Ancient Grains: A Key Solution to Address Climate Change and Food Security

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Chapter 4

Ancient Grains: A Key Solution to Address Climate Change and Food Security

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Ancient grains were the first unbred grains to be domesticated by early human civilizations in the Fertile Crescent, which is a crescent-shaped region in the Middle East believed to be the cradle of crop farming approximately 8000 BC or earlier. Native seeds are local varieties that grow naturally or that are cultivated in specific locations over several generations. Polyculture dates back thousands of years and was the most prevalent form of agriculture worldwide, until the first green revolution (1940–1960) that was initiated by Dr. Norman Borlaug in Mexico. At present, monoculture or single-species farming techniques are the most popular forms of farming worldwide (80–85% of total farming). Polyculture is still applied in Latin America; however, in parts of Africa, Eastern Asia, and the Himalayas, polyculture is applied in only 15–20 % of the total farming area. Currently, there is increasing awareness that relying on only a few cultivated crops to feed the world could potentially threaten food security in the future. Additionally, there has been renewed interest in ancient grains and native seeds, as native seeds are more nutritious and hardier than modern grains. In this review, we discuss important aspects of ancient grains production: how agroecology and women movements curate native crops and intrinsic cultivation methods; how ancient grains can enhance food security in the context of climate change; the origins, uses, nutritional properties and health benefits of popular ancient grains and their conservation in seedbanks; and recent genomic studies on ancient grains.

Introduction: Historical Information and Definition

Seeds are the foundation of human society and have been present throughout human history (*1*). Carvalho (*2*) stated that "Seeds are the first link in the food chain. Whoever controls the seeds, controls the availability of food."

Recent findings suggest that starch, especially from grains, has been part of the humankind's diet since the Paleolithic age (more than 100,000 years) (*3*). These findings refute the popular idea that the Paleolithic diet was based solely on meat (*3*). According to Fuller, an archeobotanist at University College London (*3*), the old-fashioned idea that hunter-gatherers did not eat starch is incorrect. Archeological evidence reveals that bread-like food was consumed at least 14,500 years ago (*4*). To produce bread-like foods, it is necessary to collect, preserve, and process starch-derived products (*3*). Arranz-Otaegui et al. (*4*) suggested that the demand for bread-like foods may have led people to domesticate grains, to provide a regular supply of grains, even before the beginning of agriculture. Additionally, new evidence suggests that grains were part of the daily diet of the ancient residents of Göbekli Tepe, a Neolithic archeological site in Turkey, and that grain seeds were ground and processed on an almost industrial scale (*5*, *6*).

From the early beginnings of human civilization to the present state, plant diversity has changed dramatically, from wide agricultural biodiversity to just a few crops being produced worldwide. However, some local farmers still grow seeds that are considered ancient or native.

There is no official definition or federal standard regarding the definition of "ancient grains"; however, they have been defined by the Whole Grains Council (WGC) (*7*) as grains that remained largely unchanged during the past several thousand years. Unlike some modern wheat varieties, these grains haven't been genetically modified or "bred" to increase yield. Ancient grains include corn (*Zea mays*), quinoa (*Chenopodium quinoa*), amaranth (*Amaranthus L.*), millets, sorghum (*Sorghum spp.*), rices (*Oryza spp.*), wild rices (*Zizania spp.*) and primitive wheat (*Triticum spp.*) Figure 1 shows some ancient grains.

Figure 1. Examples of ancient grains. Photo courtesy of Bruna Mattioni and Melanie Kessler-Mathieu.

The definition of ancient grains excludes modern wheat but encompasses "ancient" wheat varieties, such as spelt, einkorn wheat, farro, heirloom wheat, and emmer (Khorasan and durum). Ancient grains have been consumed by humans since the beginning of civilization; however, they have been largely ignored by western countries, because of their poor yield and difficult processing (dehulling). Primitive wheat varieties have been selectively bred for economic advantages. Since the last decade, ancient or heritage grains are making a comeback and are becoming a modern trend. It is now recognized that these ancient grains may be a solution to the current problems of crop diseases and the global food insecurity caused by climate change. Acknowledging the potential of these ancient grains may provide solutions for improving public health, sustainability, pest resistance, and farmer welfare. According to market data forecasts (*8*), the ancient grain market was estimated to hold a value of USD 457.35 million globally in 2022 and can be expected to expand at a growth rate [compound annual growth rate (CAGR)] of 35.5 % (USD 6.3 billion) by 2027.

