *italica*). Here it is proposed to classify the cultivated representatives into the cultivar group Foxtail Millet.

Foxtail millet is very variable and numerous cultivars exist, differing in time to maturity, height, size, habit and structure of inflorescence, number, colour and length of bristles, and colour of grain. Primitive cultivars have numerous, strongly branched culms (like green foxtail), while advanced cultivars produce a single culm with a large, solitary inflorescence.

Three cultivar subgroups can be distinguished within the cultivar group Foxtail Millet (comprising all cultivated culta): subgroup Indica (occurring in India, Sri Lanka, Pakistan and Nepal), subgroup Maxima (occurring in the Far East) and subgroup Moharia (occurring in Europe, Russia, Near East and Afghanistan). Their main differences are (average values for the 3 subgroups Indica, Maxima, and Moharia respectively): plant height: 122, 85 and 59 cm; number of tillers: 7, 3 and 12; leaf size: 32 cm × 2 cm, 26 cm × 3 cm and 18 cm × 1.5 cm; sheath length: 15, 14 and 9.5 cm; peduncle length: 31, 30 and 27 cm; inflorescence length × width: 18 cm × 2 cm, 15 cm × 2 cm and 8 cm × 1 cm; inflorescence habit: loose and erect or nodding, lobed and pendulous, and compact and erect. Group Maxima includes the most advanced cultivars, group Moharia the most primitive.

Green foxtail occurs worldwide as an extensively variable, annual weed, especially in temperate regions. It is typically a small erect or decumbent plant up to 1.5 m tall with several strongly branched culms; its panicles are spikelike and densely flowered, usually less than 10 cm long, branches up to 1.5 cm long bearing clusters of spikelets; spikelet elliptical, 2–2.5 mm long, subtended by 1–3 persisting, long bristles, disarticulating from the rachis below the glumes; the caryopsis is tightly enclosed by the indurate lemma and palea.

Foxtail millet has largely lost the ability of natural seed dispersal (persistent spikelets at maturity facilitate harvesting), and shows a tendency toward uniform plant maturity. After cultivation, some degree of natural seed dispersal frequently persists for several generations and plants compete with wild green foxtail.

A robust weed, occurring in Asia, Europe and North America, known as giant green foxtail, is a derivative of a natural hybridization between green foxtail and foxtail millet; it is erect and larger (up to 2.5 m tall; panicles up to 20 cm long; panicle branches up to 4 cm long) than green foxtail.

Several wild *Setaria* species are important as forage and are also extensively harvested as wild cereals, e.g. *S. pumila* (Poiret) Roemer & Schultes (synonym: *S. pallide-fusca* (Schumach.) Stapf & Hubbard) is a complex annual species, occurring in Africa, Asia and Australia, and in India some forms are cultivated as a crop; *S. sphacelata* (Schumach.) Stapf & Hubbard ex M.B. Moss is a polyploid complex originating from tropical Africa, but cultivated as a forage throughout the tropics; grain of *S. palmifolia* (Koenig) Stapf is commonly used as a substitute for rice by forest tribes in the Philippines; in New Guinea this species is vegetatively propagated for the edible young shoots which are cooked as a green vegetable.

Ecology Foxtail millet has a C4-cycle photosynthetic pathway. It can be grown in semi-arid regions with rainfall less than 125 mm in the 3–4 months of growth. It does not tolerate waterlogging and is susceptible to long periods of drought. In the tropics it can be grown from sea-level up to 2000 m altitude. It prefers a fertile soil but can be grown successfully on a wide range of soils, from light sands to heavy clays, and even yields reasonably on poor or marginal soils.

Propagation and planting Foxtail millet is propagated by seed, either broadcast or drilled, needing a seed rate of 8–10 kg/ha when grown in pure stands. In India, it is often grown in mixtures with finger millet, cotton and sorghum.

Husbandry Foxtail millet is usually grown as a rainfed crop, but it may also be grown under irrigation. Sometimes it is grown as a catchcrop when the paddy rice has failed. The crop responds well to manuring; in practice only irrigated crops are manured.

Diseases and pests The most serious diseases are blast (*Piricularia setariae*), downy mildew (*Sclerospora graminicola*), leaf rust (*Uromyces setariae-italiae*) and smut (*Ustilago crameri*). The major pests are shoot fly (*Atherigona biseta*), borers, caterpillars and birds. In stored grain, seed smut (*Sorosporium bullatum*) and kernel smut (*Ustilago paradoxa*) may cause considerable losses in addition to the common cereal storage insects.

Harvesting Foxtail millet is harvested manually by cutting off the spikes, or mechanically with a combine or binder. When grown for fodder, it should be harvested before flowering.

Yield The average annual yield of rainfed foxtail millet is 800–900 kg/ha of grain and 2500 kg/ha of straw. Much higher yields can be obtained with irrigation (in China experimental yields reached 11 t/ha).

Handling after harvest Foxtail millet is usually husked just before processing because husked grains are readily infested with insects. Husking can be done with a stone roller or with rice milling machinery. The millet bran (comprising 20–30% of the spikes) is rich in oil (about 9%) which can be extracted, or the bran is used as animal feed. In China, mini crisp chips are made by cooking husked grains, pressing the product to 1 mm thickness, drying, frying in oil and flavouring. Crispy rolls are prepared from husked grains which are soaked in water, ground and, after addition of sugar, toasted between 2 iron plates and formed into rolls.

Genetic resources Large collections of foxtail millet germplasm are present at the National Gene Bank of China, Institute of Germplasm Resources (CAAS, Beijing, 15 000 accessions) and at the International Crops Research Institute for the Semi-Arid Tropics (ICRISAT, India, about 1400 accessions). Smaller collections are present at various other national genebanks and research centres, e.g. in Thailand at the National Corn and Sorghum Research Centre in Pakchong.

Breeding In crop–weed complexes like foxtail millet, variation is extensive and often continuous. Variation is often maintained by farmers selecting a range of phenotypes for sowing with different ripening times, because this allows for harvesting over an extended period of time and eliminates the necessity of prolonged seed storage.
Major breeding objectives are developing high-yielding cultivars which produce protein-rich seed and are resistant to diseases, pests and lodging, and adapted to local ecological circumstances. In China, for example, cultivars with a short growing cycle and a high drought and cold tolerance have been developed; these can be grown in the summer season after winter wheat.

Prospects Foxtail millet has lost its importance as a major food crop in competition with wheat, maize, sorghum and rice. However, it may remain an important crop, especially on poor agricultural land in regions with low rainfall or a short growing season. Breeding results in China are such that an expansion of foxtail millet cultivation is foreseen for the near future.

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M. Rahayu & P.C.M. Jansen

Sorghum bicolor (L.) Moench

Methodus pl.: 207 (1794).
GRAMINEAE
$2n = 20$

Synonyms *Holcus bicolor* L. (1771), *Andropogon sorghum* (L.) Brot. (1804), *Sorghum vulgare* Pers. (1805).

Vernacular names Sorghum, sorgo, guinea corn (En). Sorgho (Fr). Indonesia: cantel, jagung cantel. Malaysia: jagung, jagong. Philippines: batad, batag (Tagalog), bukakau (Ilokano). Laos: khauz fa:ngz. Thailand: khao-panghangchang (northern), samutkhodom (central), mutkhodom (southern). Vietnam: mi[ees]n, c[or] mia hai m[aaf]u.

Origin and geographic distribution The greatest variability in cultivated and wild sorghum is found in north-eastern Africa. It is thought that the crop was domesticated in Ethiopia by selection from wild sorghum types (*S. bicolor* (L.) Moench subsp. *verticilliflorum* (Steud.) Piper, synonym: *S. arundinaceum* (Desv.) Stapf), between 5000 and 7000 years ago. It was probably distributed from this centre of origin along shipping and trade routes through the Middle East to India at least 3000 years ago. From there, it is thought to have been carried to China along the silk route and through coastal shipping to Burma (Myanmar) and other parts of South-East Asia. One distinctive group of sorghums, amber cane sorgos, is found in India, Burma (Myanmar) and coastal areas of China and Korea. These are quite different from the sorghums of mainland China. Glutinous-starch sorghums are found in Burma (Myanmar), Thailand and other parts of South-East Asia where glutinous starch is preferred, and these types were presumably selected locally by farmers. Sorghum was first taken to the Americas through the slave trade from West Africa. It was introduced into the United States for commercial cultivation from North Africa, South Africa and India during the latter years of the 19th Century. It was subsequently introduced into South America and Australia, where it has become an established grain and fodder crop. It is now widely distributed in drier areas of Africa, Asia, the Americas and Australia. It is cultivated between sea-level and altitudes of 2200 m and at latitudes of up to 50°N in the United States and Russia and 40°S in Argentina.

Uses Sorghum is an important staple food, particularly in semi-arid tropical regions of Africa and Asia, and an important feed grain and fodder crop in the Americas and Australia. In the simplest food preparations, the whole grain is boiled to produce a food resembling rice, roasted (usually at the dough stage), or popped like maize. However, the grain is normally ground or pounded to form a flour, often after hulling to remove pigmented pericarp. The flour is used to make thin or thick porridge, leavened or unleavened bread, or beer. The processes, which vary considerably from region to region, often involve the use of alkali and fermentation to improve digestibility, particularly in the case of high-tannin sorghums. Beer production is important in Africa, where sorghum grain is germinated, dried and ground to form malt, and sorghum flour is used as a substratum for fermentation. In China, sorghum is extensively distilled to make a popular spirit and vinegar. Sorghum grain is a significant component of cattle, pig and chicken feeds in the United States, Central and South America, Australia and China, and is becoming important in chicken feed in India. It requires processing by grinding, rolling, flaking, or steaming, to maximize its nutritional value.

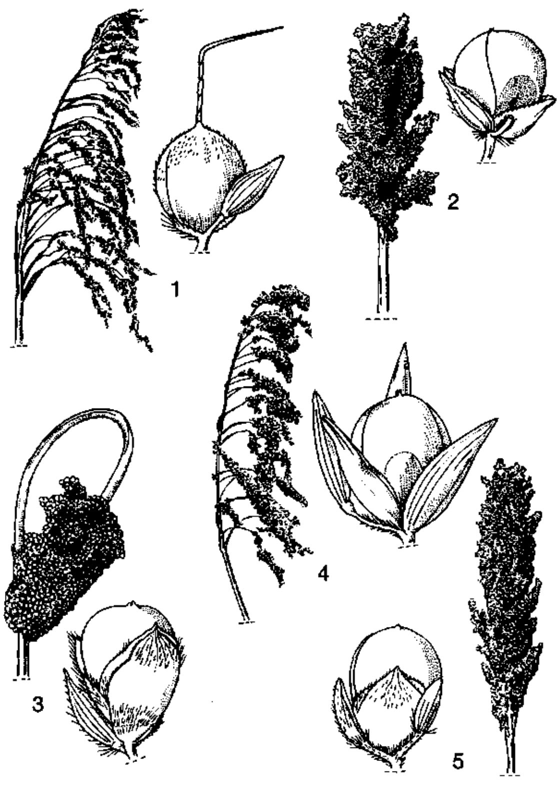
Sorghum plant residues are also used extensively as building material, fuel and animal feed. The dried stems can be used as roofing or fencing materials. The stover remaining after harvesting the grain is cut and fed to cattle, sheep and goats, or may be grazed. In many dryland areas where animal feed is in short supply, this use is as important as grain production. Sorghum is also grown for forage, either for direct feeding to ruminants or for preservation as hay or silage. Sweet-stemmed sorghums are used for animal feed and for extraction of sugar and syrup.

Production and international trade Sorghum grain is the fifth most important cereal in the world after wheat, rice, maize, and barley. World production is between 55 and 70 million t of grain per annum from between 40 and 45 million ha. Because the crop is a dryland one and is generally grown in marginal environments, productivity and areas sown vary substantially from season to season due to variation in rainfall. Average figures must therefore be treated with some caution. The most important producers are the United States, with an annual production of 15 million t from 4 million ha, India (12 million t from 13 million ha), China (5.5 million t from 1.5 million ha), Mexico (5 million t from 1.5 million ha), Nigeria (4.5 million t from 4.5 million ha) and Sudan (3 million t from 5 million ha). Sorghum is a minor crop in South-East Asia. The main producers are Thailand (250 000 t from 175 000 ha) and Burma (Myanmar) (180 000 t from 150 000 ha). Small areas are also grown in Indonesia, the Philippines and Vietnam. World trade in sorghum is limited. Most sorghum is consumed by its producers and little enters the cash economy for sale.

Properties 100 g of air-dried sorghum grain contains: water 8–16 g, protein 8–15 g, fat 2–6 g, carbohydrates 70–80 g, fibre 1–3 g, and ash 1–2 g. The energy value ranges from 1300–1600 kJ/100 g edible portion. The tannin content of sorghum is important in considering nutritional value, as tannins bind proteins and reduce their digestibility. Much of the protein in sorghum is prolamine, which is nutritionally valueless. Maximum available protein is usually 8–9%. Sorghum grain is deficient in lysine, methionine and threonine.

The composition of the green plant varies according to age and cultivar but it normally contains 78–86 g of water per 100 g of fresh material. On a dry basis it contains per 100 g: protein 12 g, carbohydrates 40–50 g, and fibre 20–30 g. The cyanogenic glycoside dhurrin occurs in the aerial parts of most sorghums. The quantity depends on the cultivar, the plant parts, their age and environmental conditions. Dhurrin is hydrolysed to hydrocyanic acid (HCN) which is highly toxic and can kill grazing animals. It is particularly concentrated in the young leaves and tillers and in plants that are suffering from drought. HCN content usually declines with age and is destroyed when the fodder is made into hay or silage. The 1000-grain weight is 13–40 g.

Description Vigorous annual grass, 0.5–5.0 m tall, with one to many tillers, originating from the base or later from stem nodes. Seedling radicle replaced by fibrous adventitious roots emerging from lowest nodes below and immediately above ground level; roots concentrated in the top 90 cm but may extend to twice that depth, spreading laterally up to 1.5 m. Stem solid, usually erect, dry or juicy, insipid or sweet; the centre may become spongy with spaces in the pith; intercalary meristems above the root band capable of differential growth, allowing fallen stems to regain upright position; at each node an axillary bud may develop into a tiller from the base, or into a branch from the stem. Leaves 7–24, according to cultivar, initially erect, later curving, borne alternately; sheath 15–35 cm long, encircling the stem with overlapping margins, often with a waxy bloom, with band of short white hairs at base near attachment; ligule usually present, short, about 2 mm long, ciliate on upper free edge; auricles triangular or lanceolate; blade lanceolate to linear-lanceolate, 30–135 cm × 1.5–13 cm, margins flat or wavy, midrib white or yellow in dry pithy cultivars or green in juicy cultivars, stomata on both leaf surfaces. Inflorescence a panicle; peduncle erect, sometimes recurved forming a goose-neck; rachis short or long, with primary, secondary and sometimes tertiary branches, bearing racemes of spikelets; length of rachis and length and closeness of panicle branches determine panicle shape, which may be densely packed, conical or ovoid, to spreading and lax; spikelets borne in pairs, one sessile and hermaphrodite, the other pedicelled and male or sterile, occasionally hermaphrodite; terminal spikelets of a raceme borne in groups of three with one sessile and two pedicelled spikelets; sessile spikelet 3–10 mm long; glumes 2, approximately equal in length, coriaceous (leathery) or chartaceous (papery), ovate, elliptical or obovate; lower glume partially enveloping the upper, 6–18-nerved, usually with a coarse keel-like nerve on each side; upper glume usually narrower and more pointed, with central keel for part of its length; glumes enclosing 2 florets; lower floret infertile, consisting of a lemma only, forming a broad ciliate membranous bract which partially enfolds the upper floret; upper floret hermaphrodite, with a membranous lemma with a two-toothed cleft at apex, teeth free or adnate to an awn, when present, from the sinus; awn kneed and twisted; palea, when present, small and thin; 2 lodicules adjacent to lemma, short, broad, truncate, fleshy with ciliate margins; stamens 3; ovary single-celled with 2 long styles ending in feathery stigmas; pedicelled spikelet variable, with long or short pedicel, persistent or deciduous, smaller and narrower than sessile spikelet; often consisting of only two glumes, sometimes upper floret with lemma, no palea, 2 lodicules and 3 stamens with functional pollen, while lower floret consisting of lemma only. Fruit a caryopsis, usually partially cov-



Sorghum bicolor (L.) Moench – habit of infructescences with spikelets of the 5 basic Sorghum cultivar groups: 1, Bicolor; 2, Caudatum; 3, Durra; 4, Guinea; 5, Kafir.

ered by glumes, rounded and bluntly pointed, 4–8 mm in diameter and varying in size, shape and colour.

Growth and development The coleoptile emerges from the soil 3–10 days after sowing and leaf emergence follows soon after, with the rate depending largely on temperature. Panicle initiation, when the apical meristem switches from producing fresh leaf primordia to producing the floral primordium, takes place after approximately one third of the growth cycle of the cultivar. By this stage the total number of leaves has been determined and about one third of total leaf area has developed. Rapid leaf development, stem elongation and internode expansion follow growing-point differentiation. Rapid growth of the panicle also occurs. By the time the flag leaf is visible, all but the final 3 to 4 leaves are fully expanded and light interception is approaching its maximum. Lower leaves have begun to senesce. During the boot stage, the developing panicle has almost reached its full size and is clearly visible in the leaf sheath. Leaf expansion is complete. The peduncle grows rapidly and the panicle emerges from the leaf sheath. Flowering follows soon after panicle emergence, with the interval largely determined by temperature. Individual heads start flowering from the tip downwards and flowering may extend over 4–9 days. Grain filling occurs rapidly between flowering and the soft dough stage, with about half the total dry weight accumulating in this period. Lower leaves continue to senesce and die. By the hard dough stage, grain dry weight has reached about three quarters of its final level. Additional leaves have been lost. At physiological maturity, determined by the appearance of a dark layer at the hilum (where the grain is attached to the panicle), maximum dry weight has been achieved. Moisture content of the grain is usually between 25–35% at this stage. The time taken between flowering and maturity depends on environmental conditions but normally represents about one third of the duration of the crop cycle. Further drying of the grain takes place between physiological maturity and harvest, which usually occurs when grain moisture content has fallen below 20%. Leaves may senesce rapidly or stay green with further growth if conditions are favourable.

The time to maturity varies greatly among cultivars, some early types taking only 100 days or less, whereas long-duration sorghums require 5–7 months.

Other botanical information At present, *S. bicolor* is considered as an extremely variable crop–weed complex, comprising wild, weedy and cultivated annual forms (classified as subspecies) which are fully interfertile. In the most widely accepted system, the cultivated forms are classified into different races on the basis of grain shape, glumes and panicle type. Five basic races and ten hybrid combinations of these races are recognized and grouped into subsp. *bicolor*. Instead of races grouped into a subspecies, a direct classification into cultivar groups is preferred. The 5 basic groups are:

- cv. group Bicolor (based on race 'bicolor' in the sense of Harlan & de Wet): characterized by open inflorescences and long clasping glumes that enclose the usually small grain at maturity. Cultivars are grown in Africa and Asia, some for their sweet stems to make syrup or molasses, others for their bitter grains used to flavour sorghum beer, but they are rarely important. They are frequently found in wet conditions.
- cv. group Caudatum (based on race 'caudatum' in the sense of Harlan & de Wet): characterized by turtle-backed grains that are flat on one side and curved on the other; the panicle shape is variable and the glumes are usually much shorter than the grain. Caudatum sorghums are widely grown in Chad, Sudan, northeastern Nigeria and Uganda.
- cv. group Durra (based on race 'durra' in the sense of Harlan & de Wet): characterized by compact inflorescences, characteristically flattened sessile spikelets, and creased lower glumes; the grain is often subspherical. Durra sorghums are widely grown along the fringes of the southern Sahara, across arid West Africa, the Near East and parts of India.
- cv. group Guinea (based on race 'guinea' in the sense of Harlan & de Wet): characterized by usually large, open inflorescences whose branches are often pendulous at maturity; the grain is typically flattened and twisted obliquely between long gaping glumes at maturity. Guinea sorghum occurs primarily in West Africa, but it is also grown along the East African rift from Malawi to Swaziland and it has also spread to India and the coastal areas of South-East Asia. Many subgroups can be distinguished, e.g. with cultivars especially adapted to high or low rainfall regimes. In the past, Guinea sorghums were often used as ship's provisions because their hard grains stored well.
- cv. group Kafir (based on race 'kafir' in the sense of Harlan & de Wet): characterized by relatively

compact panicles that are often cylindrical in shape, elliptical sessile spikelets and tightly clasping glumes that are usually much shorter than the grain. Kafir sorghums are important staples across the eastern and southern savanna from Tanzania to South Africa.

The other 10 cultivar groups (based on the hybrid races of the same names in the sense of Harlan & de Wet) exhibit various combinations and intermediate forms of the characteristics of the 5 basic cultivar groups, e.g. cv. group Guinea-Bicolor, cv. group Caudatum-Bicolor, cv. group Kafir-Bicolor, cv. group Durra-Bicolor, etc.

The wild representatives are classified as *S. bicolor* (L.) Moench subsp. *verticilliflorum* (Steud.) Piper (synonyms: *S. arundinaceum* (Desv.) Stapf, *S. bicolor* (L.) Moench subsp. *arundinaceum* (Desv.) de Wet & Harlan): tufted annuals or weak biannuals, with slender to stout culms up to 4 m tall; leaf blade linear-lanceolate, up to 75 cm × 7 cm; panicles usually large, somewhat contracted to loose, up to 60 cm × 25 cm, branches obliquely ascending, spreading or pendulous; racemes 1–5-noded, fragile; sessile spikelet lanceolate to elliptical, 5–8 mm long, usually ciliate, glumes coriaceous, lemmas ciliate and upper one usually awned, grain pointed obovoid; pedicelled spikelet male or neuter and often longer than the sessile spikelet. The subspecies is further divided into 4 overlapping types ('races'), of which *verticilliflorum* is most widely distributed, extending across the African savanna and introduced into tropical Australia, parts of India and the New World; it has large and open inflorescences with spreading but not pendulous branches.

The weedy representatives are classified into the complex of hybrids, collectively named *Sorghum ×drummondii* (Steud.) Millsp. & Chase (synonyms: *S. sudanense* (Piper) Stapf, *S. bicolor* (L.) Moench subsp. *drummondii* (Steud.) de Wet); it occurs as a weed in Africa wherever cultivated grain sorghums and their closest wild relatives are sympatric because they cross freely; it represents the intermediate population occurring in the intermediate habitat of recently abandoned fields and of field margins as a very persistent weed; stem up to 4 m tall; leaf blade lanceolate, up to 50 cm × 6 cm; panicle variable, usually rather contracted, up to 30 cm × 15 cm, often with pendulous branches; racemes more or less crowded, mostly 3–5-noded, tardily disarticulating at maturity; sessile spikelet pointed, elliptical, 5–6 mm long, lemmas hyaline ciliate, grain resembling the grain from the cultivar from which the weed was derived; pedicelled spikelet male or neuter. A well-known forage grass, Sudan grass, belongs to this complex.

Ecology Sorghum is adapted to a wide range of environmental conditions and will produce significant yields under conditions that are unfavourable for most other cereals. Sorghum is particularly adapted to drought and has a number of morphological and physiological characteristics that contribute to this, including an extensive root system, waxy bloom on leaves that reduces water loss, and the ability to stop growth in periods of drought and resume it when the stress is relieved. Sorghum is characterized by the C4-cycle photosynthetic pathway. It is a short-day plant with a wide range of different reactions to photoperiod. It is also highly influenced by temperature, with the result that many cultivars can show markedly different appearance and productivity in different environments. Some tropical cultivars fail to flower or to set seed at high latitudes.

Sorghum also tolerates waterlogging and can be grown in areas of high rainfall. It is, however, primarily a plant of hot, semi-arid tropical environments with rainfall from 400–600 mm that are too dry for maize. It is also grown widely in temperate regions and at altitudes of up to 2300 m in the tropics. Sorghum tolerates a wide range of temperatures. Sterility can occur when night temperatures fall below 12–15°C during the flowering period. Sorghum is killed by frost.

Sorghum can be grown successfully on a wide range of soil types. It is well suited to heavy Vertisols found commonly in the tropics, where its tolerance of waterlogging is often required, but is equally suited to light sandy soils. It tolerates a range of soil pH from 5.0–8.5 and is more tolerant of salinity than maize. It is adapted to poor soils and can produce grain on soils where many other crops would fail.

Propagation and planting Sorghum is normally grown from seed. A fine seed-bed is preferable but is often not achieved. The seed is usually sown directly into a furrow following a plough, but can also be broadcast and harrowed into the soil. Optimum plant spacing depends on soil type and availability of moisture. For favourable conditions, row spacings of 45–60 cm and plant-to-plant spacings of 12–20 cm, giving populations of about 120 000 plants per ha, are normal. For drier or less fertile conditions, wider spacing and lower plant populations are usually optimal. The seed rate varies from 3 kg/ha in very dry areas to 10–15 kg/ha under irrigation. Occasionally, seedlings are grown in a nursery and transplanted into the field early in the dry season, e.g. on the floodplains round Lake Chad in Africa. Sorghum can also be propagated vegetatively by splitting tillers from established plants and transplanting them, a practice that is often used by small farmers to fill gaps. Ratooned crops give low grain yields.

Husbandry Sorghum is usually grown as a rainfed crop, sown after the onset of the monsoon season. Seeding rates are often higher than optimum to compensate for poor seed-bed or to allow for unfavourable moisture conditions. Subsistence farmers rarely apply fertilizer, as responses depend on moisture availability which is usually very uncertain. Under more favourable conditions, chemical fertilizers and farmyard manure are used with advantage, but even so the quantities used are usually below optimum. The application of 25–50 kg/ha of nitrogen often proves to be appropriate. In large-scale cultivation in the United States, high fertilizer doses are applied, comparable to those for maize.

The crop is usually weeded by a combination of inter-row cultivation with animal-drawn implements and hand weeding within rows. Thinning is carried out at the same time as hand weeding, or at intervals during the crop cycle, particularly where thinnings are used to feed livestock. Little chemical weed control is practised as it is usually uneconomical, although effective herbicides are available.

The parasitic weed *Striga* is a major pest of sorghum, particularly in Africa, where severe infestations can lead to land being abandoned. *Striga* is also an important problem in Burma (Myanmar) and India. *Striga* can be controlled by cultural methods such as the use of rotations of crops that are not susceptible and rigorous removal of the weeds before flowering. Application of fertilizer also helps to control *Striga*.

Diseases and pests The most severe disease problem of sorghum in South-East Asia is grain moulds, caused by a complex of fungal pathogens (predominantly *Curvularia lunata*, *Fusarium* spp., and *Phoma sorghina*) that infect the grain during development and can lead to severe discolouration and loss of quality. This disease is most severe in seasons where rains continue through the grain maturity stage and delay the harvest. In Thailand, sorghum is sown late in the rainy season in order to escape grain mould damage. Important foliar diseases in South-East Asia include anthracnose (*Colletotrichum graminicola*), leaf blight (*Exerohilum turcicum*), zonate leaf spot (*Gloeocercospora sorghi*), and tar spot (*Phyllacora sorghi*). Charcoal rot (*Macrophomina phaseolina*) is an important root and stem rot of sorghum in Thailand and the Philippines, particularly when terminal drought stress is severe. Chemical control of these diseases is rarely if ever practised. Other diseases of sorghum that are important in other areas of the world include downy mildew (*Peronosclerospora sorghi*), rust (*Puccinia purpurea*), and ergot (*Claviceps sorghi*).

The main insect pests of sorghum are shoot fly (*Atherigona soccata*), stem borers (*Busseola fusca* and *Chilo partellus*), sorghum midge (*Contarinia sorghicola*), and head bugs (*Calocoris angustatus*). The main control methods for these pests are cultural. Early sowing is particularly important as a mechanism to avoid large insect populations at times when plants are most susceptible to damage. High levels of host plant resistance are also available for sorghum midge, but only low levels of resistance for the other pests. As in the case of diseases, chemical control of insect pests is rarely practised. Sorghum is very susceptible to damage by storage pests, the main ones being rice weevil (*Sitopholus oryzae*), flour beetle (*Tribolium castaneum*) and the grain moth (*Sitotroga cerealella*). Damage can be minimized by drying grain adequately before storage. Cultivars with hard grain also suffer less damage.

Harvesting Sorghum is usually harvested by hand. The heads can be cut or the whole plant cut and the heads removed later. Sorghum is harvested by combine in Thailand, where short-statured cultivars are preferred for grain production.

Yield Sorghum is often grown in marginal areas that are not suitable for many other crops. Its average grain yields on farmers' fields are therefore often low. The average grain yield in Thailand is 1.5 t/ha and that in Burma (Myanmar) is 1.2 t/ha. However, sorghum has high yield potential and under favourable conditions can produce much higher yields. In China, where it is grown with high levels of inputs, sorghum yield averages 3.6 t/ha and in the United States it averages 3.8 t/ha. Yields up to 6 t/ha have been reported from experimental fields.

Rainfed forage sorghum is usually cut only once, soon after flowering. Other forage sorghum crops are grown under more favourable conditions, often with irrigation and high levels of fertilizer applied, and can be harvested and then left to regrow (ratoon). Forage yields from single-cut cultivars and hybrids can reach 20 t/ha of dry matter. Multi-cut cultivars and hybrids usually give only slightly higher total yields over all cuts but produce better quality forage.

Handling after harvest Sorghum grain is highly susceptible to storage pests, and proper handling after harvest is very important. The harvested grain is usually sun-dried, often on the head. Heads, particularly those to be retained for seed, may be stored hanging from the ceilings of kitchens over cooking fires where the smoke helps to deter insect attack. Alternatively, the heads may be threshed after drying and the grain stored in various traditional granaries, above or below ground, designed to prevent insect attack. Forage sorghum can be fed to livestock while still green or can be stored in various ways for later use. The forage is often dried and stacked or can be made into silage. Stover left after harvest of grain is often grazed by animals.

Genetic resources A major collection of sorghum germplasm is maintained and distributed to interested researchers by the International Crops Research Institute for the Semi-Arid Tropics (ICRISAT) in India. The collection extends to over 35 000 accessions of landraces from all the major sorghum-growing regions of the world. Other smaller collections are maintained in regional genebanks in Africa and by many national research programmes in Africa, Asia and the Americas.

Breeding High-yielding improved cultivars of sorghum are available in most of the main producing countries. These include cultivars and hybrids produced using cytoplasmic male sterility systems. The main breeding objectives include high grain yield, white grain for human consumption, and red or brown grain for feed purposes and brewing. Incorporation of resistance to major yield-limiting diseases and pests, and tolerance of abiotic stresses is of high priority for most sorghum improvement programmes. In many countries the emphasis is on producing cultivars which combine high grain yield with high stover yields because of the importance of sorghum crop residues as animal feed. Special cultivars with high biomass production and good forage quality are bred for animal feed.

Prospects Sorghum has traditionally been used as human food in most sorghum-growing areas of the world. But, as the population becomes more affluent, eating habits change and the consumption of other preferred cereals increases and the consumption of sorghum declines. This trend is likely to continue, although the demand for sorghum as food is still likely to remain substantial in many production areas. Demand for sorghum for non-traditional uses is likely to increase. In particular, the use of sorghum as a feed grain, already well established in many industrialized countries, is likely to become more common in developing countries. Similarly, as increased affluence results in increased demand for meat and dairy products, the use of sorghum as a forage crop in intensive production systems in many tropical regions is likely to expand. The use of sorghum as a raw material for industrial processes will also increase. Research should focus on innovations that are likely to reduce the costs of production of sorghum. This should include research to increase yield levels of available cultivars, and to improve agronomic practices. Emphasis should be placed on enhancing resistance to the main biotic and abiotic stresses.

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Triticum L.

Sp. pl.: 85 (1753); Gen. pl. ed. 5: 37 (1754).
GRAMINEAE
$x = 7$; $2n = 6x = 42$ (*T. aestivum*); $2n = 4x = 28$ (*T. turgidum*)

Major species and synonyms
- *Triticum aestivum* L., Sp. pl.: 85 (1753). Synonyms: *T. sativum* Lamk (1779, excl. *T. turgidum* L.), *T. vulgare* Vill. (1787), *T. cereale* Schrank (1789).
- *Triticum turgidum* L., Sp. pl.: 86 (1753). Synonyms: *T. durum* Desf. (1798), *T. dicoccum* Schübler (1818), *T. dicoccoides* Körn. ex Schweinf. (1908).

Vernacular names General: Wheat (En, Am). Blé (Fr). Indonesia: gandum. Malaysia: gandum. Philippines: trigo. Thailand: khao-sa-le, sa-le. Vietnam: l[us]a m[if], l[us]a mi[ees]n.
- *T. aestivum*: Bread wheat, common wheat (En, Am). Blé tendre (Fr).
- *T. turgidum*: Durum wheat, emmer wheat, macaroni wheat (En, Am). Blé dur (Fr).

Origin and geographic distribution Early wheats were first domesticated between 7500 and 6500 BC in the Fertile Crescent region of the Middle East. Wheat was cultivated in ancient Greece, Persia, Egypt, and throughout Europe in prehistoric times. It was an important crop in South-West Asia when history was first recorded. By the third millennium BC, the crop had reached China. In 1529, the Spanish introduced wheat to the New World. It was first cultivated in the Philippines in 1664. Of all the cereals, wheat is the most widely adapted, being grown from sea-level to altitudes of more than 4500 m, and from the equator to within the Arctic Circle. About 90% of the area under the cultivated wheats is planted to bread wheat and 10% to durum wheat. Wheat is not widely grown within South-East Asia, but pockets of wheat are cultivated in most countries.

Uses Wheat provides almost 20% of all human food energy. It is made into various products including bread (leavened, flat and steamed), chupatties, pastries, crackers, biscuits, pretzels, noodles, farina, macaroni, spaghetti, bulgur, couscous, breakfast foods, baby foods, and food thickeners. It is also used as a brewing ingredient in certain beverages.

In South-East Asia, wheat utilization has been adapted to the local cuisine. For example, in Thailand, whole wheat may be boiled and added to rice and curries, fried with vegetables, and used for desserts; cracked wheat is added to boiled porridge with vegetables and pork, to chilli paste that is eaten with rice, to 'tabooleh' salad with chillies, and to desserts with coconut milk; wholemeal flour is used to make noodles and baked or steamed breads, and as gluten for meat substitutes. In the Philippines, 'pandesal' (breakfast bread) is a sought after specialty. In most of South-East Asia, wheat products are in transition from a luxury to a staple food. In many Asian countries, wheat flour is mixed with substitute components (5–30%), such as starch from maize, rice, and cassava, to produce bakery products of acceptable appearance, flavour and nutritional quality.

By-products of flour milling, particularly the bran, are used almost entirely to feed livestock, poultry or prawns. Because of its relatively high content of protein (25%), and vitamins (B-complex and E), wheat germ (from wheat embryos) is sold as a human food supplement.

Industrial uses of wheat products centre on the production of glues, alcohol, oil and gluten. Straw is fed to ruminants or used for bedding material, thatching, wickerwork, newsprint, cardboard, packing material, fuel and as substrate for mushroom production.

Production and international trade In 1992, world wheat production was 567 million t, produced on 220 million hectares. Major producers are the United States, Canada, Russia and China. Developing countries were responsible for 35% of global wheat production. In South and East Asia, China, India, and Pakistan are the principal producers. During the 1990–1992 crop years, Burma (Myanmar) devoted 130 000–140 000 ha to wheat production. Small areas of wheat have been grown in rotation with rice or other local crops for many centuries in the highlands of Java (Indonesia), the northern highlands of Luzon (the Philippines), the northern mountains of the Cao Bang, Son La, and Lai Chau Provinces of Vietnam, and in the northern highlands of Thailand. Areas have never exceeded 2000 ha in any of these countries. During the Spanish occupation of the Philippines, some wheat was exported through the galleon trade from Manila to Acapulco (Mexico).

All countries in South-East Asia import wheat, totalling 6.6 million t annually in 1991–1993. Indonesia imported the largest share (2.5 million t), followed by the Philippines (1.8 million t), Malaysia (1.1 million t), Thailand (0.6 million t), Vietnam (0.3 million t), and Singapore (0.2 million t). The world price of wheat has fluctuated between US$ 110–210 per t over the last 10 years.

Average per capita wheat consumption in South-East Asia is 14 kg/year, and is growing at a rate of 4.8% per year. The global annual per capita consumption is 106 kg. Imports have caused financial strain in these countries, which has provided an incentive to promote domestic production.

Properties The composition of a wheat grain (caryopsis) is 7–8% of coat material, 90% endosperm and 2–3% embryo. The embryo mainly comprises oil and protein, and little starch. The endosperm is starchy, and is surrounded by the aleurone layer which is rich in proteins. When a wheat grain is milled, the outer layers and embryo are separated from the endosperm. The pulverized endosperm becomes the wheat flour, while the other parts form the bran.

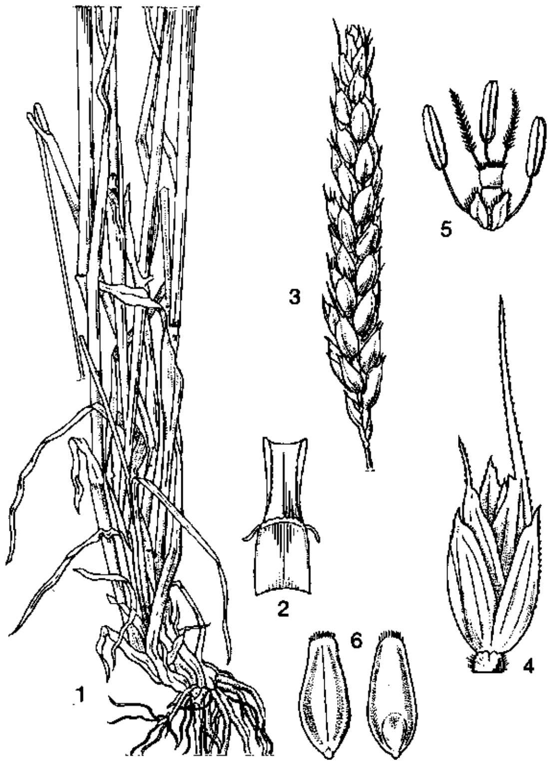
The endosperm varies both in hardness and vitreousness: hard bread wheats high in gluten protein tend to be vitreous and low-protein soft wheats tend to be opaque. Hard wheats are best suited for bread making while the soft wheats are best for biscuits and pastries. Flour colour varies from white to slightly yellow.

Grain protein content for bread-making purposes must be 11–15%. More gluten-type proteins increase the strength of the dough produced, allowing the expanding loaf to retain its shape during baking. Loaf volume is one of the most important final quality criteria. Protein levels may be less than 10% for biscuits, cakes and pastries. Chupatties, arabian breads, steamed bread, and noodles require intermediate quality characteristics. Durum wheat is used to make pasta products. The grain is vitreous, amber in colour, and is much harder than bread wheat. The coarse flour (semolina) is used to make spaghetti, macaroni, certain noodles, etc. Gluten strength tends to be low. Protein should have a minimum level of 12%, and the grain must contain a high amount of β-carotene, which imparts the desired yellow colour.

Wheat contains high levels of energy-producing carbohydrates. The energy value of wheat is 1300–1500 kJ/100 g. The constituents of the whole grain per 100 g are: water 11–14 g, protein 8–16 g, fat 1.7–4.0 g, carbohydrates 69–72 g, fibre 2–3 g, and ash 1.5–1.8 g. Constituents of white flour are per 100 g: water 12.0–12.4 g, protein 10–12 g, fat 1–1.2 g, carbohydrates 74–76 g, fibre 0.3–0.4 g, and ash 0.3–0.5 g. Wheat is deficient in the amino acids lysine and threonine, and somewhat in isoleucine and valine. It is a good source of B-group vitamins and minerals.

The 1000-seed weight is 30–50 g.

Description Annual herbs, often strongly tufted. Stem (culm) cylindrical, with solid nodes and hollow internodes. Leaves in 2 vertical rows at the nodes, with a rounded, auricled sheath, a membranous ligule and a linear, parallel-veined, flat blade; uppermost leaf is called the flag leaf. Inflorescence a distichous spike; rachis zigzag, disarticulating (wild species) or tough (cultivars); spikelets solitary at each node of the rachis, awned or awnless, laterally compressed, 3–9-flowered; florets bisexual, the 1 or 2 uppermost ones usually rudimentary, sometimes only 1 of the florets bisexual; disarticulation above the glumes and between the florets; glumes chartaceous, subequal, 5–11-veined, asymmetrically 1–2-keeled, apiculate to awned; lemma rounded on back or keeled at least toward the tip, awned or blunt; palea 2-keeled, ciliate on the keels; lodicules 2, ciliate; stamens 3; pistil with an ovary that is tipped by a small fleshy hairy appendage and with 2 plumose stigmas. Fruit an ellipsoid caryopsis; endosperm forms the major part of the fruit; the embryo consists of a disklike scutellum, a conical coleoptile enclosing the plumule with 3 immature



Triticum aestivum L. – 1, habit; 2, ligule and auricles; 3, awnless spike; 4, spikelet; 5, floret (lemma and palea removed); 6, grains.

leaves and the shoot apex, and a coleorhiza which forms the primary root.

- *T. aestivum*: Plant 40–150 cm tall, forming 2–6 seminal roots and many secondary roots, often strongly tillering (up to 40 tillers per plant, depending on cultivar and environment, but normally 2–5). Stem smooth, with 4–7 nodes and internodes, sometimes more; internodes becoming larger from bottom to top. Leaf blade 15–40 cm × 1–3 cm, glabrous or pubescent. Spike 5–15 cm long excluding the awns, varying in shape, size and density; awns, when present, up to 16 cm long. Caryopsis ventrally with a central groove, reddish-brown, yellow, white or intermediate hues.
- *T. turgidum*: Spike usually bearded and compressed, narrow across the faces, much wider across the 2-rowed profiles; spikelets usually compressed, crowded, imbricate in the lateral rows; glumes 1-keeled, the keel formed by the sharply winged adaxial vein, the other main abaxial vein quite conspicuous but usually not definitely rugose; lemma usually long-awned.