In addition to ancient grains, in this review, we also discuss native seeds. Native seeds are cultivated locally and passed down from generation to generation; they are locally selected every year, according to the best adaptation features for that location (*9*). When farmers exchange seeds with neighbors and choose the best varieties according to the environment, they genetically improve these plants unintentionally.

All these seeds contribute to improving agricultural diversity, which refers to biological diversity in agriculture, food systems (which includes the variability of crop and livestock species and intraspecific diversity, associated wild species), and different agroecosystems that farmers manage (*10*). Farmers engaged in native seed preservation are typically smallholders, farmers, or peasants, who seek yield stability, risk avoidance, soil conservation, and pest and disease management (*10*).

Biodiversity is important; therefore, there is an International Treaty for Plant Genetic Resources for Food and Agriculture (*11*) as an objective of the Food and Agriculture Organization (FAO) of the United Nations. The main aims of the treaty are: Recognize the enormous contribution of farmers to the diversity of crops that are cultivated and consumed worldwide; Establish a global system to provide farmers, plant breeders, and scientists access to plant genetic material (seed banks); Ensure that recipients share the benefits they derive from the use of these genetic materials.

Agroecology, Native Seeds, and Women Movements

Conserving native seeds is an effective way to drive food sovereignty movements (*12*). Note that native seeds are considered local staple food. Before the Green Revolution, families used to store surplus seeds every year after harvest to plant again the next year; therefore, there was no need to buy seeds every year (*13*, *14*). This rendered autonomy to the farmers; on the contrary, the agribusiness system does not offer this autonomy (*14*).

In general, not all governments are willing to invest in seed banks, and many do not have an interest in them. Public policies targeted towards farmers and peasants serve native seed preservation; these policies are essential to keep farmers and peasants in rural areas and help them produce native food and protect plant seeds (*15*).

There is a concern that the seeds sent to the seed bank can be used and patented by large corporate companies; the country of origin may no longer have access unless they pay to buy seeds from the companies (*16*). If farmers and peasants must pay for the seeds and herbicides sold by large biotech companies, they can be eventually excluded from the food production chain. In non-developed countries, any inability to buy a technological package contributes to an increase in poverty (*15*). However, improving seed quality and productivity is important, because it allows all farmers and peasants autonomy (*16*).

In addition, these seeds can be used as genetic resources to improve the responses to pests, pathogens, and climate change. Nutritionally, agricultural biodiversity is paramount for supplying a large variety of foods that are essential for maintaining healthy diets and preventing malnutrition (*10*).

Promoting native seed conservation is an effective way to protect local biodiversity and knowledge. In terms of *in-situ* conservation, gender is important for implementing equitable and effective biodiversity conservation practices. Before planning the next step in conservation and gender equality in the local communities and addressing gender disparity, it is important to understand how gender norms and roles impact *in-situ* conservation (*17*).

In many parts of the world, the conservation of biodiversity depends on women. For example, in the Central Andes, rural women play a vital role in managing the native potato diversity. In a rural area, the primary reason for maintaining native plant diversity is to ensure long-term subsistence and nurture the associated cultural and spiritual values. In such areas, women are responsible for storage, selecting seed varieties, and deciding the number of varieties that will be saved, sold, or used for home consumption, all of which affect *in-situ* conservation (*17*). In Brazil, peasant women are also primarily responsible for the storage and exchange of native seeds (*13*).

Unfortunately, in the agriculture sector, women empowerment is severely ignored. Notably, there are systemic barriers beyond patriarchal social norms that limit women from achieving their full potential (*17*).

However, in some regions, a few movements and policies support women's participation in seed curation and conservation, to provide autonomy and enhance regional food security. In Chile, a project led by the Asociación Nacional de Mujeres Rurales e Indígenas (ANAMURI) (National Association of Rural and Indigenous Women) (*17*) supports the participation of women in the agriculture sector. The Papa Andina program in Andean countries (Bolivia, Ecuador and Peru) and the Brazilian Movimento das Mulheres Camponesas (Peasant Women Movement) (*13*) serves a similar purpose.