Growth and development Phasic development of wheat is influenced by temperature, and the cultivar's vernalization and daylength response.

After water has been imbibed, germination begins as the endosperm is broken down to provide nutrients to the emerging coleoptile. Optimum germination occurs between 12–25°C. The scutellum initially supports early growth and subsequently serves as temporary storage of starch from the endosperm. The seminal roots emerge first. Once the roots start to absorb nutrients and water, the coleoptile emerges 4–6 days after germination. The seminal roots may remain functional for life unless destroyed by diseases or mechanical injury, but they constitute only a small portion of the total root system. The first true leaf of the seedling emerges from the coleoptile. Secondary roots start to develop about two weeks after seedling emergence. They arise from the basal node and form the permanent root system, which spreads out and may penetrate as deep as 2 m, but normally no more than 1 m. Leaf and tiller production increase rapidly soon after crop emergence. Cultivars with tall, weak tillers tend to lodge. All spike-bearing tillers eventually flower almost simultaneously.

Flowering begins at the middle third of the spike, then rapidly progressing both upward and downward. Most flowers bloom in mid-morning before noon. Wheat is normally self-pollinated; cross pollination is only 1–4%. Pollen is largely shed within the floret. Stigmas remain receptive for 4–13 days. Pollen is viable for up to 30 minutes only. Grains in the centre of the spike and in the proximal florets tend to be larger. Physiological maturity is the stage when the moisture content of the fully formed grain has dropped to 25–35%. The complete crop cycle of spring wheat varies from 80–115 days in South-East Asia.

Other botanical information *Triticum* consists of a polyploid series of 10–20 species in which there are diploid, tetraploid and hexaploid representatives with chromosome numbers of $2n = 14$, 28 and 42. Only the diploids are genetically true *Triticum*, the others intergeneric hybrids between *Triticum* and certain species of *Aegilops* L. Selection at each level has proceeded from wild species to cultivated species whose grain is tightly invested by lemma and palea, and then to free-threshing naked species. There are hardly any cultivated diploids (only some *T. monococcum* L. cultivars), and no wild hexaploids.

The hexaploid *T. aestivum* is believed to be of hybrid origin having the genome set AABBDD, with AA originating from *T. monococcum* or *T. urarti* Thumanjan ex Gandilyan, BB from *Aegilops speltoides* Tausch and DD from *A. tauschii* Cosson (synonym *A. squarrosa* auct.). Some authors, however, do not agree with this view, since the identity and origin of the B genome is questionable. They contend that the evolutionary history of bread wheat may possibly never be discovered because the introgression that took place to create the present-day constitution of bread wheat is too complex. Some authors keep the genus *Aegilops* separate from the genus *Triticum*, others unite the two into *Triticum*. Bread wheat is a very variable crop, bearing a heavy burden of names and classifications in the taxonomic literature. The distinction of cultivar groups is most appropriate for a purely cultivated complex crop like wheat. About 25 000 cultivars are known. The major cultivar groups are:

- cv. group Aestivum (based on *T. aestivum* L.; synonyms: *T. aestivum* L. var. *aestivum*, *T. aestivum* L. subsp. *vulgare* (Vill.) Mac Key, *T. vulgare* Vill. subsp. *vulgare*). This is the free-threshing common or bread wheat, thought to have been developed somewhere near the south-western corner of the Caspian Sea, being the most important cultivar group comprising the majority of the modern wheat cultivars.
- cv. group Compactum (based on *T. compactum* Host; synonyms: *T. aestivum* L. subsp. *com-*

pactum (Host) Mac Key). This is the free-threshing club wheat, developed in Afghanistan and adjacent regions and probably also in Switzerland and Austria.
- cv. group Macha (based on *T. macha* Dekapr. & Menabde; synonyms: *T. aestivum* L. subsp. *macha* (Dekapr. & Menabde) Mac Key, *T. spelta* L. subsp. *macha* (Dekapr. & Menabde) V. Dorof.). This is makha wheat, perhaps the oldest hexaploid not free-threshing wheat, indigenous to western Georgia but hardly cultivated any more.
- cv. group Spelta (based on *T. spelta* L.; synonyms: *T. vulgare* Vill. subsp. *spelta* Körn., *T. sativum* Lamk subsp. *spelta* Aschers. & Graebn., *T. aestivum* L. subsp. *spelta* (L.) Thell.). This is spelt wheat, a not free-threshing wheat, with only 2–3 florets per spikelet, cultivated in small quantities in Europe, Africa and on the plateau of western Iran. It is a wheat that can be cultivated under extreme circumstances, not demanding fertile soils, being relatively disease resistant, and having good taste, food and baking qualities. Before 1850 it was a very important wheat in Europe, declining afterwards but now gaining in popularity in 'organic' wheat cultivation.
- cv. group Sphaerococcum (based on *T. sphaerococcum* Percival; synonyms: *T. aestivum* L. subsp. *sphaerococcum* (Perc.) Mac Key). This is the free-threshing Indian dwarf wheat and originated in northwestern India and adjacent regions.
- cv. group Vavilovii (based on *T. vavilovii* (Tum.) Jakubc.; synonyms: *T. vulgare* Vill. var. *vavilovii* Tum. ex Fljaksb., *T. aestivum* L. subsp. *vavilovii* (Tum.) Sears). This is the not free-threshing vavilov wheat, indigenous to Armenia, cultivated in small quantities in Asia Minor, Turkey, Armenia and Azerbajdzan. It is characterized by its branching spikelets.

The tetraploid wheats are believed to have a genome from *Triticum* plus one derived from *Aegilops speltoides*. The cultivated tetraploid wheats are *T. timopheevii* Zhuk. cv. group Timopheevii, with genome AAGG, originating from western Georgia and the more important emmer wheat, *T. turgidum* L., with genome AABB. The following cultivar groups are distinguished in the cultivated emmer wheats:
- cv. group Carthlicum (based on *T. carthlicum* Nevski; synonyms: *T. turgidum* L. subsp. *carthlicum* (Nevski) A. & D. Löve). This is the free-threshing Persian wheat, cultivated in the Caucasus, Georgia, Armenia, Iran and Irak.
- cv. group Dicoccum (based on *T. dicoccum* Schübler; synonyms: *T. vulgare* Vill. subsp. *dicoccum* Körn., *T. turgidum* L. subsp. *dicoccum* (Schrank) Thell.). This is emmer, the oldest cultivated wheat, domesticated in the area of Palestine, southwestern Syria and northwestern Jordan. It has dense, bearded spikes, 2-grained spikelets and the grains are not free-threshing. At present it is still cultivated in Ethiopia, Iran, Turkey, Transcaucasia, former Yugoslavia, the Czech Republic, Slovakia and India.
- cv. group Durum (based on *T. durum* Desf.; synonyms: *T. vulgare* Vill. subsp. *durum* Körn., *T. aestivum* L. subsp. *durum* (Desf.) Thell., *T. turgidum* L. subsp. *turgidum* convar. *durum* (Desf.) Mac Key). This is the free-threshing durum wheat or macaroni wheat, domesticated in the Mediterranean, and cultivated all over the world in regions with a hot dry climate. It has its greatest diversity in Ethiopia.
- cv. group Polonicum (based on *T. polonicum* L.; synonyms: *T. turgidum* L. subsp. *polonicum* (L.) A. & D. Löve, *T. turgidum* L. subsp. *turgidum* convar. *polonicum* (L.) Mac Key). This is the free-threshing Polish wheat, occasionally cultivated in the same areas as cv. group Durum.
- cv. group Turgidum (based on *T. turgidum* L.; synonyms: *T. vulgare* Vill. subsp. *turgidum* Körn., *T. aestivum* L. subsp. *turgidum* (L.) Domin, *T. durum* Desf. subsp. *turgidum* (L.) V. Dorof.). This is the free-threshing rivet wheat or cone wheat, cultivated in northern Africa, southern and central Europe, Asia Minor, Pakistan, Iran and Irak.

Triticale (*Triticosecale* Wittmack) is a cereal derived from hybridization of rye and wheat. After several cycles of selection, the resulting triticale cultivars show characteristics in between wheat and rye. Breeders strive to combine the hardiness of rye with the high yield and quality of wheat. Tetraploid ($2n = 28$), hexaploid ($2n = 42$) and octoploid ($2n = 56$) forms exist, but the hexaploid forms are most successful. As a new food crop, triticale fell short of expectations, but it is becoming increasingly popular as a forage crop. Only where wheat does not grow well because of adverse conditions, triticale is a promising human food crop. It is estimated that it is grown annually on 1.5 milllion ha with Poland, France, Russia and Australia as the main producers.

Ecology Wheat has a C3-cycle photosynthetic pathway and is essentially a temperate climate crop. It requires 1475–1600 growing degree-days (GDD) for a complete crop cycle. Optimum temperatures for development are 10–24°C. Relatively low temperatures result in the highest yields. Temperatures above 35°C stop photosynthesis and growth, and at 40°C the crop is killed by the heat. In tropical areas, wheat is best grown at higher elevations or in the cooler months of the year. The minimum amount of water required for an acceptable crop is 250 mm in the top 1.5 m of soil. Wheat does not grow well under very warm conditions with high relative humidity, unless irradiation and nutrient availability are very favourable. In addition, wheat diseases are generally encouraged by such climatic conditions.

Soils best suited for production are well aerated, well drained, and deep, with 0.5% or more organic matter. Optimum soil pH ranges between 5.5 and 7.5. Wheat is sensitive to soil salinity.

Propagation and planting Wheat is propagated by seed. It requires a fine seed-bed that is free of weeds. Seed-bed preparation following rice can be labour-intensive and time-consuming. Heat during critical stages should be avoided. Therefore it is crucial to establish and adhere to an optimum planting calendar, to allow the wheat to flower under the most favourable or coolest environmental conditions and hence to maximize yield. If irrigation is not available, then a compromise has to be made by seeding when soil moisture is optimal. Wheat can be sown by hand or machine. When broadcast, the seed is incorporated with a rakelike tool, covered by an animal-drawn plough or incorporated by a machine-drawn disc. The seed may also be dribbled directly into a furrow behind a plow and covered, or machine-planted in rows (spaced at 10–35 cm). Machine drilling uses less seed, promotes uniform germination and stand, and usually gives higher yields. Sowing depth varies from 2–12 cm, with deeper planting required in dry conditions to reach the soil moisture. However, care must be taken not to sow too deep. When using a no-till planting machine, row-seeding can be done straight into the stubble of the previous crop. Experiments involving zero or minimum tillage and straw mulching have not led to practical application in South-East Asia. For a rainfed crop, it is recommended to plant when the soil profile is close as possible to being fully charged with moisture, but when there is least risk of monsoon rains. Seeding rate is commonly 100–150 kg/ha, resulting in 250–300 plants/m^2. The aim is to eventually obtain 400–600 spikes/m^2. It is advisable to use certified seed that has been treated with fungicides against soil- and seedborne diseases.

Husbandry Uniform crop stand and early vigour discourage weed growth. In this respect tillering allows the crop to compensate for poor stands and variable weather conditions. Tiller production depends on the formation of secondary roots, plant density, available nutrients and climatic conditions. Yield losses due to weeds are caused by early competition in the first 4–5 weeks. The more common weeds are: *Amaranthus* spp., *Cynodon dactylon* (L.) Pers., *Cyperus rotundus* L., *Digitaria* spp., *Echinochloa* spp., *Eleusine indica* (L.) Gaertner, *Eragrostis* spp., *Portulaca oleracea* L., *Trianthema portulacastrum* L., and volunteer rice. Weeds can be controlled by hand weeding, proper crop rotation, pre-seeding irrigation, machine cultivation, or application of chemical herbicides.

Irrigation has great potential to increase wheat production. It can be practised in basins, by furrow, or using overhead sprinklers. Care must be taken not to over-irrigate since wheat, unlike rice, is very sensitive to early waterlogging. When wheat is grown after rice the risk of waterlogging is considerable, since the rice fields are puddled, which decreases their ability to drain, and since rice farmers are used to applying large amounts of water. Irrigation timing is based either on pre-defined crop stages or on estimates of soil moisture depletion.

The mean nutrient removal per 1 t/ha of grain is 40–43 kg N, 5–8 kg P, 25–35 kg K, 2–4 kg S, 3–4 kg Ca, 3–3.5 kg Mg, and smaller amounts of micronutrients. The exact values depend on the available nutrients and water in the soil, the temperature, and the cultivar. For irrigated wheat in northern Thailand, 60 kg/ha of nitrogen is recommended, 30 kg/ha if rainfed. Responses to phosphorus and potassium are rare or absent in parts of Thailand and the Philippines. Organic manures and composts may be used. Boron deficiency, resulting in grain set failure, has been observed on certain soils. Soil acidity can be a constraint, as observed in wheat production at lower elevations in Indonesia. Liming might raise the pH, but its economics are unknown.

Wheat is best rotated with non-graminaceous crops, particularly with pulses.

Diseases and pests On average, diseases and pests destroy 20% or more of potential grain harvest either in the field or in storage. The major diseases caused by obligate pathogens of wheat are stem rust (*Puccinia graminis* f.sp. *tritici*) and leaf rust (*Puccinia recondita* f.sp. *tritici*). In cooler regions, stripe or yellow rust (*Puccinia striiformis*) may occur. The rusts infect the foliage and sometimes the spikes, resulting in maximum yield losses of 30–50%. The major diseases caused by non-obligate pathogens are spot blotch (*Bipolaris sorokiniana*), head scab and foot/root rot (*Fusarium* spp.), and sclerotium foot rot (*Sclerotium rolfsii*). Regionally important diseases are tan spot (*Drechslera tritici-repentis*), powdery mildew (*Erysiphe graminis*), speckled leaf blotch (*Septoria tritici*), glume blotch (*Septoria nodorum*), alternaria leaf blight (*Alternaria* spp.), loose smut (*Ustilago tritici*), rhizoctonia root rot (*Rhizoctonia* spp.), bacterial leaf streak or black chaff (*Xanthomonas campestris* pv. *undulosa*), and BYDV (barley yellow dwarf virus). The most common fungi in stored wheat are various species of *Aspergillus* and *Penicillium*.

Field pests include various aphids (which may also transmit viruses), termites, grasshoppers, planthoppers, leafhoppers, bugs, thrips, beetles, grubs, worms, maggots, miners, midgets, sawflies, nematodes (of the roots and the grain), and birds. Storage pests include the rice weevil (*Sitophilus oryzae*), the lesser grain borer (*Rhizopertha dominica*), the Angoumois grain moth (*Sitotroga cerealella*), and the khapra beetle (*Trogoderma granarium*). Rodents, mainly the black rat (*Bandicota bengalensis*), also damage stored seeds.

Suitable genetic resistance is available for most diseases. Resistances remain insufficient for spot blotch, several of the root diseases, and most pests. Given the very disease-conducive environment in South-East Asia, occasional chemical control will probably never be completely eliminated. Seed treatment is usually an economic option.

Harvesting In South-East Asia wheat is usually harvested with sickles and rarely with machines. A crop harvested at physiological maturity must be dried thoroughly before threshing. Tillers are stacked or spread out to dry in the sun. Threshing, which is more difficult with wheat than with rice, may be done by beating with flails, trampling by humans or animals, or by driving a small tractor over the straw. A wheat sheaf may also be beaten by hand against a low wall, an oil drum, or a wagon bed, so that the grains fall into a container or onto a mat. Grain losses can be considerable with these procedures. Pedal or motor-driven paddy rice threshers are also used.

Yield Commercial yields in South-East Asia vary from 200–300 kg/ha to 2.5 t/ha. Mean yield is estimated at 1 t/ha. At higher elevations (above 1200 m in Indonesia) and the more northern latitudes (northern Vietnam, northern Thailand), experimental yields may reach 3–4 t/ha. Yields tend to be rather low due to high temperature, high humidity, disease pressure, and the low levels of fertilizer applied. Mean yield throughout the developing world is 2.4 t/ha, with the world average only slightly better at 2.5 t/ha. Maximum recorded spring wheat yields are 13 t/ha.

Handling after harvest After threshing, the straw, chaff, immature grains, sand, stones and other foreign matter are separated from the grain. Laborious, time-consuming, and less than perfect hand-winnowing is the most common cleaning practice in South-East Asia. Low-cost, hand-driven or motorized blowers are becoming popular for cleaning and additional drying. Rooftops and highway pavements are also used for drying. A grain moisture content of 13–14% is considered safe for storage. High temperatures and moist conditions may result in spoilage. There are well-designed large-scale, commercial seed storage facilities in some Asian countries. On the farm, low-cost seed storage techniques such as tins, metallic drums, earthen jars, or polyethylene containers have been adopted. Bamboo and mud silos are used to store larger amounts of seed. Regular redrying may be necessary to maintain seed viability, if the seed is not stored in an airtight container. Drying in the sun is by far the most common form of insect control, as most insects will leave the grain when temperatures reach 40–44°C. Control with commercial insecticides is rare because of the costs involved and because seeds for planting and consumption are stored together. Rodents are controlled by keeping them out of the facilities.

Genetic resources The national wheat programmes in the region generally obtain a considerable part of their germplasm from the International Maize and Wheat Improvement Center (CIMMYT, Mexico) and from the International Center for Agricultural Research in the Dry Areas (ICARDA, Syria). These centres have large breeding programmes, and maintain extensive germplasm collections, including of wild relatives of wheat. Other large national collections are kept in India, the United States and Russia. National breeding programmes maintain key germplasm in storage.

Breeding Most wheat-producing countries in South-East Asia have established their own National Wheat Programme. Local crossing is rare; the national breeders request germplasm from programmes in neighbouring countries or from CIMMYT or ICARDA. Homozygous advanced lines are mostly requested, but some segregating germplasm is also used. Throughout the region, material is tested in 20–30 different locations. Emphasis is on evaluating performance under high humidity and temperature, in the presence of the major diseases (e.g. *Bipolaris* or *Fusarium*).

Prospects During 1983–1991 per capita wheat consumption in South-East Asia grew by 4.8% per year, and demand is expected to increase further. Wheat is not really a tropical crop and should be promoted as an alternative crop only in the cool, dry season, or in the highlands, preferably with irrigation. Many years of adaptive research are still needed to develop wheat that reliably produces 2–3 t/ha in farmers' fields. Progress is required in the arena of breeding and agronomic research, and also in establishing an attractive pricing and marketing structure for farmers. The crucial factor is a stable and long-term commitment from the respective national governments.

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Zea mays L.

Sp. pl.: 971 (1753).

GRAMINEAE

$2n = 20$

Vernacular names Maize, Indian corn (En). Corn (Am). Maïs (Fr). Indonesia: jagung. Malaysia: jagong. Philippines: mais. Cambodia: pôôt. Laos: khauz ph'ô:d, khauz sa:li:. Thailand: khaophot. Vietnam: ng[oo], b[aws]p.

Origin and geographic distribution Maize was first cultivated by Indian tribes some 7000 years ago and is thought to have originated in Mexico and Central America. Early civilizations of the Americas depended on maize cultivation. In the 16th Century it was introduced into South-East Asia by the Portuguese. It is still one of the most important grain crops and is geographically one of the most widely planted cereals. It is grown from latitudes up to 58°N in Canada and Russia, throughout the tropics, to latitudes of 42°S in New Zealand and the South American continent, and in areas below sea-level in the Caspian Plain and up to areas as high as 3600 m in Peru. Maize is not known from the wild.

Uses Maize kernels are used for three main purposes:

- as a staple food, particularly in the tropics;
- as feed for livestock and poultry, particularly in the industrialized countries of the temperate zones, providing over two-thirds of the total trade in feed grains;
- as a raw material for many industrial products.

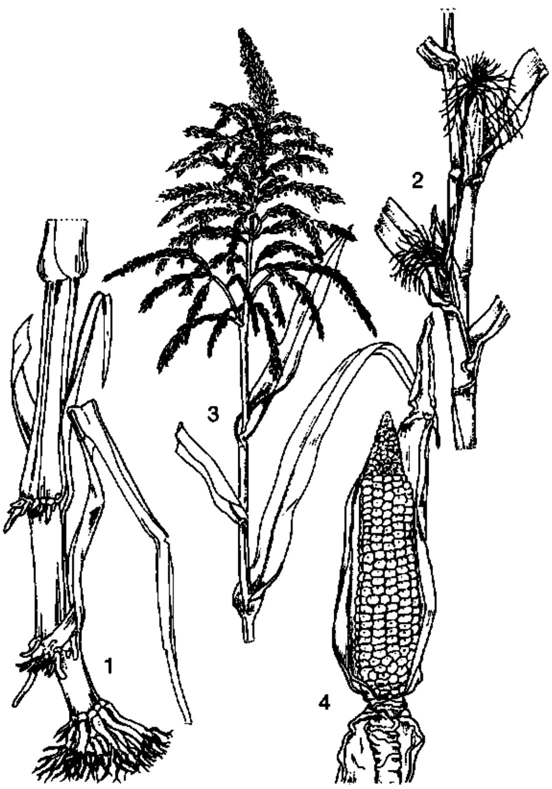
Maize grain is prepared and consumed in a multitude of ways. For human consumption it is usually ground or pounded and the meal may be boiled, roasted or fermented. The main industrial products are starch, oil, syrup, organic liquids and alcoholic beverages. Most industrial products are usually obtained by the wet-milling process, in which the grain is steeped, after which the germ and bran are separated from the endosperm. The main product is starch. Oil obtained from the germ is made into soap or glycerine, but can be refined to produce a cooking or salad oil. The residues from the production of starch or oil, together with the bran, are used in animal feeds. 100 kg of whole maize, with a 16% moisture content, yields about 64 kg pearl starch and 3 kg oil; the remainder is used as feed. The starch may be used as human food or made into sizing, laundry starch and other products. Dry milling produces grits, consisting of coarsely ground endosperm from which most of the bran and the germ have been separated.

Maize also has a great number of subsidiary uses. Mature plants are used for animal feed. Silage maize is one of the leading crops in industrialized western countries; special cultivars and production technology have been developed. Crop residues such as the stalks are used for fuel or compost. The inner husks of the ear and the fibre in the stems have been used for making paper. Unripe ears can be consumed as a vegetable (baby corn, boiled or roasted corn).

Production and international trade Present world production (1993) is about 470 million t grain from about 127 million ha. The major producing countries are the United States with an annual production of 161 million t, China, the second largest producer (103 million t), Brazil (30 million t), Mexico (19 million t), and France (15 million t). The main producing countries in South-East Asia are Indonesia with an annual production of 6.6 million t, the Philippines (5.4 million t) and Thailand (3.8 million t). Only a small proportion of the total production enters world trade. The United States is the principal exporter, followed by France, China, Argentina, South Africa and Thailand. Other countries exporting small amounts include Indonesia. The largest importers of maize are Japan and the former Soviet Union. In Indonesia and the Philippines maize is mainly grown as a subsistence crop; between 60–75% of the production is consumed directly by the farm households, the remainder is processed by animal-feed mills and maize-oil factories. Maize is less profitable per ha than some other food crops and has a negative income elasticity (decreasing demand with rising income). Cultivation of maize remains popular in areas where limited water availability or relatively low temperatures do not permit rice production, as in parts of China, western Pakistan, northern India, the Philippines, Laos, Cambodia, Vietnam and Indonesia. In South-East Asia, it is mainly grown by smallholders.

Properties The average composition per 100 g edible portion is approximately: water 10 g, protein 10 g, fat 4.5 g, carbohydrates 70 g, fibre 2 g, ash 2 g. The energy value averages 1525 kJ/100 g. The protein content varies from 6–15%, of which zein predominates. Maize is deficient in tryptophane and lysine, but cultivars with higher lysine and tryptophane content have been bred, using the recessive gene Opaque-2. The starch of the endosperm usually consists of a mixture of about three-quarters amylopectin and one-quarter amylose. The endosperm, which accounts for 80% of the weight of the kernel, is poor in phosphorus and calcium and contains most of the starch and two-thirds of the protein. More than 80% of the fat and most minerals are in the embryo or germ, which constitutes about 12% of the kernel. Yellow maize contains some provitamin A due to cryptoxanthin. Most vitamins are found in the outer layers of the endosperm and in the aleurone layer. Maize is unsuitable for making leavened bread as it lacks gluten. The 1000-kernel weight is usually 250–300 g.

Description A robust, monoecious, annual grass, 1–4 m tall. Root system consisting of adventitious roots, developing from the lower nodes of the stem below and often also just above the soil surface, usually limited to the upper 75 cm of the soil, but single roots sometimes penetrating to a depth of 200 cm and more. Stem usually simple and 1.7–3 m tall, solid, with clearly defined (8–)14(–21) nodes and internodes. Leaves 8–21, borne alternately on either side of the stem at the nodes, with overlapping sheaths, auricled above, and linear-lanceolate blades, 30–150 cm × 5–15 cm, acuminate, with pronounced midrib; ligule about 5 mm long, colourless. Male and female inflorescences separate on the same plant; male inflorescence ('tassel') a terminal panicle, up to 40 cm long, axis bearing a variable number of lateral branches, with paired spikelets, one sessile and the other with short pedicels, 8–13 mm long, each with 2 glumes and 2 florets, consisting of an ovate lemma, a thin palea, 2 fleshy lodicules, and 3 stamens; female inflorescence ('ear') a modified spike, usually 1–3 per plant, developed in the axil of one of the largest leaves, about half way up the stem, enclosed by 8–13 modified leaves ('husks'), with paired, sessile spikelets, each with 2 glumes enclosing 2 florets, the lower of which is sterile, consisting solely of a short lemma and palea, and the



Zea mays L. – 1, basal plant part; 2, central plant part with female inflorescences; 3, upper plant part with male inflorescence; 4, ripe infructescence.

upper pistillate, with a short, broad lemma and palea, no lodicules, and a single basal ovary and a long threadlike style and stigma ('silk'), which grows up to 45 cm in length and emerges from the top of the inflorescence, and is receptive throughout most of its length. Mature infructescence ('ear' or 'cob') enclosed by husks, 8–42 cm × 3–7.5 cm. Grains or 'kernels' (caryopsis) 30–1000 per ear, usually obovate and wedge-shaped, variously coloured from white, through yellow, red and purple to almost black.

Growth and development The coleoptile emerges from the soil usually 4–6 days after planting. The plant may sometimes have a few basal branches ('tillers') that are of value in low density stands. At a later stage some whorls of aerial roots ('brace roots') may develop from the lower nodes above the ground which partly help to anchor the plant firmly, while also contributing to the uptake of water and nutrients. Flower initiation is generally 20–30 days after germination. With a four-month cultivar the tassel emerges 50–60 days after planting and the silk appears about a week later. Compared with rice and other cereals, maize has a long post-floral period of 7–8 weeks. The period from planting to harvesting varies considerably. It may be as short as 70 days in some very early cultivars and as long as 200 days in some very late cultivars. Climatic conditions, latitude and altitude influence growth duration.

Other botanical information *Z. mays* is a highly variable, cross-pollinating, markedly heterogeneous, complex species, in which all forms hybridize freely. The cultivars can be divided into groups according to the structure and shape of the grain. The following cultivar groups are distinguished:

- cv. group Dent Corn or Dent Maize (synonyms: *Z. mays* L. convar. *dentiformis* Koern., *Z. indentata* Sturt., *Z. mays* L. var. *indentata* (Sturt.) Bailey). The sides of the grain have corneous endosperm, but soft white starch, extending to the apex, shrinks on drying to produce the characteristic dent. The wedge-shaped grains are usually yellow or white. It is the principal maize of the Corn Belt of the United States and northern Mexico.
- cv. group Flint Corn or Flint Maize (synonyms: *Z. mays* L. convar. *mays* or group *vulgaris* Koern., *Z. indurata* Sturt., *Z. mays* L. var. *indurata* (Sturt.) Bailey). The grain can be coloured variously and consists mainly of hard endosperm with a little soft starch in the centre; it has rounded ends and is smaller than dent maize; it matures earlier, is hardier, and when dried it is more resistant to insect attack. It is the predominant type grown in Europe, Asia, Central and South America and parts of tropical Africa.
- cv. group Pod Corn or Pod Maize (synonym: *Z. tunicata* Sturt.). This is the most primitive form of maize in which the grain is enclosed in floral bracts. It is not grown commercially but is preserved by some Indians who believe it to have magical properties. The earliest domesticated maizes were pod corns.
- cv. group Pop Corn or Pop Maize (synonym: *Z. mays* L. convar. *microsperma* Koern., *Z. everta* Sturt., *Z. mays* L. var. *everta* (Sturt.) Bailey). Popcorn has small grains with a high proportion of very hard corneous endosperm and a little soft starch in the centre; on heating the steam generated inside the grain causes it to pop and explode, the endosperm becoming everted about the embryo and hull to produce a palatable

white fluffy mass. In rice popcorn cultivars the grains are pointed and tend to be imbricated; in pearl popcorn cultivars the grains are rounded and very compact. Popcorn is most important in the United States and Mexico.

- cv. group Soft Corn or Soft Maize, Flour Corn or Flour Maize (synonyms: *Z. amylacea* Sturt., *Z. mays* L. var. *amylacea* (Sturt.) Bailey, *Z. mays* L. convar. *amylacea* (Sturt.) Grebensc.). The grain can have all colours, it usually has no dent and the endosperm consists of soft starch. When parched it can be chewed more easily than flint corn and it is also easier to grind. It is one of the oldest maize forms and was widely grown in the drier parts of the United States, western South America and South Africa.
- cv. group Sweet Corn or Sweet Maize (synonyms: *Z. mays* L. convar. *saccharata* Koern., *Z. mays* L. var. *rugosa* Bonaf., *Z. saccharata* Sturt.). The grain contains a glossy endosperm with little starch, giving a wrinkled appearance after drying. The grain is usually eaten as a fresh vegetable; it is mostly grown in the United States, but becoming popular in South-East Asia.
- cv. group Waxy Corn or Waxy Maize (synonyms: *Z. mays* L. convar. *ceratina* Kuleshov, *Z. mays* L. subsp. *ceratina* (Kuleshov) Zhuk.). The starch is composed entirely of amylopectin and is used for the manufacture of adhesives. It is mainly grown in eastern Asia.

A compact filling gives the endosperm a horny, transparent appearance and improves the storability of the grain; a less compact filling gives the kernel a chalky, meal-like appearance.

A great many cultivars belonging to the various grain types are grown in different parts of the world. The important aspects influencing tropical smallholders in choosing cultivars are growth duration, taste and cooking quality, yield stability and production, storability and suitability for intercropping.

Ecology With its large number of cultivars differing in period to maturity, maize has a wide range of tolerance of temperature conditions. It is characterized by the C4-cycle photosynthetic pathway. It is essentially a crop of warm regions where moisture is adequate. The bulk of the crop is grown in tropical and subtropical regions. It is less suited to semi-arid or equatorial climates. It is predominantly grown in areas with isotherms of 21–30°C at tasseling. The minimum temperature for germination is 10°C. The crop requires an average daily temperature of at least 20°C for adequate growth and development. The time of flowering is influenced by photoperiod and temperature. Maize is considered to be a quantitative short-day plant. It is grown mainly from 50°N to 40°S and from sea-level up to about 3000 m altitude at the equator. At higher latitudes, up to 58°N, it can be grown for silage. Maize is specially sensitive to moisture stress around the time of tasseling and fertilization. It also needs optimum moisture conditions at the time of planting. In the tropics it does best with 600–900 mm of rain during the growing season. The shoot/root ratio is fairly high, rendering maize sensitive to drought.

Maize can be grown on a wide variety of soils, but performs best on well-drained, well-aerated, deep soils containing adequate organic matter and well supplied with available nutrients. The high yield of maize is a heavy drain on soil nutrients. Maize is often used as a pioneer crop, because of the high physical and chemical demands it makes of the soil. Maize can be grown on soils with a pH from 5–8, but 5.5–7 is optimal. It belongs to the group of crops that is considered to be sensitive to salinity. Since a young crop leaves much of the ground uncovered, soil erosion and water losses can be severe and attention should be paid to adequate soil and water conservation measures.

Propagation and planting Maize is nearly always planted through direct seeding. In China and Vietnam, however, a transplanting technique has been adopted. Maize should preferably be sown early in the season, as soon as soil conditions and temperature are favourable. Seed may be planted mechanically, but in smallholder cultivation it is usually sown by hand. This requires 5–10 man-days/ha. Seed is dropped in the plough furrow or in holes made with a planting stick. Planting may be done on hills or in rows, on flat land or on ridges. On heavy soils ridging is advisable, to improve drainage. Distance between the rows varies from 60–100 cm; crop density depends on soil conditions, rainfall, method of irrigation, cultivar and cropping system. Wide spacing results in more weed growth and increases the occurrence of erosion. A uniform crop stand is very important, as the tillering capacity of maize is limited. Average plant density varies from 20 000–80 000 plants/ha. An average seed rate of 10–25 kg/ha is fairly common; in Indonesia higher rates are not unusual to ensure reasonable plant stands at harvest time. The depth of planting is commonly 3–6 cm, depending on soil conditions and temperature. Deep sowing is recommended on light, dry soils. On smallholdings the land is usually cultivated by

hand or by animal traction. The usual depth of ploughing is about 8–10 cm. In Indonesia ploughing is done just before or at planting time. Sometimes animal manure or fertilizers are applied at the time of planting.
Maize cropping in South-East Asia is mainly carried out within the following three cropping systems: (a) permanent upland cultivation, (b) wetrice system, and (c) shifting cultivation. Rotations or intercropping with other rainfed crops include soya bean, groundnut, other pulses, cassava, sweet potato, vegetables, tobacco and cotton. Maize is suitable for off-season cropping in rice fields, provided moisture and drainage are adequate.

Husbandry Adequate weed control is very important. Maize is very sensitive to weed competition during the first 4–6 weeks after emergence. It should be planted as soon as possible after the preparation of the seed-bed. Interrow cultivation to control weeds and to break up a crusted soil surface may be done until the plants reach a height of about 1 m. Weeding by hand requires a minimum of 25 man-days/ha. Chemical weed control is gradually gaining importance, because hand weeding is time-consuming and is usually carried out rather late in the growing season. The herbicide most widely used for post-emergence spraying is 2,4-D. Ridging or earthing-up is sometimes practised. Irrigation is used in areas of low rainfall and is particularly valuable at the time of tasseling and fertilization.
Maize usually responds well to fertilizers, provided other growth factors are adequate. The quantity of manure applied by smallholders is usually very limited. Improved cultivars can only reach their high yield potential when supplied with sufficient nutrients. A maize crop of 2 t/ha grain and 5 t/ha stover removes about 60 kg N, 10 kg P and 70 kg K from the soil. Nitrogen uptake is slow during the first month after planting, but increases to a maximum during ear formation and tasseling. Maize has a high demand for nitrogen, which is often the limiting nutrient. High nitrogen levels should be applied in 3 doses, the first at planting, the second when the crop is about 50 cm tall, and the third at silking. Phosphate is not taken up easily by maize and, moreover, many tropical soils are deficient in available phosphate. It is advisable to apply organic manures to improve soil structure and supply nutrients, all before ploughing.

Diseases and pests Downy mildew (*Sclerospora* spp.) is the most serious disease of maize in South-East Asia. Severe losses are recorded annually in India, Indonesia, the Philippines and Thailand. Maize is most susceptible during the first 2 weeks after planting. Several cultural practices reduce the severity of downy mildew either by eliminating the pathogens from a particular area, reducing primary inoculum, or by stimulating early plant growth. Ridomil is an effective fungicide now widely used against downy mildew. Commercial cultivars (open-pollinated or hybrid) released in South-East Asia usually have some resistance. Other diseases are leaf blight (*Helminthosporium turcicum* and *H. maydis*), rust (*Puccinia* spp.), stalk and ear rots caused by various pathogens, and maize smut (*Ustilago maydis*). Stem borers, corn-ear worms and army worms are among the most serious pests. The principal pests of stored maize are Angoumois grain moth (*Sitotroga cerealella*), grain weevils (*Oryzaephilus surinamensis*, *Sitophilus oryzae*) and rodents.
The semi-parasitic weed striga (*Striga* spp.), a serious problem in maize in Africa, is not of great importance in South-East Asia.

Harvesting Maize is usually harvested by hand. Mechanical harvesting is practised on large farms in Thailand and parts of the Philippines. The stage of maturity can be recognized by yellowing of the leaves, yellow dry papery husks, and hard grains with a glossy surface. In the dry season maize is often left in the field until the moisture content of the grain has fallen to 15–20%. In hand harvesting the ears should be broken off with as little attached stalk as possible. They may be harvested with the husks still attached. These may be turned back and the ears tied together and hung up to dry.

Yield Maize yields vary greatly, from about 1 t/ha for smallholders up to about 9 t/ha. Average yields of maize in t/ha are as follows (1993): United States 6.3, Europe 4.7, Africa 1.7, South America 2.7, Indonesia 2.2, the Philippines 1.7 and Thailand 3.2.

Handling after harvest The major problems in most maize-producing areas are reducing the moisture content of the grain to 12–15%, protection from insects and rodents, and proper storage after harvest. A high moisture content with high temperatures can cause considerable damage, making the product unsuitable for human consumption. Maize for home consumption is either sun-dried on the cob for several days by hanging up tied husks, or put in a well-ventilated store or crib. Shelling (the removal of grains from the cob) is usually carried out by hand, though several hand and pedal-powered mechanical shellers are now available. The average recovery is about 75%. The shelled grain is dried again for a few days and then stored in bags, tins or baskets. The optimum moisture content for storage is 12–13%, but often it is not below 18%. In Indonesia seed for the next crop is generally selected from the last harvest. The selected ears are stored at home in the husk above the fireplace to prevent losses by insects. Crop residues are removed from the field and then used as fodder, fuel, etc.

Genetic resources International institutes such as CIMMYT (International Maize and Wheat Improvement Center, Mexico) and IITA (International Institute of Tropical Agriculture, Nigeria) play a major role as conservators and suppliers of germplasm. Both institutes frequently cooperate with national breeding programmes. Many tropical countries maintain their own germplasm collections.

Breeding Maize is a cross-pollinated crop with many cultivars, most of which are adapted to or bred for particular geographical areas. Many tropical countries have their own breeding programmes producing cultivars for their special needs, e.g. human nutrition, silage, or industrial processing. The extinct wild maize and the first domesticates in Mexico and Central America were pod corns and popcorns with very small ears. Maize evolved into a highly productive crop in a comparatively short time. Greatly increased yields became attainable through the discovery and development of hybrid maize in the early part of the 20th Century, created by crossing two or more inbred lines. Attempts to improve yield of open-pollinated maize resulted in the production of synthetic (mixture of inbred lines) and composite (mixture of improved selections) cultivars. These are usually superior to local, open-pollinated cultivars, but not as productive as the best single- and double-cross cultivars adapted to a particular environment. Hybrid seed is commonly used in high-input farming with high fertilizer use and adequate facilities for seed production. In low-input farming composite or synthetic cultivars may be preferable, as they permit seed to be kept from one crop to the next. The wider genetic base of these cultivars provides a better adjustment to variable growing conditions. The use of hybrid seed under such conditions would be hampered by problems such as the production and distribution of high-quality seed by government agencies or commercial seed firms, and the need for higher inputs. In the meantime the use of composites or synthetics, which are better adapted to the smallholder's needs, could be an improvement over the existing maize cultivars. It is estimated that 45% of the maize area in South-East Asia is still planted with local unimproved cultivars, 45% with improved open-pollinated cultivars and only 10% with hybrids. In maize breeding attention is paid to grain yield, duration of growth, resistance to diseases and pests, response to nitrogen, tolerance of heat and drought, tolerance of acid soils, resistance to lodging, ear characteristics and protein content.

Prospects The potential yield of maize is higher than that of rice or wheat. It may be expected that maize will assume a proportionally larger and more important role in world food production. Maize will remain an important cereal in South-East Asia because:
- it gives the highest yield per man-hour of invested labour;
- the husks provide protection against birds and rain;
- it is easy to harvest and to store and it does not shatter;
- it can be harvested over a long period (first the immature ears, a few weeks later the mature ones);
- it can tolerate a wide range of temperatures; and
- the demand for maize as food and feed is increasing.

Yields can be improved considerably. Low yields are due to a combination of the following factors:
- maize is mainly cultivated as a rainfed crop;
- farmers have been slow to adopt available improved cultivars and advanced cropping techniques;
- there is a shortage of high quality seed;
- maize cropping is much less profitable than certain other food crops.

These aspects are closely related to marketing, prices, transport facilities, drying, storage, processing and usage. Often there is no efficient agency for the distribution of seed. Farmers need to have access to improved seed, fertilizers, crop protection chemicals and other inputs. Cultivars and cropping techniques that fit well into the prevailing cropping systems should be developed. The improved cultivars available today are not always suitable for local mixed intercropping systems. Therefore research should be more closely geared to farmers' needs.

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3 Minor cereals

Brachiaria ramosa (L.) Stapf

GRAMINEAE

Synonyms *Panicum ramosum* L., *P. supervacuum* C.B. Clarke, *Urochloa ramosa* (L.) Nguyen.

Vernacular names Browntop millet, pedda sama, anda korra (En). Indonesia: rebha pereng-perengan (Madurese), au kawunga (Sumba). Vietnam: v[ix] th[ar]o nh[as]nh.

Distribution Tropics of the Old World, including most parts of South-East Asia; occasionally grown elsewhere (e.g. in the United States).

Uses Where it is grown as a cereal, the flour made from the grain is usually mixed with flour from finger millet. The grass is well liked by stock both fresh and as hay, and the grains are also used as bird feed.

Observations Loosely tufted annual, up to 70 cm tall, erect or geniculate, sometimes rooting at the lower nodes, glabrous to puberulent. Leaf blade linear, 3–15 cm × 3–10 mm. Inflorescence a 4–16 cm long panicle with 3–8 spike-like racemes up to 5 cm long, bearing distant obovoid spikelets 3–4 mm long, usually paired on unequal pedicels; spikelet with sterile or staminate lower floret and bisexual upper floret. *B. ramosa* grows as a weed in shallow soil on rock outcrops, on roadsides, on light or heavy soils, in thin forest, up to 200 m altitude.