In South Korea, there is a women's movement, as well as a patriotic farmers' movement, in which farmers, agricultural scientists, and consumers drive food sovereignty (*12*). In Korea, native seeds are called t'ojong seeds, and they are cultivated by small-scale farmers in a separate part of their land, as part of a growing strategy, or in urban gardens in cities. The t'ojong seed movement is a response to market-based attacks on the domestic control of the food supply; however, it holds a different meaning for each group of people, while representing food sovereignty for most of them. For some groups, the movement is related to a connection with their ancestors and the Earth. This allows people with diverse viewpoints to understand agricultural produce as "their own"; everyone can agree that this is a positive term (*12*). South Korean farmer activists have featured prominently among and alongside the representatives of the transnational peasant movement, La Via Campesina; this organization was the first to articulate the demands for food sovereignty (*12*).

In Africa, at present, more than 65 % of the population is dependent on agriculture for both labor and subsistence. They are mostly peasants, who own around two hectares of productive land and produce most of the food consumed by Africans; around 80 % of the produce is from seeds that have been saved, stored, exchanged, and locally traded in farmer-managed seed systems or local markets. The peasants focus on the diversity of crops according to the season, use intercropping systems, and alter the planting practices to better suit climate change. The cropping system used in Africa allows peasants access to seeds in sufficient quantities and is suitable for local soil and climatic conditions.

This is possible because of the seed exchanges between farmers who plant, harvest, store, consume, and sell the surplus, thus, providing a solid base for alternative seed sovereignty systems to thrive outside the credit and corporate markets (*18*).

However, the New Green Revolution, often referred to as the second wave of colonialism (*1*), has resulted in significant changes in the agriculture sector. On one hand, it can increase crop productivity, but on the other hand, it excludes small farmers, who already produce most of the food for Africa; in the future, it will decrease seed diversity. One of the most important aspects of the New Green Revolution is that farmers must buy the seeds, pesticides, and machinery required to plant, harvest, transport, and store the produce on a large scale. However, individual farms do not have the necessary land or resources to implement such large-scale processes (*1*). Therefore, there are concerns that in Africa, the modernization of agriculture can cause more poverty than increasing access to food, due to the local organization of food system production.

Note that in most countries, farmers can save and exchange seeds among themselves; they already produce seeds from plants, and the exchange generally involves a simple process (*1*).

On-farm seed conservation is recognized in a few global treaties, e.g., the International Treaty on Plant Genetic Resources for Food and Agriculture and the Convention on Biological Diversity. Seed sovereignty is the right to save, grow, sell and share seeds. It refers to the fundamental right of people "to breed and exchange diverse open source seeds which can be saved and which are not patented, genetically modified, owned or controlled by emerging seed giants" (*19*). Thus, there is an urgent need to build decentralized farmer's seed networks, to promote the sharing of seeds and local agricultural knowledge, with support from civil society organizations and government extension workers and technicians.

Notably, ancient and native seeds, along with intercropping and growing diversity, can contribute to food security, reduce food scarcity, and increase nutrient and micronutrient intake, especially in developing and underdeveloped countries (*10*).

In each country and community, there is a system of production according to the local needs, along with a tradition of reciprocity and symbolism, which must be considered and respected before any action is taken regarding any project or policy toward improving biodiversity and ensuring preservation.

Seeds of Interest

Ancient grains are a group of grains that contain cereals and pseudocereals (seeds that are processed and consumed like grains). They are staple crops in many parts of the world but have been progressively abandoned during agricultural revolutions to profit from just a few modern crops. However, today, these grains are becoming increasingly popular in Western countries. The grain family contains corn (teosinte), millets, ancient varieties of wheat (e.g., Khorasan wheat or Kamut), freekeh, farro, spelt, rye, rice, wild rices, barley and others. Pseudocereals are a group of plants that do not belong to the Poaceae family but produce starch-rich seeds that can be used in food applications, similar to cereal grains. The most widely known pseudocereals are quinoa, amaranth, and buckwheat. Thus, the appeal and production of ancient grains are on a rise, and the examples explained in this section indicate some of the most popular ancient grains from a consumer standpoint (*20*).