In India (parts of Madras and Mysore), it is grown as a cereal and considered superior to *Panicum sumatrense* Roth ex Roemer & Schultes. Cultivated browntop millet has larger inflorescences than its weedy relatives and has lost the ability of natural seed dispersal. Types with different degrees of spikelet disarticulation commonly occur in the same field. It often occurs as an encouraged weed in fields of finger and foxtail millet. The All India Coordinated Minor Millets Programme in Bangalore maintains 50 accessions of browntop millet. The closely related species, *B. deflexa* (Schumach.) C.E. Hubbard ex Robijns (animal fonio or Guinea millet), occurring wild from Senegal to Yemen, Pakistan and India and southwards to southern Africa, is cultivated as a cereal in the Futa Jalon highlands of Guinea and Senegal and is sometimes considered as a variety or cultivar of *B. ramosa*.

Selected sources 1, 7, 8, 20, 23, 26, 27, 28, 30, 34.

Cyanotis axillaris (L.) Sweet

COMMELINACEAE

Synonyms *Commelina axillaris* L., *Tradescantia axillaris* L., *Amischophacelus axillaris* (L.) Rolla Rao & Kammathy.

Vernacular names Baghanulla (En, India). Philippines: alikbangon (Tagalog), sabilau (Bisaya). Thailand: phakplap-na (Bangkok), yaphophot-lek (Prachin Buri), kinkungluang (Chiang Mai).

Distribution From India and Sri Lanka to China, and throughout South-East Asia to Australia.

Uses In times of famine, seed can be eaten like a cereal. The whole plant is a good forage and medicinally it is applied externally against ascites.

Observations Subsucculent creeping or ascending perennial herb, up to 70 cm long, rooting at the nodes. Leaves oblong to lanceolate, 2–15 cm × 4–12 mm with amplexicaul sheath. Flowers 2–6, in sessile, axillary fascicles, mostly covered by a floral leaf sheath, regular, bisexual, 3-merous, blue-purple, with 6 stamens. Fruit a capsule, 6–7 mm long, loculicidal, 3-valved. Seed brown with numerous pits and a small apical, conical point. *C. axillaris* is a common, slowly growing weed in clearings, open sites along streams, rice fields, damp meadows, up to 250 m altitude. In Java, it flowers from July to December. The flowers open only once for a few hours. On a dry weight basis the seed contains approximately 60% starch and 15% protein. It is laborious to collect sufficient seed for a meal, but the food is considered very nutritious.

Selected sources 1, 3, 4, 35.

Digitaria cruciata (Nees ex Steudel) A. Camus

GRAMINEAE

Synonyms *Panicum cruciatum* Nees ex Steudel, *Paspalum sanguinale* Lamk var. *cruciatum* J.D. Hooker.

Vernacular names Raishan (En, India). Vietnam: t[us] ch[if]nh ch[es]o.

Distribution Himalaya region, Khasi Hills in Assam (India), southern China and northern Vietnam (possibly also in northern Burma (Myanmar)). Cultivated on a small scale in the Khasi Hills.

Uses The grain is eaten as a cereal and its glutinous flour is used to make bread or porridge. It is sometimes mixed with rice or other cereals. Fresh and dried wild plants and the straw of the cultivated types are an important all-season forage, much relished by cattle.

Observations Annual grass with prostrate to decumbent, branched culms rooting at the nodes, up to 130 cm long but usually much shorter. Leaf blade linear, up to 21 cm × 1 cm, scabrid, glabrous to hairy. Inflorescence consisting of 2–10 racemes arranged paired or subwhorled on a central axis 1–4 cm long; racemes up to 18 cm long, reflexed at maturity; spikelet ellipsoidal, about 3 mm × 1 mm, pale or purplish pale, consisting of two florets, the lower one sterile and the upper one bisexual. Caryopsis tightly enclosed by the chartaceous lemma and palea. The wild form (var. *cruciata*) is common and widespread throughout the mountain area in open sites between 2000–3000 m altitude. The cultivated form (var. *esculenta* Bor, preferably classified as cv. group Esculenta) has much longer racemes and the grain does not shatter easily; it is only cultivated in the Khasi Hills of Assam (in 1952 about 40 ha). It is intercropped with maize or vegetables or as a secondary crop following Irish potato. It has a growth cycle of about 4 months. About 1 month before harvesting the culms are tied together. At harvest the grains are rubbed off by hand, dried and stored. Grain yield is about 800 kg/ha. To prepare the grain for food the amount required is dried over a fire, pounded in a mortar and winnowed.
D. compacta Veldkamp, which has similar uses, also occurs in the same area.

Selected sources 2, 3, 6, 14, 16, 20, 25, 32, 34, 36.

Digitaria exilis (Kippist) Stapf

GRAMINEAE

Synonyms *Paspalum exile* Kippist, *Syntherisma exilis* (Kippist) Newbold.

Vernacular names Fonio (millet), fundi, hungry rice (En). Fonio (Fr).

Distribution Fonio millet is only known from cultivation and is grown throughout West Africa from upper Senegal to Lake Chad, decreasing in importance as a cereal from west to east; it is a staple crop in parts of Guinea and Nigeria. It is one of the oldest known cereals of Africa (known from 5000 BC) and has its greatest diversity in the upper basin of the river Niger.

Uses The very small grains have an attractive flavour and are used to make porridge or, ground to flour, often mixed with the meal of other cereals to make bread and other baked food. It is also used for brewing beer. The straw is used as forage.

Observations Erect, free-tillering annual grass, about 45 cm tall. Leaves linear to lanceolate, glabrous, up to 15 cm long. Inflorescence a terminal digitate panicle of 2–4 slender sessile racemes, up to 15 cm long; spikelet long ellipsoid, 2 mm long, acute, glabrous, pale green, with a sterile lower floret and a bisexual fertile upper one. Caryopsis very small, usually yellow, about 2000 per g. It can grow on poor, shallow soils, in areas with more than 400 mm average annual rainfall. Based on inflorescence morphology 5 cultivar groups can be distinguished (Densa, Gracilis, Mixta, Rustica and Stricta). Cultivars also differ in growing period, which varies from 3–4 months. The crop is usually grown solely, sometimes mixed with sorghum or pearl millet. Weeding is seldom necessary as the crop is grown very densely. Birds cause serious losses. The crop is harvested manually with a sickle; the cut plants are tied into sheaves, dried and stored. Threshing is by trampling or beating and hulling is done in a mortar. Average yield varies with cultivar and environmental conditions from (150–)600–800(–over 1000) kg/ha. Per 100 g edible portion the grain contains approximately: water 6 g, protein 8.7 g, fat 1.1 g, carbohydrates 81 g, fibre 1.1 g and ash 2.1 g. Germplasm collections of *Digitaria* species are available in Australia (CSIRO), Ethiopia (ILCA), Colombia (CIAT) and France (ORSTOM). So far *D. exilis* has been largely neglected in scientific research and breeding programmes. *D. longiflora* (Retzius) Persoon, widely distributed in the tropics and subtropics of the Old World, including South-East Asia, used to be considered as the possible ancestor of *D. exilis*, but this view has been abandoned. The grain of *D. longiflora*, however, is sometimes used as a famine food; it is a pioneer on moist sandy to rocky soils. *D. iburua* Stapf greatly resembles *D. exilis* and is cultivated as a cereal in the Haussa region of northern Nigeria and in the Atakora mountains in Togo and Benin. It is called black fonio because of its dark brown spikelets, but its grain is white.

Selected sources 6, 13, 14, 16, 20, 24, 26, 27, 28, 34, 36.

Eragrostis tef (Zuccagni) Trotter

GRAMINEAE

Synonyms *Poa tef* Zuccagni, *Poa abyssinica* Jacq., *Eragrostis abyssinica* (Jacq.) Link.

Vernacular names Teff (En).

Distribution Teff is native to Ethiopia, where it is the most important cultivated cereal. It has been introduced into other parts of the world, mainly as an important forage grass (e.g. in southern Africa, India and Australia).

Uses In Ethiopia, the grains are ground to flour and primarily used to make a kind of large, sour-tasting pancake (injera), which with a spicy sauce (wot) forms the basic diet. The grains are also used to make porridge, unleavened bread, cake and beer. The grass, including its hay and straw, is an excellent forage. The straw, mixed with clay, is also used to construct houses, stoves and granaries.

Observations Annual, tufted grass, 60–120 cm tall with erect, slender, glabrous culms. Leaf blade linear, 25–45 cm × 0.1–0.4 cm. Inflorescence a loose open panicle, 15–35 cm long; branches very slender, long, drooping, alternate; spikelet usually 5-flowered, small, about 8 mm long. Caryopsis extremely small, 1–1.5 mm × 0.75–1 mm, white or reddish brown, 2500–3000 per g. Ethiopia is the only country in the world that grows teff as a cereal crop which is also preferred above all other grains. Teff is cultivated at altitudes of (1300–)1900–2100(–2800) m with average growing temperatures of 25–28°C, and average annual rainfall of 400–2500 mm. Teff has a C4-cycle photosynthetic pathway. Heavy loams are preferred, but soils should have good permeability and not be subject to surface crusting which kills off delicate young plants. To prevent the tiny grains being washed away, shallow trenches are dug 3–6 m apart before sowing to ensure quick drainage of water. Young plants display some tolerance of waterlogging. The advanced crop is tolerant of drought. Teff is little affected by diseases and pests. The growth period varies from 2–4 months. Yield ranges from 300–3000 kg/ha, averaging 800 kg/ha. Per 100 g edible portion the grain contains approximately: water 11.2%, protein 9.1%, fat 2.2%, carbohydrates 74.3%; it is rich in Fe and Ca. The grain can be stored for many years in traditional store houses without being damaged by insects. There are many cultivars, and the white-grained ones are preferred; in Ethiopia 2225 germplasm accessions are available. *E. pilosa* (L.) P. Beauvois is considered to be the possible ancestor of teff and is widespread in the tropical and warm temperate areas of the Old World, including South-East Asia where it is used as a forage. As a famine crop and as an extremely palatable forage, teff might be of interest for the cooler parts of South-East Asia.

Selected sources 3, 12, 17, 20, 21, 27, 29, 34.

Hygroryza aristata (Retzius) Nees ex Wight & Arnott

GRAMINEAE

Synonyms *Leersia aristata* (Retzius) Roxb., *Pharus aristatus* Retzius, *Zizania aristata* (Retzius) Kunth.

Vernacular names Bengal wild rice (En). Thailand: puchaoloitha, ya-phonglom. Vietnam: thia thia.

Distribution From India to Indo-China, including Burma (Myanmar) and Thailand. In Assam (India) sometimes cultivated in rivers for forage use.

Uses The grain is eaten in times of scarcity. The whole plant constitutes a good forage, and cattle and buffalo are fond of it.

Observations Glabrous perennial aquatic grass, floating and forming dense mats in quiet water, or creeping on wet ground. Stem up to 1.5 m long, spongy, diffusely branched, rooting at the nodes. Leaf sheath inflated; leaf blade elliptical, 3–6 cm × 5–17 mm. Inflorescence a panicle with 4–5 major branches whorled at the top of the peduncle; spikelet one-flowered on pedicel up to 2 mm long; glumes absent; lemma coriaceous, 5-veined, long-awned, palea 3-veined, stamens 6. Caryopsis subcylindrical, 2–3 mm long, with long linear hilum. *H. aristata* is found in shallow (up to 60 cm deep) water of permanent or semi-permanent lakes, ponds, swamps, canals and slow-moving streams, up to 350 m altitude. In the dry season the plant survives in muddy areas. Sometimes a troublesome weed in navigation and irrigation canals. The grains are sweet and oleaginous. They are said to be cooling and useful in biliousness.

Selected sources 3, 7, 19, 20, 33, 35.

Panicum sumatrense Roth ex Roemer & Schultes

GRAMINEAE

Synonyms *Panicum miliare* auct., non Lamk, *P. attenuatum* Willd., *P. psilopodium* Trin.

Vernacular names Sama, little millet, Indian millet (En). Vietnam: k[ee] sumatra.

Distribution *P. sumatrense* occurs wild and as a weed in Pakistan, India, Sri Lanka, Nepal, Burma (Myanmar), Thailand, China, the Philippines and Indonesia. In India, Sri Lanka, Pakistan, Nepal and Burma (Myanmar) it is also cultivated as a cereal and is particularly important in the Eastern Ghats of India.

Uses The grain is cooked and eaten like rice, or ground to flour to make bread. The whole plant and the straw are also used as forage.

Observations Erect to decumbent, annual grass, up to 2 m tall. Decumbent plants root at the lower nodes, stem strongly branched, producing up to 46 erect branched flowering culms; erect plants rarely root from the lower nodes, stem producing up to 26 flowering culms. Leaf blade linear-lanceolate, up to 56 cm × 21 mm, glabrous to sparsely hirsute. Inflorescence an open to compact panicle up to 50 cm long, with 14–52 branches; spikelet lanceolate, up to 2.5 mm long, glabrous. Caryopsis shiny white to almost black, the grain tightly enclosed by the lemma and palea. The complex species *P. sumatrense* is very variable, and wild and cultivated forms have been classified as subspecies (wild: subsp. *psilopodium* (Trin.) de Wet; cultivated: subsp. *sumatrense* [sensu de Wet]), but it is proposed here to classify the cultivated forms as cultivar group Sama. Both forms cross freely and form fully fertile hybrids. The cultivated forms have lost the ability of natural seed dispersal and are usually more robust than the wild ones. They are thought to have been domesticated from the wild form which is an agressive colonizer of cultivated fields. Two cultivar subgroups have been distinguished: Nana (synonym: race Nana), comprising the most common cultivars with decumbent stems and erect open inflorescences, and Robusta (synonym: race Robusta), mainly restricted to the Eastern Ghats of India, comprising cultivars with erect stems and compact inflorescences becoming curved when mature. In the Eastern Ghats, sama is cultivated between 300–1000 m altitude, where average annual rainfall is 950–1200 mm. The growth cycle varies from 2.5–5 months. It produces a crop even on very poor soils and is usually sown together with a major cereal. It is harvested manually with sickles, then threshed by trampling with cattle, and the grains are removed by pounding. Yield is 200–600 kg/ha, increasing to 900 kg/ha in a good season.

Selected sources 3, 5, 7, 10, 12, 19, 20, 27, 34, 35.

Sorghum propinquum (Kunth) Hitchc.

GRAMINEAE

Synonyms *Andropogon propinquum* Kunth, *Sorghum affine* (J.S. Presl) Camus, *S. halepense* (L.) Pers. var. *propinquum* (Kunth) Ohwi.

Vernacular names Wild sorghum (En). Indonesia: glagah rayung (Javanese), kano-kano (Ternate), berang (Minahasa). Malaysia: tebu tikus. Thailand: ya-pong. Vietnam: m[is]a mi[ees]n.

Distribution From southern India and Sri Lanka throughout South-East Asia and southern China.

Uses The grain is used as famine food and the whole plant as a forage. It is cultivated as a forage in Taiwan.

Observations Perennial grass with a few stout rhizomes. Stem 2–3 m tall, erect. Leaf blade 30–100 cm × 1–5 cm. Inflorescence a loose panicle, 20–60 cm long, with racemes composed of 2–6 spikelet pairs (one sessile, one pedicelled) borne on the primary branches; pedicelled spikelet staminate or sterile; sessile spikelet 2-flowered but only upper floret perfect, deciduous when mature. Caryopsis obovoid, very small. *S. propinquum* is found on river banks, roadsides, open hill slopes in grassland and forest, up to 1000 m altitude. It is a wild diploid South-East Asian species which is thought to have contributed to the development of the grain sorghum cultivars. Its taxonomic status however, is still under discussion, as is the whole *Sorghum* taxonomy. *S. nitidum* (Vahl) Pers. may have similar uses. It is also a wild perennial diploid with a similar distribution but without rhizomes and its stem is bearded at the nodes.

Selected sources 3, 4, 7, 19, 20, 27, 34.

Zizania palustris L.

GRAMINEAE

Vernacular names American wild rice, Indian rice, manomin (En). Folle avoine (Fr).

Distribution Widely distributed in south-eastern Canada and north-eastern United States; the grains were collected as a wild cereal along the shores of the Great Lakes long before recorded history. Trials to domesticate *Z. palustris* have been in progress since the 1950s and hence its cultivation is increasing, including outside its area of natural distribution.

Uses The grains are cooked and eaten as rice. They have a high protein and carbohydrate content, are low in fat, have a good taste, and are considered to be a gourmet food. The wild populations constitute an excellent fodder, especially for birds (e.g. water fowl).

Observations Annual aquatic grass, 60–70 (–160) cm tall, with shallow root system consisting of straight, spongy roots bearing few root hairs. Stem strongly tillering (up to 50 tillers per plant). Leaf blade linear, 6–32 mm wide; mature plants usually bear 5–6 leaves above the water. Inflorescence a slender much-branched panicle; top portion of the panicle bearing erect female spikelets, the lower branches bearing pendulous male spikelets; the lemma of the female spikelet bears a long awn; cross pollination is common. Caryopsis cylindrical, 8–16 mm × 1.5–4.5 mm; the dark brown to purple-black grain is tightly enclosed by the palea and lemma. The crop can be grown similarly to water-grown rice, but is adapted to deeper and cooler water. The grains have a dormancy period of at least 3 months and should be stored in water of 3°C to keep their viability. Yield ranges from 480–1250 kg/ha. Once harvested the grains are left in the open air to ferment for 4–7 days. The fermented grain is put in an oven for about 2 hours at a temperature of over 125°C. Moisture is reduced to less than 10%, the kernel shrinks and becomes loose in the hull and the starch gelatinizes. Breeding programmes in Canada and the United States are developing disease-resistant cultivars with non-shattering grains adapted to various local requirements. Germplasm is abundantly available and variation is large. The closely related American *Z. aquatica* L. hybridizes freely with *Z. palustris* and the two species are sometimes considered conspecific. *Z. latifolia* (Griseb.) Turcz. ex Stapf, which is mainly cultivated as a vegetable in South-East Asia, is a near relative of *Z. palustris*. It might be possible to develop *Zizania* cultivars that are interesting for South-East Asia.

Selected sources 9, 11, 15, 18, 20, 22, 27, 31, 34.

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H.N. van der Hoek & P.C.M. Jansen

4 Cereals with other primary use

Tentative list of species in other commodity groups (parenthesis), which are used also as cereal. Synonyms in the indented lines.

Avena sativa L. (forages)
Avena sterilis L. (forages)
Bambusa bambos (L.) Voss (bamboos)
Bromus insignis Buse (forages)
Dactyloctenium aegyptium (L.) Willd. (forages)
Dendrocalamus strictus (Roxb.) Nees (bamboos)
Digitaria ciliaris (Retzius) Koeler (forages)
    Digitaria marginata Link
    Digitaria sanguinalis auct., non (L.) Scopoli
    Digitaria adscendens Henrard
Digitaria longiflora (Retzius) Persoon (forages)
Echinochloa colona (L.) Link (forages)
    Panicum colonum L.
Echinochloa crus-galli (L.) P. Beauvois (forages)
    Panicum crus-galli L.
Echinochloa stagnina (Retzius) P. Beauvois (forages)
    Panicum stagninum Retzius
Helictotrichon virescens (Steudel) Henrard (forages)
    Avena junghuhnii Buse
Ischaemum rugosum Salisb. (forages)
Leptochloa chinensis (L.) Nees (forages)
Melocanna baccifera (Roxb.) Kurz (bamboos)
Panicum notatum Retzius (forages)
    Panicum miliare Lamk
    Panicum montanum Roxburgh
Paspalidium flavidum (Retzius) Camus (forages)
    Panicum flavidum Retzius
    Paspalidium geminatum (Forsskal) Stapf
    Panicum geminatum Forsskal
Paspalum conjugatum Bergius (forages)
Paspalum scrobiculatum L. (forages)
Pennisetum clandestinum Hochst. ex Chiov. (forages)
Pennisetum macrostachyum (Brongn.) Trinius (ornamental plants)
Setaria palmifolia (Koenig) Stapf (forages)
    Panicum palmifolium Koenig
Sorghum nitidum (Vahl) Persoon (forages)
    Andropogon amboinicus Merrill
Thyrsostachys oliveri Gamble (bamboos)
Zizania latifolia (Griseb.) Turcz. ex Stapf (vegetables)

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Acronyms of organizations

- AARD: Agency for Agricultural Research and Development (Jakarta, Indonesia).
- AB-DLO: Research Institute for Agrobiology and Soil Fertility – Agricultural Research Service (Wageningen, the Netherlands).
- AICMMP: All India Coordinated Minor Millets Programme (India).
- AICSIP: All India Coordinated Sorghum Improvement Project (Hyderabad, India).
- AICWP: All India Coordinated Wheat Programme (India).
- APSA: Asia and Pacific Seed Association (Bangkok, Thailand).
- BORIF: Bogor Research Institute for Food Crops (Bogor, Indonesia).
- CGIAR: Consultative Group on International Agricultural Research.
- CIAT: Centro Internacional de Agricultura Tropical [International Center for Tropical Agriculture] (Cali, Colombia).
- CIMMYT: Centro Internacional de Mejoramiento de Maiz y Trigo [International Maize and Wheat Improvement Center] (Mexico City, Mexico).
- CIRAD: Centre de Coopération Internationale en Recherche Agronomique pour le Développement (Paris, France).
- CPRO-DLO: Centre for Plant Breeding and Reproduction Research – Agricultural Research Service (Wageningen, the Netherlands).
- CRI: Central Rice Research Institute (Cuttack, India).
- CRIFC: Central Research Institute for Food Crops (Bogor, Indonesia).
- CSIRO: Commonwealth Scientific and Industrial Research Organization (Canberra, Australia).
- DGIS: Directorate-General for International Cooperation (The Hague, the Netherlands).
- ESCAP-CGPRT Centre: Regional Coordination Centre for Research and Development of Coarse Grains, Pulses, Roots and Tuber Crops in the Humid Tropics of Asia and the Pacific (Bogor, Indonesia).
- FAO: Food and Agriculture Organization of the United Nations (Rome, Italy).
- FINNIDA: Finnish International Development Agency (Helsinki, Finland).
- FRIM: Forest Research Institute of Malaysia (Kuala Lumpur, Malaysia).
- IARC: International Agricultural Research Centre (under the aegis of the CGIAR).
- IBPGR: International Board for Plant Genetic Resources (now IPGRI) (Rome, Italy).
- ICARDA: International Center for Agricultural Research for Dry Areas (Aleppo, Syria).
- ICRISAT: International Crops Research Institute for the Semi-Arid Tropics (Patancheru, India).

- IEBR: Institute of Ecology and Biological Resources (Hanoi, Vietnam).
- IITA: International Institute of Tropical Agriculture (Ibadan, Nigeria).
- ILCA: International Livestock Center for Africa (Addis Ababa, Ethiopia).
- ILRI: International Institute for Land Reclamation and Improvement (Wageningen, the Netherlands).
- IPB: Institut Pertanian Bogor [Bogor Agricultural University] (Bogor, Indonesia).
- IPGRI: International Plant Genetic Resources Institute (formerly IBPGR) (Rome, Italy).
- IRRI: International Rice Research Institute (Los Baños, the Philippines).
- ISNAR: International Service for National Agricultural Research (The Hague, the Netherlands).
- ISTA: International Seed Testing Association (Zürich, Switzerland).
- LEI-DLO: Agricultural Economics Research Institute – Agricultural Research Service (The Hague, the Netherlands).
- LIPI: Lembaga Ilmu Pengetahuan Indonesia [Indonesian Institute of Sciences] (Jakarta, Indonesia).
- MARDI: Malaysian Agricultural Research and Development Institute (Serdang, Malaysia).
- NARS: National Agricultural Research System.
- NBPGR: National Board for Plant Genetic Resources (New Delhi, India).
- NCSRC: National Corn and Sorghum Research Centre (Nakorn Ratchasima, Thailand).
- NIAR: National Institute for Agrobiological Resources (Tsukuba, Japan).
- NPGRL-IPB: National Plant Genetic Resources Laboratory – Institute of Plant Breeding (Los Baños, the Philippines).
- NSSL: National Seed Storage Laboratory (Fort Collins, United States).
- NSSLGR: National Rice Seed Storage Laboratory for Genetic Resources (Prathum Thani, Thailand).
- ORSTOM: Office de la Recherche Scientifique et Technique Outre-Mer (Paris, France).
- PAGV: Research Station for Arable Farming and Field Production of Vegetables (Lelystad, the Netherlands).
- PCARRD: Philippine Council for Agriculture, Forestry and Natural Resources Research and Development (Los Baños, the Philippines).
- PROSEA: Plant Resources of South-East Asia (Bogor, Indonesia).
- PUDOC-DLO: Centre for Agricultural Publishing and Documentation–Agricultural Research Department (Wageningen, the Netherlands).
- RDCB: Research and Development Centre for Biology (Bogor, Indonesia).
- TISTR: Thailand Institute of Scientific and Technological Research (Bangkok, Thailand).
- UNITECH: Papua New Guinea University of Technology (Lae, Papua New Guinea).
- VIR: N.I. Vavilov Institute of Plant Industry (St. Petersburg, Russia).
- WARDA: West African Rice Development Association (Bouaké, Ivory Coast).
- WAU: Wageningen Agricultural University (Wageningen, the Netherlands).

Glossary

abaxial: on the side facing away from the axis or stem (dorsal)

abscission: the natural detachment of leaves, branches, flowers or fruits

acaulescent: lacking a visible stem

accession: in germplasm collections: plant material of a particular collection, usually indicated with a number

accessory buds: those additional to the axillary and normal buds; more than one bud in an axil

accrescent: increasing in size with age

achene: a small dry indehiscent one-seeded fruit

acicular: needle-shaped; sharp pointed

actinomorphic: radially symmetrical; applied to flowers which can be bisected in more than one vertical plane

aculeate: furnished with prickles; prickly

acuminate: ending in a narrowed, tapering point with concave sides

acute: sharp; ending in a point with straight or slightly convex sides

adaxial: on the side facing the axis (ventral)

adnate: united with another part; with unlike parts fused, e.g. ovary and calyx tube

adpressed (appressed): lying flat for the whole length of the organ

adventitious: not in the usual place, e.g. roots on stems, or buds produced in other than terminal or axillary positions on stems

albumen: the nutritive material stored within the seed, and in many cases surrounding the embryo (endosperm)

aleurone layer: a special peripheric layer in most seeds, especially in grasses, often rich in protein

allele: one of a number of alternative forms of a gene that can occupy a given genetic locus on a chromosome

allopolyploid (alloploid): a polyploid with more than two sets of chromosomes, derived from different species; allotriploid with three sets, allotetraploid with four sets, etc.

allozyme: one of a number of forms of the same enzyme having different electrophoretic mobilities and which are specified by alternative alleles at the same genetic locus

alternate: leaves, etc., inserted at different levels along the stem, as distinct from opposite or whorled

amplexicaul: stem-clasping, when the base of a sessile leaf or a stipule is dilated at the base, and embraces the stem

amylopectin: a branch-chained polysaccharide found in starch with a structure similar to glycogen and does not tend to gel in aqueous solutions

amylose: a component of starch characterized by its straight chains of glucose units and by the tendency of its aqueous solution to set to a stiff gel

analgesic: producing insensibility to pain without loss of consciousness

androecium: the male element; the stamens as a unit of the flower

aneuploid: with other than the exact multiple of the haploid chromosome complement

aneuploidy: having a chromosome number that is not an exact multiple of the usual haploid number (n)

annual: a plant which completes its life cycle in one year

annular: used of any organs disposed in a circle

annulate: ring-shaped

annulus: a ring or a ring-like part

anterior: of time, previous; of place, position in front, or turned away from the axis

anther: the part of the stamen containing the pollen

anthesis: the time the flower is expanded, or, more strictly, the time when pollination may take place

anthocyanin: the blue, sometimes red, colouring of plant parts

antioxidant: a substance that opposes oxidation or inhibits reactions promoted by oxygen or peroxides; many of these substances are used as preservatives in various products

apetalous: without petals or with a single perianth

apex (plural: *apices*): tip or summit of an organ

apical: at the apex of any structure
apiculate: ending abruptly in a short point
apomict: an organism reproducing by apomixis
apomixis: reproduction by seed formed without sexual fusion (apomictic)
appendage: a part added to another; attached secondary or subsidiary part, sometimes projecting or hanging
appressed (adpressed): lying flat for the whole length of the organ
areole: irregular squares or angular spaces marked out on a surface, e.g. of a fruit; a small cell or cavity
aril: an expansion of the funicle enveloping the seed, arising from the placenta; sometimes occurring as a pulpy cover (arillus)
aristate: awned
armed: bearing some form of spines
articulate: jointed, or with places where separation takes place naturally
articulation: a joint, popularly applied to nodes of grasses
ascending: curving or sloping upwards
asexual: sexless; not involving union of gametes
attenuate: gradually tapering
auricle: a small lobe or ear
auriculate: eared, having auricles
autopolyploid (autoploid): polyploid with more than two sets of similar chromosomes derived from the same species
awn: a bristle-like appendage, especially occurring on the glumes of grasses
axil: the upper angle between the leaf and the stem
axillary: arising from the axil
axis: the main or central line of development of a plant or organ
back cross: a cross between the heterozygous F_1 generation and (usually) the homozygous recessive parent, which allows the different genotypes present in the F_1 to be distinguished
bark: the tissue external to the vascular cambium collectively, being the secondary phloem, cortex and periderm
basifixed: attached or fixed by the base
basipetal: developing from the apex toward the base
beak: a long, prominent and substantial point, applied particularly to prolongations of fruits
bearded: awned; having tufts of hairs
beri-beri: a disease caused by the lack of or inability to assimilate thiamine, marked by inflammatory or degenerative changes of the nerves, digestive system and heart
berry: a juicy indehiscent fruit with the seeds immersed in pulp; usually several-seeded without a stony layer surrounding the seeds
biennial: a plant which flowers, fruits and dies in its second year or season
bifid: divided in two, usually equal parts
bilocular: with two compartments or cells
biotype: a population in which all the individuals have the same genetic constitution
biseriate: arranged in two rows
bisexual: having both sexes present and functional in the same flower
blade: the expanded part, e.g. of a leaf or petal
blast: a disease that suggests the effects of a noxious wind, causing the foliage or flowers to wither
booting: in cereals the development of the flag leaf from which sheath eventually the inflorescence emerges
bract: a reduced leaf subtending a flower, flower stalk or the whole or part of an inflorescence
bracteole: a secondary bract on the pedicel or close under the flower
bran: the broken husks or outer coats of cereal grain, separated from the flour or meal by sifting or bolting
breeding: the propagation of plants or animals to improve certain characteristics
bristle: a stiff hair or a hair-like stiff slender body
bunch: cluster, growing together
bunch grass: grass growing in clusters
caducous: falling off early
callus: small hard outgrowth at the base of spikelets in some grasses; tissue that forms over cut or damaged plant surface
calyx: the outer envelope of the flower, consisting of sepals, free or united
cambium (plural: *cambia*): a layer of nascent tissue between the wood and bark, adding elements to both
campanulate: bell-shaped
canopy: the uppermost leafy layer of a tree, forest or crop
capitate: headed, like the head of a pin in some stigmas, or collected into compact headlike clusters as in some inflorescences
capsule: a dry dehiscent fruit composed of two or more carpels and either splitting when ripe into valves, or opening by slits or pores
carpel: one of the foliar units of a compound pistil or ovary; a simple pistil has only one carpel
cartilaginous: hard and tough
caruncle: an outgrowth of a seed near the hilum
caryopsis: the fruit of a grass, in which the outer

layer (testa) of the seed proper is fused to the ovary wall

cellulose: the residue when hemicellulose is extracted from the holocellulose; often referred to as α-cellulose

chalaza: basal part of the ovule or seed where it is attached to the funicle and the point at which vascular tissues enter and spread into the ovule

chartaceous: papery

chromosome: a structural unit in the nucleus which carries the genes in a linear constant order; the number is typically constant in any species

ciliate: with a fringe of hairs along the edge

ciliolate: fringed with small hairs

circumscissile: dehiscing or falling off along a circular line

cleft: cut halfway down

cleistogamous: pollination and fertilization taking place within the unopened flower

clone: a group of plants originating by vegetative propagation from a single plant and therefore of the same genotype

clustered: with several stems

coarse grains: all cereals other than rice and wheat

coleoptile (coleoptilum, coleophyllum): the first leaf in germination of monocotyledons, which sheathes the succeeding leaves

coleorhiza: the sheath of a monocotyledonous embryo, when pierced by the true radicle

combine: a harvesting machine that heads, threshes and cleans grain while moving over a field

compatibility: in floral biology: capable of cross- or self-fertilization; in plant propagation: stock-scion combinations resulting in a lasting union

compound: of two or more similar parts in one organ, as in a compound leaf or compound fruit

concave: hollow

conduplicate: folded lengthwise

conical: having the shape of a cone (cone-shaped)

connate: united or joined

conspecific: belonging to the same species

contorted: twisted or bent

cordate: heart-shaped, as seen at the base of a leaf, etc., which is deeply notched

coriaceous: of leathery texture

corolla: the inner envelope of the flower consisting of free or united petals

cotyledon: seed-leaf, the primary leaf; dicotylous embryos have two cotyledons and monocotylous embryos have one

cover crop: a crop planted to prevent soil erosion and to provide humus and/or fodder

crenate: the margin notched with blunt or rounded teeth

crop-weed complex: an aggregate of culta and taxa, of cultivated and wild plants belonging to the same species and which are morphologically difficult to distinguish

cross pollination: the transfer of pollen from one flower to the stigma of a flower of another plant which is not of the same clone

crown: the base of a tufted, herbaceous, annual or perennial grass

culm: the stem of grasses and sedges

cultigen: a plant species or race that has arisen or is known only in cultivation

cultivar (*cv.*, plural: *cvs*): an agricultural or horticultural variety that has originated and persisted under cultivation, as distinct from a botanical variety; a cultivar name should always be written with an initial capital letter and given single quotation marks (e.g. banana 'Gros Michel')

culton (plural: *culta*): same meaning as taxon (plural: taxa) but for cultivated plants (comprising usually a cultivar or a cultivar group)

cuneate: wedge-shaped; triangular, with the narrow end at the point of attachment, as the bases of leaves or petals

cupule: a small cuplike structure; the cup of such fruits as the acorn, consisting of an involucre composed of adherent bracts

cuspidate: abruptly tipped with a sharp rigid point

cuticle: the outermost skin of plants, consisting of a thin continuous fatty film

cutting: portion of a plant, used for vegetative propagation

cyme: a determinate inflorescence, often flat-topped, in which each growing point ends in a flower and the central flowers open first

cymose: bearing cymes or inflorescences related to cymes

damping-off: a disease of seeds or seedlings caused by fungi which cause various effects, from failure to germinate to the dying off of the seedling

deciduous: shedding or prone to shedding, applied to leaves, petals, etc.

decumbent: reclining or lying on the ground, but with the summit ascending

decurrent: extending down and adnate to the petiole or stem, as occurs in some leaves

decussate: of leaves, arranged in opposite pairs on the stem, with each pair perpendicular to the preceding pair *deflexed (reflexed)*: abruptly recurved; bent downwards or backwards

dehiscent: opening spontaneously when ripe, e.g. capsules, anthers

deltoid: shaped like an equal-sided triangle

dentate: margin prominently toothed with the pointed teeth directed outwards

denticulate: minutely toothed

determinate: of inflorescences, when the terminal or central flower of an inflorescence opens first and the prolongation of the axis is arrested; of shoot growth, when extension growth takes the form of a flush, i.e. only the previously formed leaf primordia unfold

dichasium (plural: *dichasia*): a cymose inflorescence with 2 equal or nearly equal lateral branches arising below the terminal flower, this pattern being repeated or not (compound and simple dichasium respectively)

dichogamy: prevention of natural self pollination in an individual flower by separation of pollen dehiscence and stigma receptivity in time

dichotomous: forked, parted by pairs

dicotyledon: angiosperm with two cotyledons or seed-leaves

didynamous: with the stamens in two pairs, two long and two short ones

dieback: the dying off of parts of the above-ground structure of a plant, generally from the top downward

digestibility: the percentage of a foodstuff taken into the digestive tract that is absorbed into the body

digitate: a compound leaf whose leaflets diverge from the same point like the fingers of a hand

dimorphic: of two forms, as may occur with branches, etc.

dioecious: with unisexual flowers and with the staminate and pistillate flowers on different plants (dioecy)

diploid: with two sets (genomes) of chromosomes, as occurs in somatic or body cells; usually written $2n$, having twice the basic chromosome number of the haploid germ cells

disk: a fleshy or elevated development of the receptacle within the calyx, corolla or stamens, often lobed and nectariferous

dispersal: the various ways by which seeds are scattered, e.g. by wind, water or animals

distal: situated farthest from the place of attachment

distichous: regularly arranged in two opposite rows on either side of an axis

dormancy: a term used to denote the inability of a resting plant or plant part (e.g. the seed, bulb, tuber, or in tree crops usually the buds) to grow or to leaf out, even under favourable environmental conditions

dorsal: back; referring to the back or outer surface of a part or organ (abaxial)

dorsifixed: attached by the back, as in the case of the attachment of anthers to a filament

drupe: a fleshy one-seeded indehiscent fruit with the seed enclosed in a strong endocarp

ear: the spike of a grass

echinate: bearing spines or bristles

ecotype: a biotype resulting from selection in a particular habitat

ellipsoid: a solid which is elliptic in outline

elliptical: oval in outline but widest about the middle

emarginate: notched at the extremity

emasculate: to remove the anthers from a bud or flower before the pollen is shed

embryo: the rudimentary plant within a seed, developed from a zygote (sexual) or from other nuclei in the embryo sac or cells of the nucellus or integuments (apomictic)

endemic: exclusively native to a specified or comparatively small region; also used as a noun for a taxon thus distributed

endo-: prefix, referring to the inside or the inner surface or part

endocarp: the innermost layer of the pericarp or fruit wall

endosperm: the starchy or oily nutritive material stored within some seeds, sometimes referred to as albumen; it is triploid, having arisen from the triple fusion of a sperm nucleus and the two polar nuclei of the embryo sac

energy value: the heat produced by the combustion of a unit weight of a fuel or food (= calorific value)

entire (botany): with an even margin without teeth, lobes, etc.

eophyll: the first fully developed foliar leaf in a seedling above the cotyledons

epiblast: the first and undeveloping leaf of the plumule of grasses, a rudimentary second cotyledon

epicotyl: the young stem above the cotyledons

epidermis: the true cellular skin or covering of a plant below the cuticle

epigeal: above the ground; in epigeal germination the cotyledons are raised above the ground

erect: directed towards summit, not decumbent

etiolation (etiolated): the appearance of plants grown in the dark, having no chlorophyll, chloroplasts not developing, internodes being greatly elongated so the plant is tall and spindly and having small, rudimentary leaves

evapotranspiration: loss of water from the soil by evaporation from the surface and by transpiration from the plants growing thereon

ex situ: in an artificial environment or unnatural habitat

exocarp: the outer layer of the pericarp or fruit wall

exsert, exserted: protrude beyond, as stamens beyond the tube of the corolla

fagopyrism: a photosensitization especially of swine and sheep that is due to eating large quantities of buckwheat and that appears principally on the nonpigmented parts of the skin as an intense redness and swelling with severe itching and the formation of vesicles and later sores and scabs

fascicle: a cluster of flowers, leaves, etc., arising from the same point

feed: food for livestock

fermentation: process like that induced by leaven in dough, with effervescence, evolution of heat, and change of properties

ferruginous: rust-coloured

fertile (botany): capable of completing fertilization and producing seed; producing seed capable of germination; having functional sexual organs

fertilization: union of the gametes (egg and sperm) to form a zygote

fibre: any long, narrow cell of wood or bark other than vessel or parenchym elements

fibrous: having much woody fibre composed of or including fibres

filament: thread; the stalk supporting the anther

filiform: slender; threadlike

fimbriate: fringed

flag leaf: in cereals the uppermost leaf from which sheath the inflorescence emerges

fleshy: succulent

floret: a small flower, one of a cluster as in grasses or *Compositae*; a grass floret typically consists of a lemma, palea, 2 lodicules, 3 stamens and a pistil with 2 plumose stigmas

flowering branch: a leafy or leafless segmented axis that bears one or more inflorescences

fodder: something fed to domesticated animals, especially coarse, dried food from plants (hay, straw, leaves)

foliaceous: leaf-like

foliolate (2-, 3-, 4- etc.): with 2-, 3-, 4- leaflets

forage: grassland and fodder plants suitable as feed for herbivores, usually with lower nutrient concentration and digestibility than concentrates such as grain

free: neither adhering nor united

fruit: the ripened ovary with adnate parts

fungicide: an agent that destroys fungi or inhibits their growth

funicle (funiculus): the little cord which attaches the ovule or seed to the placenta

gamete: a unisexual protoplasmic body, incapable of giving rise to another individual until after conjugation with another gamete

gash: a deep long cut

gene: the unit of inheritance located on the chromosome

genetic erosion: the decline or loss of genetic variability

geniculate: abruptly bent so as to resemble the knee-joint

genome: a set of chromosomes as contained within the gamete and corresponding to the haploid chromosome number of the species

genotype: the genetic makeup of an organism comprising the sum total of its genes, both dominant and recessive; a group of organisms with the same genetic makeup

genus (plural: *genera*): the smallest natural group containing distinct species

germ: a bud or growing point the ovary or young fruit a reproductive cell, especially in bacteria

germplasm: the genetic material that provides the physical basis of heredity; also a collection of genotypes of an organism