Corn

Modern corn or maize (*Zea mays* L.) is an important crop in the global economy, because of its technological and nutritional value (*21*). At the industrial level, it is used in the feed and fuel industries and as a raw material for diverse products. Global corn production was ~1147 million tons in 2018, and the major corn-producing countries were the United States of America, China, and Brazil) (*22*).

Corn domestication occurred approximately 9000 years ago, from wild annual teosinte (*Zea mays* spp. *parviglumis*) in Mexico, during a single event (*21*, *22*). The corn species adapted from a tropical to a temperate climate and underwent some morphological transformations, especially in the inflorescence architecture, resulting in landraces, or races with high genetic diversity (*22*).

Corn production migrated from the Americas to Europe, Africa, and Asia, while adapting to specific environments, yield, nutritive value, and cultural use and cultivating resistance to biotic and abiotic stresses (*22*).

At present, corn is domesticated and bred, to achieve high productivity, resulting in the genetic erosion of native corn. This compromises food security and can potentially affect indigenous foods.

However, landraces are still available and have been produced in the Andean region, to maintain the *in-situ* conservation of biodiversity. Notably, landraces are important, genetically diverse resources that are crucial for crop improvement and food security (Figure 2). In general, farmers and peasants select corn landraces for subsistence for traditional agricultural practices, based on environmental changes, yield, nutritive value, cultural use, and resistance of the plant to biotic and abiotic stresses (*22*).

Figure 2. Ancient corn varieties. Photos courtesy of USDA-ARS.

Purple corn (*Z. mays var. indurata)* also known as Indian corn, calico corn or anthocyanin-rich corn is one ancient corn variety that has become popular. This variety is cultivated in Latin America, has been studied for its nutritional value, and exhibits antioxidant, anticancer, antidiabetic, anti-obesity, and anti-inflammatory properties (*23*).

Quinoas

Quinoa (*Chenopodium quinoa*) is a pseudocereal that belongs to the Amaranth family that originates from the Andean region of South America. The origin of quinoa is estimated to be 5000–7000 years ago in Chile and Peru. Owing to its high genetic variability, quinoa has a widely distributed center of origin and multiple diversifications, resulting in the current variety of plants and ecotypes that have different characteristics (*24*). The most important agronomic features of quinoa are tolerance to water deficits, salinity, frost, poor soils, and high market prices (*25*).

In addition, quinoa is naturally gluten-free and has a high nutritional value, mainly because of its bioactive compound content, being rich in protein, dietary fiber, B vitamins, and dietary minerals in amounts greater than those in many grains. The food industry is developing novel functional food products using quinoa e.g., enriched and gluten-free bread, pasta products, and beverages. Grain is also an excellent ingredient that can be used by the culinary industry, to develop nutritious and tasteful fine-cuisine dishes (*26*).

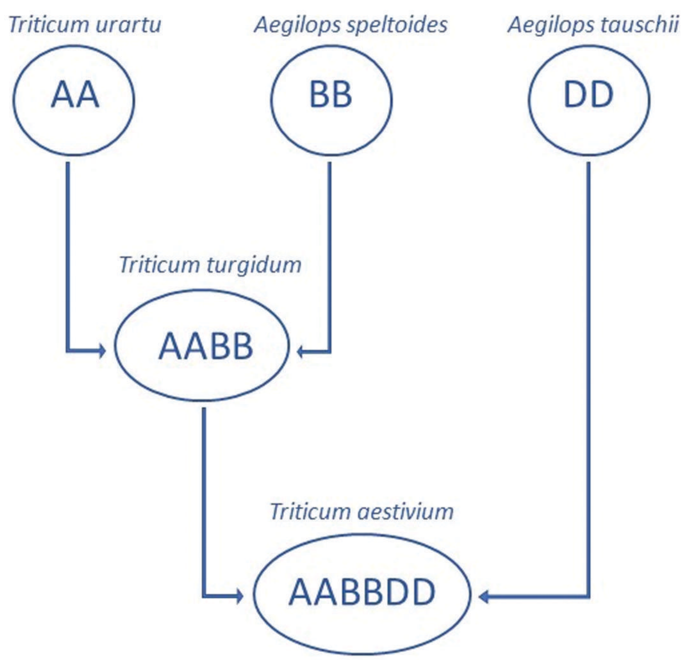

Figure 3. Model of the phylogenetic history of bread wheat (Triticum aestivum; AABBDD). Data from reference (*34*).

Ancient Wheat (*Triticum* spp.)

Wheat is considered an ancient grain; the last genome hybridization that resulted in modern wheat occurred 9,000 years ago (*27*). Einkorn is the denomination of diploid (AA) of hulled wheat grains, such as *T. monococcum* and *T. urartu* (*28*, *29*). Emmer varieties include tetraploid hulled wheat (AABB), whereas non-hulled tetraploid (AABB) wheat is denominated durum, and both are derived from *T. turgidum*. Spelt wheat is fully hexaploid (AABBDD) wheat (*29*). In addition, the taxonomies of Kamut, Khorasan, and Farro remain unclear. Farro is used to describe all hulled wheat (*28*), but is more accepted as emmer (*29*, *30*). Kamut is the commercial name of Khorasan wheat, a hybrid of *T. polonicum* and *T. durum* (*31*), but its taxonomy is not clear (*32*).

The basic genome (A) of bread wheat and other polyploid wheats, such as *T. turgidum* (AABB), *T. timopheevii* (AAGG), and *T. zhukovskyi* (AAGGAmAm), plays a central role in the evolution, domestication, and genetic improvement of wheat (*33*).

The first hybridization seems to have occurred several hundred thousand years ago between wild einkorn *T. urartu* (AA genome) and *Aegilops speltoides* (SS genome), forming *T. turgidum* (AABB), an ancestor of the wild emmer, and *T. turgidum* ssp. *durum* (*27*). *Aegilops speltoides,* an ancestor of the B genome (*33*)*,* is known as "small spelt" in English and "petit épeautre" in French (*28*).

The second hybridization between *T. turgidum* and *Aegilops tauschii* (DD genome) resulted in the ancestral *T. aestivum* (AABBDD) species approximately 9,000 years ago (*27*). *Aegilops tauschii* (the donor of the D genome) strongly influences the morphology and development of spikes and seeds (*33*) (Figure 3).

Teff

Teff (*Eragrostic tef*) is an annual cereal grass that belongs to the family Poaceae. It is native to the Horn of Africa, especially Eritrea and Ethiopia. Teff was one of the first cereals to be domesticated and originated in Ethiopia between 4000 BC and 1000 BC. It is cultivated for its edible seeds and is the base ingredient of a flatbread called "injera" and a traditional beer called "tella" in Ethiopia. Still to this day, it is the most important staple crop in Ethiopia and Eritrea (*35*). Teff grains are one of the smallest cereal grains (less than 1 mm in diameter); therefore, it is almost always produced as whole-grain flour. In addition, because of its small size, teff has a greater proportion of bran and germ, which are the parts of the seeds that have the highest concentrations of nutrients (*36*). The grains have a mild and nutty flavor and are a good source of protein and fiber; furthermore, they are high in minerals, such as magnesium and calcium. Teff is a gluten-free grain that has recently gained popularity in developed countries where methods have been developed to process teff for a wide range of baking applications, such as bread and pasta (*37*). Colored teff is currently gaining popularity among health-conscious consumers, because of its high polyphenol and tannin content, which can be a source of antioxidants, with anti-diabetic and anti-cancer properties. Teff has a short life cycle (2–6 months) and can be harvested several times per year. Because of its C4 physiology, teff is drought-resistant, resilient, and well-adapted to a wide range of environmental conditions; therefore, teff has gained popularity as a forage crop for livestock (*38*).