gibbous: marked by convexity; swollen on one side

glabrescent: becoming glabrous or nearly so

glabrous: devoid of hairs

glandular: having or bearing secreting organs or glands

glaucous: pale blueish-green, or with a whitish bloom which rubs off

globose: spherical or nearly so

glomerule: a condensed head of almost sessile flowers; a cluster of heads in a common involucre

glucoside: compound that is an acetal derivative of sugars and that on hydrolysis yields glucose

glume (plural: *glumes*): the chaffy or membranous two-ranked members of the inflorescence of grasses and similar plants; lower glume and upper glume, two sterile bracts at the base of a grass spikelet

gluten: a tough, sticky protein substance occurring in some cereal grain

glutinous: covered with a sticky exudation

gonorrhoea: a venereal disease characterized by inflammation of the mucous membrane of the

genitourinary tract and a discharge of mucus and pus
grain (botany): a general term for cereals; those grasses cultivated for food; the caryopsis or the fruit of cereals
gynoecium: the female part or pistil of a flower, consisting, when complete, of one or more ovaries with their styles and stigmas
habit: external appearance or way of growth of a plant
haploid: having a single set (genome) of chromosomes in a cell or an individual, corresponding to the chromosome number (n) in a gamete
harvest-index: the total harvestable produce as a fraction of the total (aboveground) biomass produced by the crop in a given year
hastate: with more or less triangular basal lobes diverging laterally
head: a dense inflorescence of small crowded often stalkless flowers (a capitulum)
herb: any vascular plant which is not woody
herbaceous: with the texture, colour and properties of a herb; not woody
hermaphrodite: bisexual; in flowers, with stamens and pistil in the same flower
heterogamous: with two or more kinds or forms of flowers
heterogeneous: lacking in uniformity; exhibiting variability
heteromorphic: varying in number or form
heterostylous: having styles of two or more distinct forms or of different lengths
hexaploid: having six sets of chromosomes ($6n$)
hilum: the scar left on a seed indicating its point of attachment
hirsute: with rather coarse stiff hairs
hispid: covered with long rigid hairs or bristles
hispidulous: minutely hispid
holocellulose: the total polysaccharide cellulose and hemicellulose fraction of wood
homogeneous: uniform as to kind; showing no variability
homozygote: an individual whose homologous chromosomes carry identical genes at corresponding loci
hops: the ripe dried pistillate catkins of a hop (*Humulus lupulus* L.) used especially to impart a bitter flavour to malt liquors
hull: see husk
husk: the outer covering of certain fruits or seeds
hyaline: colourless or translucent
hybrid: the first generation offspring of a cross between two individuals of different species or genotype
hybridization: the crossing of individuals of different species
hypocotyl: the young stem below the cotyledons
hypogeal: below ground; in hypogeal germination the cotyledons remain below ground within the testa
imbricate: overlapping like tiles; in a flower bud when one sepal or petal is wholly external and one wholly internal and the others overlapping at the edges only
in situ: in the natural environment
in vitro: outside the living body and in an artificial environment
inbred line: the product of inbreeding; a line originating by self pollination and selection
inbreeding: breeding through a succession of parents belonging to the same stock
incised: cut deeply
incompatibility: in floral biology: not capable of cross- or self-fertilization; in plant propagation: not capable to make stock–scion combinations resulting in a lasting union
indehiscent: not opening when ripe
indeterminate: of inflorescences, a sequence in which the terminal flowers are the last to open, so that the floral axis may be prolonged indefinitely by the terminal meristem; of shoot growth: when the shoot apex forms and unfolds leaves during extension growth, so that shoot growth can continue indefinitely
indigenous: native to a particular area or region
indumentum: a covering, as of hairs, scales, etc.
induplicate: with the margins bent inwards and the external face of these edges applied to each other without twisting; V-shaped in cross section, trough-shaped
inferior: beneath, lower, below; an inferior ovary is one which is below the sepals, petals and stamens
inflexed: bent or curved inward toward the centre
inflorescence: the arrangement and mode of development of the flowers on the floral axis; the branch that bears the flowers, including all its bracts and branches
infructescence: a ripened inflorescence in the fruiting stage
insecticidal: destroying or controlling insects
insecticide: an agent that destroys insects
integument: the envelope of an ovule
internode: the portion of the stem (culm) between two nodes
introrse: turned inward, towards the axis, as the dehiscence of an anther
irregular flower: in which parts of the calyx or

corolla are dissimilar in size and shape; asymmetrical or zygomorphic
isozyme: any of two or more chemically distinct but functionally similar enzymes
joint; jointed: an articulation (e.g. a node); articulated, falling apart at the joints
juvenile phase (stage): the period between germination and the first signs of flowering, during which vegetative processes preclude flower initiation even under the most favourable conditions
keel: the principal vein of a sepal or glume
kernel: the nucellus of an ovule or of a seed, that is, the whole body within the coats
lacerate: torn; irregularly cleft or cut
laciniate: slashed, cut into narrow lobes
LAI (leaf area index): a measure of the photosynthetic area over a given area of ground
lamina: see blade
lanceolate: lance-shaped; much longer than broad, being widest at the base and tapering to the apex
landrace: a locally developed kind of cultivar, without formal recognition, and usually much more variable than an official registered cultivar and from which usually several cultivars can be selected
LAR (leaf area ratio): the ratio of the photosynthetic surface area of a leaf to its dry weight
lateral: on or at the side
lax: loose, distant
leaflet: one part of a compound leaf
lemma: the lower of the two glumes which surround each floret in the spikelet of grasses
lenticular: shaped like a double-convex lens
lignine: an incrusting or impregnating substance on the cell-wall, producing woody tissue; it is insoluble in water or ether, soluble in alcohol and alkalis, and is the remainder after the cellulose has been removed by chemical means
ligulate: with or possessing a ligule; possessing an elongated flattened strap-shaped structure
ligule: a membranous outgrowth on the upper surface of a grass leaf at the junction of the sheath and the blade which may be presented by a ridge or by a line of hairs
limb: the expanded part of a tubular corolla, as distinct from the tube or throat; the lamina of a leaf or of a petal; the branch of a tree
line: used in plant-breeding for a group of individuals from a common ancestry
linear: long and narrow with parallel sides
lobe: any division of an organ or specially rounded division
lobed: divided, but not to the base
locular: divided by internal partitions into compartments as in anthers and ovaries
locule: the cavity of an ovary or anther
loculicidal: the cavity of a pericarp dehiscent by the back, the dorsal suture
lodging: beating (as a crop) flat to the ground
lodicule: one of 2 or 3 scales appressed to the base of the ovary in most grasses, believed to be rudiments of ancestral perianth parts, by their ability to swell having a function in opening the floret
longitudinal: lengthwise
macronutrients: chemical elements of which relatively large quantities are essential for the growth of a plant (such as N, P, K, Ca, Mg)
Malesia: the biogeographical region including Malaysia, Indonesia, the Philippines, Singapore, Brunei and Papua New Guinea
mass selection: a system of breeding in which seed from individuals selected on the basis of phenotype is used to grow the next generation
meiosis: nuclear divisions in which the diploid chromosome number is reduced to half that of the parent cell to give the haploid number, as in gametes
membranous: thin and semi-transparent, like a fine membrane
meristem: undifferentiated tissue of the growing point whose cells are capable of dividing and developing into various organs and tissues
merous (4–, 5– etc.): with 4, 5 etc. parts or numbers of sepals, petals etc.
mesocarp: the middle layer of the pericarp or fruit wall which is often fleshy or succulent
mesocotyl: an interpolated node in the seedling of grasses, so that the sheath and cotyledon are separated by it
micropyle: a minute opening in the integument of an ovule through which the pollen tube penetrates
midrib: the main vein of a leaf which is a continuation of the petiole
mildew: a superficial usually whitish growth produced on organic matter or living plants by fungi
mitosis: a process that takes place in the nucleus of a dividing cell, involves typically a series of steps consisting of prophase, metaphase, anaphase, and telophase, and results in the formation of two new nuclei each having the same number of chromosomes as the parent nucleus
monocotyledon: angiosperm having a single cotyledon or seed-leaf
monoculture: the cultivation during an extended

period of time of a single product to the exclusion of other possible uses of the land

monoecious: with unisexual flowers, but male and female flowers borne on the same plant

mucro: a sharp terminal point

mucronate: ending abruptly in a short stiff point

mycotoxins: metabolites produced by fungi on the seed that have toxic effects in higher organisms

naturalized: introduced into a new area and established there, giving the impression of wild growth

nausea (nauseous): an uncomfortable feeling in and about the stomach associated with aversion to food and a need to vomit

necrosis: death of a portion of tissue often characterized by a brown or black discoloration

nectary: a group of modified subepidermal cells in flowers or leaves (extrafloral) secreting nectar

neuritis: an inflammatory or degenerative lesion of a nerve marked especially by pain, sensory disturbances, and impaired or lost reflexes

neuter: sexless, neither male or female; having neither functional stamens nor pistils

node: the point on the stem or branch at which a leaf or lateral is borne

nucellus: the nutritive tissue in an ovule

nutlet: a small nut (a hard and indehiscent one-seeded fruit); variously applied to any dry independent fruit as an achene or part of a schizocarp

ob-: prefix, indication inverse or opposite condition (obtriangular, obcordate, etc.)

oblanceolate: reverse of lanceolate

oblong: longer than broad, with the sides parallel or almost so

oblongoid: a solid object which is oblong in section

obovate: reverse of ovate

obovoid: a solid object which is obovate in section

obtuse: blunt or rounded at the end

ocrea: a tubular stipule or pair of opposite stipules so combined

opaque: not pervious to radiant energy and especially light

opposite: of leaves and branches when two are borne at the same node on opposite sides of the stem

orbicular: flat with a more or less circular outline

ovary: that part of the pistil, usually the enlarged base, which contains the ovules and eventually becomes the fruit

ovate: egg-shaped in outline or in section; a flat surface which is scarcely twice as long as broad with the widest portion below the middle

ovoid: a solid object which is egg-shaped (ovate in section)

ovule: the immature seed in the ovary before fertilization

paddy: wet land in which rice is grown; threshed unmilled rice

palea: the upper of two membranous bracts enclosing the flower in grasses

palmate: of leaflets, leaf-lobes or veins, with the different elements arising from the same point

panicle: an indeterminate branched racemose inflorescence

paniculate: resembling a panicle

pantropical: distributed throughout the tropics

parasitic: deriving nourishment from some other organism

parenchyma: tissue composed of more or less isodiametric cells, e.g. the pith and mesophyll

parthenocarpy: the production of fruit without true fertilization

partite (parted): cleft, but not quite to the base

pedicel: stalk of each individual flower of an inflorescence

peduncle: the stalk of an inflorescence or partial inflorescence

pendent, pendulous: drooping; hanging down from its support

perennial: a plant living for many years and usually flowering each year

perfect flower: a flower possessing both male and female organs

perianth: the floral leaves as a whole, including both sepals and petals if both are present

pericarp: the wall of the ripened ovary or fruit whose layers may be fused into one, or may be more or less divisible into exocarp, mesocarp and endocarp

peristalsis: successive waves of involuntary contraction passing along the walls of the intestine and forcing the contents onward

persistent: remaining attached; not falling off, not deciduous; applies to organs that remain in place after they have fulfilled their natural functions

petal: a member of the inner series of perianth segments which are often brightly coloured

petiole: the stalk of a leaf

phenotype: the physical or external appearance of an organism as distinguished from its genetic constitution (genotype); a group of organisms with similar physical or external make-up

phloem: the principal food-conducting tissue of vascular plants; the bast element of a vascular bundle and basically composed of sieve elements, parenchyma cells, fibres and sclereids

photoperiod: length of day favouring optimum functioning of an organism

phylogenetic: based on natural evolutionary and genealogic relationships
physiological varieties (races): pathogens of the same species which are structurally similar, but which differ in physiological and pathological characteristics
phytosanitary: of or relating to health or health measures of plants
pilose: hairy with rather long soft hairs
pistil: the female part of a flower (gynoecium) of one or more carpels, consisting, when complete, of one or more ovaries, styles and stigmas
pistillate: a unisexual flower with pistil, but no stamens
pith: the soft core occurring in the structural centre of a log; the tissue, sometimes soft, in the centre of the stem of a non-woody dicotyledon
placenta: the part of the ovary to which the ovules are attached
ploidy: degree or repetition of the basic number of chromosomes
plumose: featherlike with fine hairs
plumule: the primary bud of an embryo or germinating seed
pollen: spores or grains borne by the anthers containing the male element (gametophyte)
pollination: the transfer of pollen from the dehiscing anther to the receptive stigma
polygamous: with unisexual and bisexual flowers in the same plant
polymorphic: polymorphous, with several or various forms; variable as to habit
polyploid: with more than two sets (genomes) of chromosomes in the somatic cells
posterior: next to or towards the main axis
prickle: a sharp, relatively stout outgrowth from the outer layers
primordium: a group of undifferentiated meristematic cells, usually of a growing point, capable of differentiating into various kinds of organs or tissues
procumbent: lying along the ground
prop roots: aerial roots
prostrate: lying flat on the ground
protandrous: of flowers, shedding pollen before the stigma is receptive
protogynous: of flowers, the stigma is receptive before the pollen is shed
protuberance: projection, an extension beyond the normal surface
proximal: the part nearest the axis (as opposed to distal)
pruinose (pruinous): having a waxy powdery secretion on the surface, a bloom
pseudoraceme: raceme-like inflorescence but not a true raceme
puberulent: covered with down or fine hairs
puberulous: minutely pubescent
pubescent: covered with soft short hairs
punctate: marked with dots or translucent glands
qualitative short-day plant: to flower, the plant needs short days (often with quantitative response); if the daylength surpasses a certain value (the critical daylength) the plant does not flower
quantitative short-day plant: plant flowers sooner under short-day conditions, but short days are not absolutely necessary to flower
raceme: an unbranched elongated indeterminate inflorescence with stalked flowers opening from the base upwards
racemose: raceme-like
rachilla: a diminutive or secondary axis, as the stalk of the spikelet in grasses; the branch that bears the flowers
rachis (plural: *rachides*): the principal axis of an inflorescence or a compound leaf beyond the peduncle or petiole
radical: arising from the root, or its crown
radicle: the first root of an embryo or germinating seed
receptacle: the flat, concave or convex part of the axis from which the parts of the flower arise
recurved: bent or curved downward or backward
reflexed: abruptly bent or turned downward or backward
regular: of a radially symmetrical flower; actinomorphic
reticulate: netted, as when the smallest veins of a leaf are connected together like the meshes of a net
retuse: with a shallow notch at a rounded apex
rhizome: an underground stem which is distinguished from a root by the presence of nodes, buds, and leaves or scales
rogue: to weed out inferior, diseased, or nontypical individuals from a crop plant or a field
rootstock: see rhizome; a stock for grafting consisting of a root and part of the main axis
rudimentary: of organs, imperfectly developed and non-functional
rust: any of numerous destructive diseases of plants produced by fungi and characterized by reddish-brown pustular lesions
scaberulous: somewhat rough
scabrid, scabrous: rough to the touch
scale: a thin scarious body, often a degenerate leaf or a trichome of epidermal origin

scarification (seed): scarifying, to cut or soften the wall of a hard seed to hasten germination
sclerenchymatous: of tissue, composed of thick-walled cells
scutellum (botany): development of part of cotyledon that separates embryo from endosperm in seed of grasses
section (botany): a taxonomic rank between the genus and the species accomodating a single or several related species
sedative: a drug that tends to calm, moderate or tranquillize nervousness or excitement
seed: the reproductive unit formed from a fertilized ovule, consisting of embryo and seed-coat, and, in some cases, also endosperm
seedling: the juvenile plant, grown from a seed
self-compatible: capable of fertilization and setting seed after self pollination
self-fertile: capable of fertilization and setting seed after self pollination
self pollination: pollination with pollen from the same flower or from other flowers of plants of the same clone
self-sterile: failure to complete fertilization and obtain seed after self pollination
seminal root: the first formed root, developed from the radicle of the seed
sepal: a member of the outer series of perianth segments
sericeous: silky
serrate: toothed like a saw, with regular pointed teeth pointing forwards
serrulate: serrate with minute teeth
sessile: without a stalk
seta (plural: *setae*): a bristle-like body
setose: set with bristles or bristle-like elements
sheaf (plural: *sheaves*) a quantity of the stalks and ears of a cereal grass bound together
sheath: a tubular structure surrounding an organ or part, as the lower part of the leaf clasping the stem in grasses
shoot: the ascending axis, when segmented into dissimilar members it becomes a stem
shrub: a woody plant which branches from the base, all branches being equivalent
simple (botany): not compound, as in leaves with a single blade
solitary: single stemmed, not clustering
spat(h)ulate: spoon-shaped
spherical: globular
spicate: spike-like
spiciform: with the form of a spike
spike: a simple indeterminate inflorescence with sessile flowers along a single axis
spikelet: a secondary spike, one of the units of which the inflorescence is made in grasses, consisting of one or more florets on a thin axis, subtended by a common pair of glumes
spine: a short stiff straight sharp-pointed hard structure usually arising from the wood of a stem
spinescent: ending in a spine or sharp point
spinose: having spines (spinous)
stamen: one of the male reproductive organs of a flower; a unit of the androecium
staminate: a flower bearing stamens but no pistil
staminode: an abortive or rudimentary stamen without or with an imperfect anther
starch: polysaccharide made up of a long chain of glucose units joined by α-1,4 linkages, either unbranched (amylose) or branched (amylopectin) at a α-1,6 linkage, and which is the storage carbohydrate in plants, occurring as starch granules in amyloplasts, and which is hydrolysed by animals during digestion by amylases, maltase and dextrinases to glucose via dextrins and maltose
sterile: failing to complete fertilization and produce seed as a result of defective pollen or ovules; not producing seed capable of germination; lacking functional sexual organs (sterility)
stigma: the portion of the pistil which receives the pollen
stipe: the support of a gynoecium or carpel
stolon: a trailing stem usually above the ground which is capable of producing roots and shoots at its nodes
stoloniferous: bearing a stolon or stolons
stover: mature cured stalks of grain with the ears removed that are used as feed for livestock
strain: a group of individuals of a common origin, usually a more narrowly defined group than a cultivar
striate: marked with fine longitudinal parallel lines, as grooves or ridges
strigose: with short stiff hairs lying close along the surface
style: the part of the pistil connecting the ovary with the stigma
sub-: prefix, meaning somewhat or slightly (e.g. subacute), or below (e.g. subterranean) or less than, imperfectly
subfamily: a taxonomic rank between the family and the tribe denoting a part of a family
subglobose: nearly globular
subspecies: a subdivision of a species, in rank between a variety and a species
subulate: awl-shaped, sharply pointed

succulent: juicy, fleshy
sulcate: grooved or furrowed
superior (ovary): an ovary with the perianth inserted below or around its base, the ovary being attached at its base only
taproot: the primary descending root, forming a direct continuation of the radicle
taxon (plural: *taxa*): a term applied to any taxonomic unit irrespective of its classification level, e.g. variety, species, genus, etc.
taxonomy: the study of principles and practice of classifying living organisms (systematics)
tepal: a segment of a perianth, applied when no distinction between sepals and petals can be made
terete: cylindrical; circular in transverse section
terminal: borne at the end or apex
testa: the outer coat of the seed
tetraploid: having four times ($4n$) the basic number of chromosomes or twice the diploid number ($2n$)
thinning: removing trees, stems or plants from immature or mature stands in order to stimulate the growth of the remaining trees, stems or plants
tiller: a shoot from the axils of the lower leaves, e.g. in some grasses and palms (making such shoots: tillering)
tissue culture: a body of tissue growing in a culture medium outside the organism
tomentose: densely covered with short soft hairs
tomentum: pubescence
tree: a perennial woody plant with a single evident trunk
triad: a special group of 2 lateral staminate and a central pistillate flower, structurally a short cincinnus; a group of three
tribe (plural: *tribae*): a taxonomic rank between the family and the genus
trigonous: three-angled, with plane faces
triploid: having three times the basic number of chromosomes, usually written $3n$
triquetrous: three-edged, with three salient angles
truncate: cut off more or less squarely at the end
tubercle: a small tuber-like excrescence
tufted: growing in tufts (caespitose)
tussock: a tuft of grass or grass-like plants
unarmed: devoid of thorns, spines or prickles
unilocular: one-celled
unisexual: of one sex, having stamens or pistils only
utricle: a small bladdery pericarp, as in *Amaranthus*
variety: botanical variety which is a subdivision of a species; an agricultural or horticultural variety is referred to as a cultivar
vein: a strand of vascular tissue in a flat organ, such as a leaf
velvety: with a coating of fine soft hairs; the same as tomentose but denser so that the surface resembles (and feels like) velvet
venation: the arrangement of the veins in a leaf
ventral: faces central axis (adaxial), opposed to dorsal (abaxial)
vermifuge: a drug serving to destroy or expel parasitic worms of the intestine
verrucose: warty
versatile (botany): turning freely on its support, as many anthers on their filaments
vesicle: a small bladder or cavity
vestigial: small and imperfectly developed
viability: ability to live, grow and develop
villose (villous): with long weak hairs
vitreous: hyaline; transparent
warty: covered with firm roundish excrescences
waterlogged: flooded with water, generally for a period of at least a few weeks
waxy: resembling beeswax in consistence or appearance
whorl: arrangement with more than two organs of the same kind arising at the same level
wing: any membraneous expansion attached to an organ
wort: a dilute solution of sugars obtained from malt by infusion and fermented to form beer
zygomorphic: irregular and divisible into equal halves in one plane only
zygote: the cell formed from the fusion of two gametes; a fertilized egg

Sources of illustrations

Figure 1. Original design PROSEA.