Amaranth

Amaranth is an 8000-year-old pseudocereal/pseudograin. It played an important role in the early civilization in the Americas and is native to Central America, southwestern North America, and the Hopewell culture of the Midwest. In the pre-Columbian era, the Aztecs and Mayas cultivated amaranth not only as a major food crop but also for ritual drinks and ceremonial purposes (*39*). In North America, amaranth was a staple crop among Native American tribes who ground the grains into flour and consumed the leaves as a leafy vegetable (*40*). Plumes were also used in the production of textiles and food dyes. The grains were ground into flour for use as another grain flour. Amaranth is consumed as a leafy vegetable. After the arrival of the Spanish conquistadors in early 1500, amaranth almost disappeared as a crop in the Americas. The cultivation of amaranth was reintroduced in the United States of America (USA) in the 1970s when the interest in and studies on amaranth were revived (*41*). The seeds were recovered from the wild varieties that grow in Mexico. Since then, amaranth has been used as food on almost every continent, including Asia, Africa, Europe (mostly Greece), and the Americas. Amaranth is highly nutritious, has a high protein content, is well balanced in amino acids, is high in lysine (an amino acid most grains are deficient in), and contains a lunasin-like peptide believed to have anti-inflammatory and anti-cancer benefits (*42*). The Amaranth family is very diverse and is a large family of around 75 species. Thus, with its fast growth, drought tolerance, and extremely low water requirements (due to its C4 physiology), the plant revived the studies on breeding and growing crops, as farmers facing the challenges of climate change seek crops that are more resilient and adaptable. The first World Amaranth Conference was held in 2018 in Tanzania and had 135 participants from Africa and the USA (*43*).

Millets

A millet is not just one grain, but a name given to a group of several small, related grains (sorghum, fonio, etc.). Millets are one of the oldest human staple crops and one of the first domesticated cereal grains. Millets are indigenous to several parts of the world; they were cultivated in East Asia (China, Japan, Russia, India, and Korea) and Africa (Mali, Nigeria, Niger, Senegal, Namibia, and Uganda) over 7000–10,000 years ago, during the Neolithic era, and then, spread to the world as a staple crop (*44*). Currently, millet is the 6th most important cereal grain in the world. China, India, and Niger are the world's largest growers of millet today (*45*). Millet in these countries is used to make whole grain flatbread ("chapatti" and "roti" in India and Asia), soups ("bajra raab" in India), sweet or savory porridges ("kasha" in Eastern Europe and "uji" in Africa), cakes in India, and fermented beverages ("boza" in Turkey and "tongba" in Nepal). Millets are a rich source of proteins, fiber, B vitamins, and numerous dietary minerals, particularly manganese. Millets are drought-tolerant C4 cereals that can grow in poor dry soils and semiarid agricultural regions (*46*). The United Nations (FAO) declared 2023 the international year of millets. Millet production is expected to increase in the USA; historically, the production increased from 217,110 metric tons in 2020 to 348,720 metric tons in 2021. This increase is due to the growing need for gluten-free products for consumers who suffer from gluten related disorders. In addition, consumers recognize the health benefits of this ancient grain. With the potential for the millet market to grow from its current value of over USD 9 billion to over USD 12 billion by 2025, the grain is expected to become a staple for households worldwide. Notably, this cereal is seen as an important food source, as the world faces critical food challenges due to global warming and climate change.

Rices

Rice are the third most consumed commodity in the world (*47*). Nowadays, two major domesticated rice species are cultivated worldwide, African rice (*Oryza glaberrima*) and Asian rice (*Oryza sativa* L.). Both belong to the genus *Oryza* L., tribe *Oryzaea Dumort*, subfamily *Ehrhartoideae Link,* family *Poaceae* (synonym: *Gramineae L.*) (*48*). Asian rice originated in the Yangtze River basin in Asia about 10,000 years ago and African rice in tropical West Africa about 3000 to 5000 years ago (*48*). Wild rice species (*Zizania spp.*) belong to the same tribe *Oryzeae* and have also been grown in other continents, such as Americas where they were consumed by native Americans (wild rice was then called "manoomin") for generations. Nowadays, wild rice species are increasing in popularity due to their nutritional qualities and taste, their consumption is becoming a trend like other ancient grains. North America is the world's primary supplier of wild rice with California and Minnesota being the main producers. Wild rices are recognized for being more colorful than the modern white rice, varying from light reddish-brown to dark brown (*49*).