Figure 2. Grass morphology: Clayton, W.D. & Renvoize, S.A., 1986. Genera graminum. Grasses of the world. Kew Bulletin Additional Series 13. Her Majesty's Stationery Office, London, United Kingdom. Fig. 1, p. 4 (five-flowered spikelet). Häfliger, E. & Scholz, H., 1980. Grass weeds 1. Panicoideae. Documenta, CIBA-GEIGY, Basle, Switzerland. Fig. 1, p. IV (habit), Fig. 2., p. V (ligules), Fig. 3, p. VI (inflorescence types); Leistner, O.A. (Editor), 1990. Grasses of southern Africa. National Botanic Gardens, Pretoria, South-Africa. Fig. 5, p. 7 (leaf), Fig. 8, p. 11 (one-flowered spikelet, floret). Percival, J., 1974. The wheat plant. Duckworth, London. Fig. 59, p. 65 (young plant with tillers). Redrawn and adapted by P. Verheij-Hayes.

Figure 3. Original design G.J.H. Grubben. Redrawn and adapted by P. Verheij-Hayes.

Amaranthus cruentus: Grubben, G.J.H., 1975. La culture de l'amarante, légume-feuilles tropical (avec référence spéciale au Sud-Dahomey) [The cultivation of amaranth, a tropical leaf vegetable (with special reference to South-Dahomey)]. Mededelingen Landbouwhogeschool Wageningen, Nederland 75-6. Fig. 4, p. 47. Redrawn and adapted by P. Verheij-Hayes.

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Coix lacryma-jobi: Innes, R.R., 1977. A manual of Ghana grasses. Land Resources Division, Ministry of Overseas Development, Surbiton, United Kingdom. Fig. 22, p. 124. Redrawn and adapted by P. Verheij-Hayes.

Echinochloa crus-galli cv. group Esculenta: Chien-chang Hsu, 1974. Taiwan grasses. Taiwan Provincial Education Association, Taipei, Taiwan. Fig. 160, pp. 531–532. Redrawn and adapted by P. Verheij-Hayes.

Eleusine coracana cv. group Finger Millet: Mansfeld, R., 1986. Verzeichnis landwirtschaftlicher und gärtnerischer Kulturpflanzen (ohne Zierpflanzen) [Register of agricultural and horticultural plants in cultivation (without ornamentals)]. Schultze-Motel, J. et al., Editors 2nd edition. Volume 3. Springer Verlag, Berlin, Germany. Fig. 225, p. 1497. Redrawn and adapted by P. Verheij-Hayes.

Fagopyrum esculentum: Mansfeld, R., 1986. Verzeichnis landwirtschaftlicher und gärtnerischer Kulturpflanzen (ohne Zierpflanzen) [Register of agricultural and horticultural plants in cultivation (without ornamentals)]. Schultze-Motel, J. et al., Editors 2nd edition. Volume 1. Springer Verlag, Berlin, Germany. Fig. 20, p. 119 (flowering branch, flower, winged fruit); Williams, J.T. (Editor), 1995. Cereals and pseudocereals. Underutilized crops series. Chapman & Hall, London, United Kingdom. Fig. 2.1, p. 90 (unwinged fruit). Redrawn and adapted by P. Verheij-Hayes.

Hordeum vulgare: Hitchcock, A.S., 1935. Manual of the grasses of the United States. United States Department of Agriculture, Miscellaneous Publication No 200. Government Printing Office, Washington D.C., United States. Fig. 533, p. 270. Redrawn and adapted by P. Verheij-Hayes.

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Oryza sativa: Grist, D.H., 1973. Rice. 5th edition. Longmans, London, United Kingdom. Fig. 5.2, p. 77. Redrawn and adapted by P. Verheij-Hayes.

Panicum miliaceum cv. group Proso Millet: Mansfeld, R., 1986. Verzeichnis landwirtschaftlicher und gärtnerischer Kulturpflanzen (ohne Zierpflanzen) [Register of agricultural and horticultural plants in cultivation (without ornamentals)]. Schultze-Motel, J. et al., Editors 2nd edition. Volume 3. Springer Verlag, Berlin, Germany. Fig. 228, appendix, Fig. 229, p. 1515. Redrawn and adapted by P. Verheij-Hayes.

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Secale cereale: Hitchcock, A.S., 1935. Manual of the grasses of the United States. United States Department of Agriculture, Miscellaneous Publication No 200. Government Printing Office, Washington D.C., United States. Fig. 477, p. 247 (habit); Mansfeld, R., 1986. Verzeichnis landwirtschaftlicher und gärtnerischer Kulturpflanzen (ohne Zierpflanzen) [Register of agricultural and horticultural plants in cultivation (without ornamentals)]. Schultze-Motel, J. et al., Editors 2nd edition. Volume 3. Springer Verlag, Berlin, Germany. Fig. 209, p. 1448 (spikelets, floret, grains). Redrawn and adapted by P. Verheij-Hayes.

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Map of South-East Asia for Prosea: original design of R. Boekelman.

Index of scientific plant names

Page numbers printed in bold refer to main treatment.

Index of vernacular plant names

Page numbers printed in bold refer to main treatment. For transcriptions of Vietnamese names, see at the end of the index.

Transcriptions of Vietnamese characters

[aa] = â	[ar] = ả	[ax] = ã	[ej] = ẹ	[oo] = ô	[ow] = ơ	[uj] = ụ	[uwx] = ữ
[aaf] = ầ	[as] = á	[ee] = ê	[er] = ẻ	[oof] = ồ	[owf] = ờ	[ur] = ủ	[ux] = ũ
[aaj] = ậ	[aw] = ă	[eef] = ề	[es] = é	[ooj] = ộ	[ooj] = ợ	[us] = ú	
[aar] = ẩ	[awf] = ằ	[eej] = ệ	[ex] = ẽ	[oor] = ổ	[owr] = ở	[uw] = ư	
[aas] = ấ	[awj] = ặ	[eer] = ể	[if] = ì	[oos] = ố	[ows] = ớ	[uwf] = ừ	
[aax] = ẫ	[awr] = ẳ	[ees] = ế	[is] = í	[oox] = ỗ	[owx] = ỡ	[uwj] = ự	
[af] = à	[aws] = ắ	[eex] = ễ	[of] = ò	[or] = ỏ	[ox] = õ	[uwr] = ử	
[aj] = ạ	[awx] = ẵ	[ef] = è	[oj] = ọ	[os] = ó	[uf] = ù	[uws] = ứ	

The Prosea Foundation (Plant Resources of South-East Asia)

Name, location, legal status and structure

- Prosea is a Foundation under Indonesian law, with an international charter, domiciled in Bogor. It is an autonomous, non-profit, international agency, governed by a Board of Trustees. It seeks linkage with existing regional and international organizations;
- Prosea is an international programme focusing on the documentation of information on plant resources of South-East Asia;
- Prosea consists of a Network Office in Bogor (Indonesia) coordinating 6 Country Offices in South-East Asia, and a Publication Office in Wageningen (the Netherlands).

Participating institutions

- Forest Research Institute of Malaysia (FRIM), Karung Berkunci 201, Jalan FRIM Kepong, 52109 Kuala Lumpur, Malaysia;
- Indonesian Institute of Sciences (LIPI), Sasana Widya Sarwono, Jalan Gatot Subroto 10, Jakarta 12710, Indonesia;
- Institute of Ecology and Biological Resources (IEBR), Nghia Do, Tu Liem, Hanoi, Vietnam;
- Papua New Guinea University of Technology (UNITECH), Private Mail Bag, Lae, Papua New Guinea;
- Philippine Council for Agriculture, Forestry and Natural Resources Research and Development (PCARRD), Los Baños, Laguna, the Philippines;
- Thailand Institute of Scientific and Technological Research (TISTR), 196 Phahonyothin Road, Chatuchak, Bangkok 10900, Thailand;
- Wageningen Agricultural University (WAU), Costerweg 50, 6701 BH Wageningen, the Netherlands.

Objectives

- to document and make available the existing wealth of information on the plant resources of South-East Asia for education, extension work, research and industry;
- to make operational a computerized data bank on the plant resources of South-East Asia;
- to publish the results in the form of an illustrated, multi-volume handbook in English;
- to promote the dissemination of the information gathered.

Target groups

- those professionally concerned with plant resources in South-East Asia and working in education, extension work, research and commercial production (direct users);
- those in South-East Asia depending directly on plant resources, obtaining relevant information through extension (indirect users).

Activities

- the establishment and operation of data bases;
- the publication of books;
- the sponsorship, support and organization of training courses;
- research into topics relevant to Prosea's purpose;
- the publication and dissemination of reports and the research results.

Implementation

The programme period has been tentatively divided into 3 phases:
- preliminary phase (1985–1986): publication of 'Plant Resources of South-East Asia, Proposal for a Handbook' (1986);
- preparatory phase (1987–1990): establishing cooperation with South-East Asia through internationalization, documentation, consultation and publication; reaching agreement on the scientific, organizational and financial structure of Prosea;
- implementation phase (1991–2000): compiling, editing and publishing of the handbook; making operational the computerized data bank with the texts and additional information; promoting the dissemination of the information obtained.

Documentation

A documentation system has been developed for information storage and retrieval called Prosea Data Bank. It consists of 6 data bases:
- BASELIST: primarily a checklist of more than 6200 plant species;
- CATALOG: references to secondary literature;
- PREPHASE: references to literature from South-East Asia;
- ORGANYM: references to institutions and their research activities;
- PERSONYM: references to specialists;
- TEXTFILE: all Prosea publications and additional information.

Publication

The handbook in blue cover (hardbound) is distributed by Backhuys Publishers, Leiden, the Netherlands (formerly by Pudoc, Wageningen, the Netherlands). The handbook in green cover (paperback) is distributed in two price-classes: a low-price paperback, distributed by Prosea South-East Asia for all developing countries; a medium-price paperback, distributed by Backhuys Publishers, Leiden, the Netherlands, for developed countries (becoming available two years after publication of the hardbound edition). The bibliographies are distributed by Prosea South-East Asia.

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In brief, Prosea is

- an international programme, focused on plant resources of South-East Asia;
- interdisciplinary, covering the fields of agriculture, forestry, horticulture and botany;
- a research programme, making knowledge available for education and extension;
- ecologically focused on promoting plant resources for sustainable tropical land-use systems;
- committed to conservation of biodiversity;
- committed to rural development through diversification of resources and application of farmers' knowledge.

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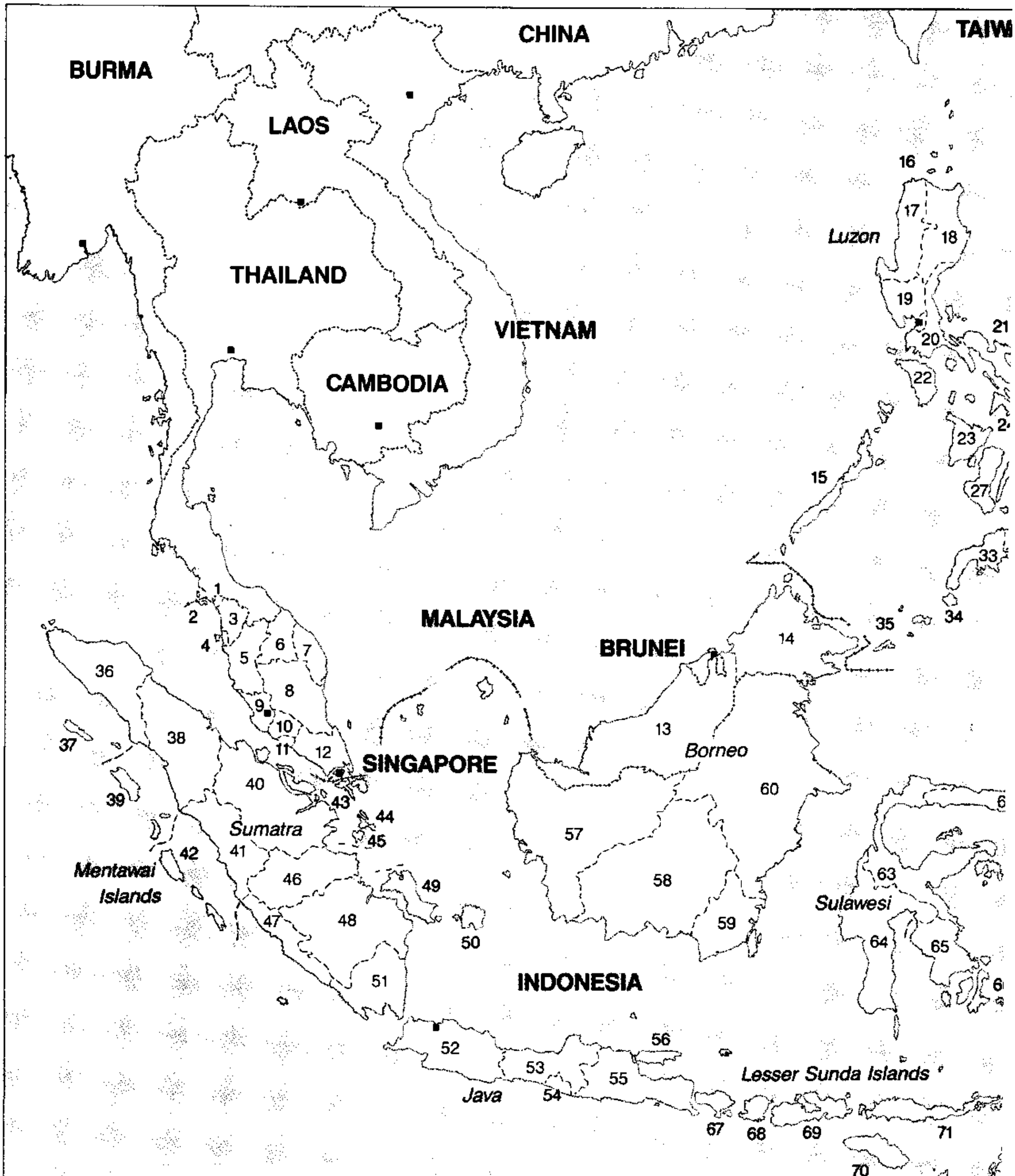
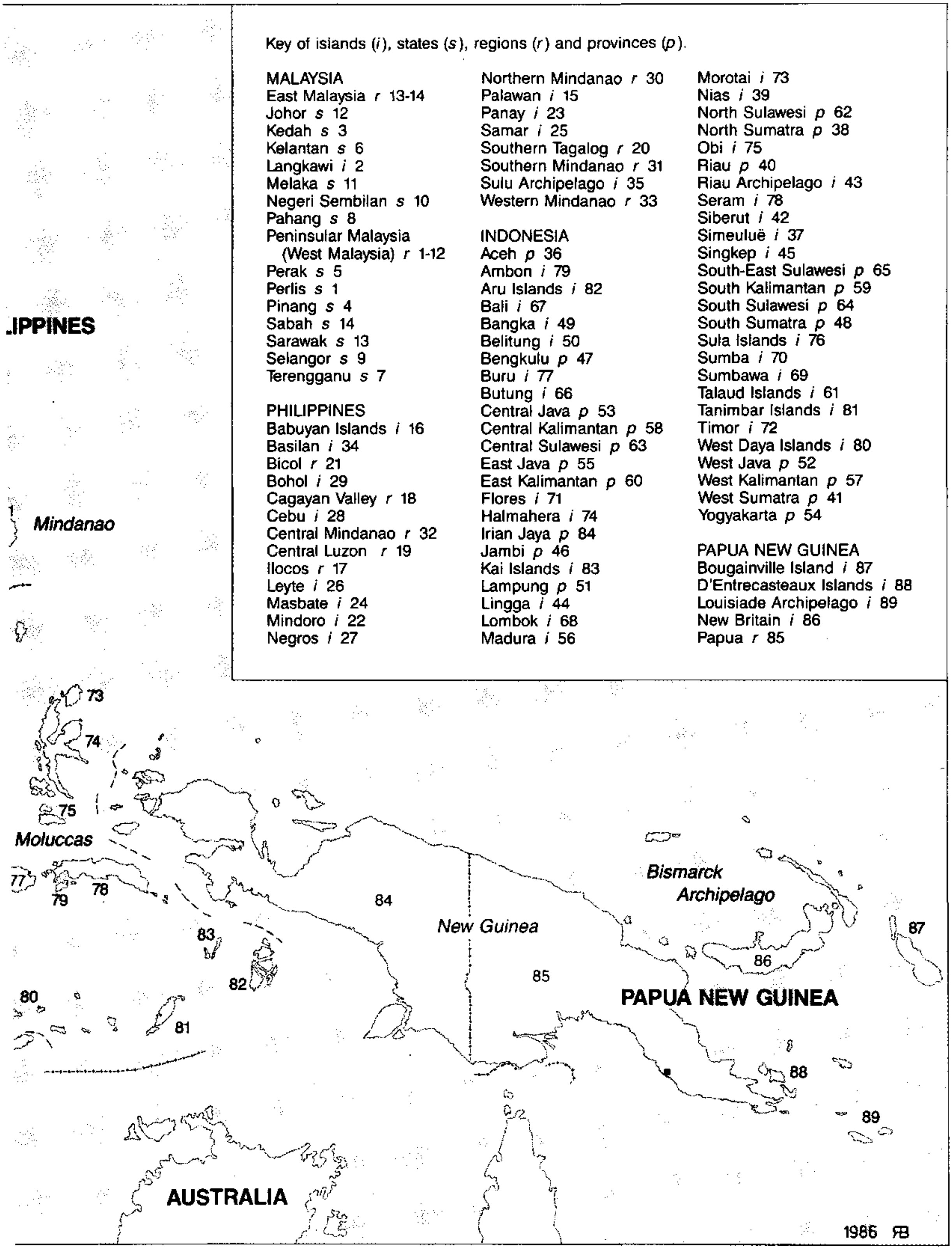


MAP OF SOUTH-EAST ASIA FOR PROSEA

Names of countries in capital letters and islands in lower case; numbers refer to the key.



Key of islands (*i*), states (*s*), regions (*r*) and provinces (*p*).

MALAYSIA
East Malaysia *r* 13-14
Johor *s* 12
Kedah *s* 3
Kelantan *s* 6
Langkawi *i* 2
Melaka *s* 11
Negeri Sembilan *s* 10
Pahang *s* 8
Peninsular Malaysia
(West Malaysia) *r* 1-12
Perak *s* 5
Perlis *s* 1
Pinang *s* 4
Sabah *s* 14
Sarawak *s* 13
Selangor *s* 9
Terengganu *s* 7

PHILIPPINES
Babuyan Islands *i* 16
Basilan *i* 34
Bicol *r* 21
Bohol *i* 29
Cagayan Valley *r* 18
Cebu *i* 28
Central Mindanao *r* 32
Central Luzon *r* 19
Ilocos *r* 17
Leyte *i* 26
Masbate *i* 24
Mindoro *i* 22
Negros *i* 27
Northern Mindanao *r* 30
Palawan *i* 15
Panay *i* 23
Samar *i* 25
Southern Tagalog *r* 20
Southern Mindanao *r* 31
Sulu Archipelago *i* 35
Western Mindanao *r* 33

INDONESIA
Aceh *p* 36
Ambon *i* 79
Aru Islands *i* 82
Bali *i* 67
Bangka *i* 49
Belitung *i* 50
Bengkulu *p* 47
Buru *i* 77
Butung *i* 66
Central Java *p* 53
Central Kalimantan *p* 58
Central Sulawesi *p* 63
East Java *p* 55
East Kalimantan *p* 60
Flores *i* 71
Halmahera *i* 74
Irian Jaya *p* 84
Jambi *p* 46
Kai Islands *i* 83
Lampung *p* 51
Lingga *i* 44
Lombok *i* 68
Madura *i* 56
Morotai *i* 73
Nias *i* 39
North Sulawesi *p* 62
North Sumatra *p* 38
Obi *i* 75
Riau *p* 40
Riau Archipelago *i* 43
Seram *i* 78
Siberut *i* 42
Simeuluë *i* 37
Singkep *i* 45
South-East Sulawesi *p* 65
South Kalimantan *p* 59
South Sulawesi *p* 64
South Sumatra *p* 48
Sula Islands *i* 76
Sumba *i* 70
Sumbawa *i* 69
Talaud Islands *i* 61
Tanimbar Islands *i* 81
Timor *i* 72
West Daya Islands *i* 80
West Java *p* 52
West Kalimantan *p* 57
West Sumatra *p* 41
Yogyakarta *p* 54

PAPUA NEW GUINEA
Bougainville Island *i* 87
D'Entrecasteaux Islands *i* 88
Louisiade Archipelago *i* 89
New Britain *i* 86
Papua *r* 85