Domesticated rice is a staple food in many different cultures around the world, it is daily consumed in Asia, Africa and South America and have good nutritional qualities. They are a starch dense food, and so a good source of energy. They are also rich in thiamin, riboflavin and niacin, poor in lysine amino acid but rich in glutamic and aspartic acid. As opposed to domesticated rice, wild rices are rich in protein and in lysine (*48*).

Ancient Grains: Nutrition and Health Benefits

Nutrition

Ancient grains tend to be more nutritious than modern grains because they still contain bran, endosperm and germ. Nowadays, they are gaining more attention because of their potential to battle hunger and malnutrition, especially since one of the main goals of the United Nations (UN) is ending hunger by 2030 (*50*). In term of nutrition, ancient grains are richer in protein than their modern counterparts. Also, some ancient grains have slow digestibility starch resulting in a lower glycemic index than the modern ones (*49*, *50*). Table 1 shows a comparison of the nutritional values between modern and ancient grains. In addition to the macronutrients, these grains are rich in bioactive compounds, mainly phenolics that have been extensively studied in recent years (*51*).

Table 1. Comparison of the Nutritional Values between Modern and Ancient Grains

Grain	*Protein (%)*	*Carbohydrate (%)*		*Lipids (%)*	*Minerals (%)*	*Reference*
		Starch	*Fiber*			
Ancient Wheat	13.5-16.0	52.0-68.0	7.2-13.9	1.7-2.8	1.7-2.6	(*50*)
Modern Wheat	~ 10.6	~58.2	~13.3	~1.8	~1.7	(*52*)
Ancient Rice	5.8-11.0	64.0-84.7	0.2-10.4	0.9-3.9	0.4-5.2	(*53*)
Modern white rice	7.5-12.6	72.8-77.5	1.2-3.1	2.1-3.2	1.1-1.6	(*54*)
Ancient corn	11.1-13.1	64.7-67.1	2.1-4.5	2.9-4.1	1.4-1.8	(*55*)
Modern Corn	3.2-9.4	18.7-74.26	0.0-7.3	1.1-4.7	1.0-1.4	(*55*)
Sorghum	7.9-11.2	68.1-74.2	2.6-4.8	2.6-3.3	1.5-1.6	(*50*, *55*)
Millet	27.8-32.5	55.6-59.0	3.7-5.7	5.1-5.7	2.2-2.8	(*56*)
Amaranth	13.1–21.5	65.0–75.0	2.7–17.3	5.6–10.9		(*57*)
Quinoa	9.1–16.7	58.1–64.2	7.0–26.5	4.0–7.6		(*57*)

Health Benefits

As whole grain preparations, ancient tend to be richer in proteins, fibers, omega-3 fatty acid, vitamins, minerals and contain many different types of compounds and phytochemicals compared to refined grains. It has been shown in recent studies that these bioactive compounds can reduce the risk for developing chronic diseases such as cancer, type 2 diabetes, obesity, cardiovascular diseases and have antioxidant, anti-inflammatory and anti-microbial properties.

Type 2 Diabetes and Obesity

Scientists and nutritionists have found that ancient grains are beneficial for preventing and managing type 2 diabetes (*58*, *59*). Adding ancient grains to diets cause a downregulation of key regulatory genes involved in glucose and fat metabolism, equivalent to a prevention or delay of type 2 diabetes development.

Refined grains, which includes white rice and products made with white wheat flour, like pasta and white bread have a high glycemic index and consequently often result in spikes of blood sugar. Ancient grains on the contrary, like spelt, Khorasan wheat, rye and others are high in fibers and proteins, which helps slow down the rate at which the glucose enters the bloodstream (they induce a low acute glycemic response compared to refined grains) and so can reduce obesity through weight loss. Indeed, fiber, fat and proteins, together are more filling, satisfying and promote satiety.

Cancer Prevention

In the past few decades, scientists have increasingly demonstrated that high consumption of whole grain prevents occurrence of several types of cancer (*60*) notably breast cancer (*61*), pancreatic (*62*) and colorectal cancer (*63*). Ancient grains and whole grains in general are a rich source of many different types of phytochemicals such as phenolic acids, carotenoids, alkylresorcinols (ARs), phytosterols, lignans, anthocyanins, vitamin E members, and polysaccharides (*64*). The anti-cancer activities and potential health benefits can be attributed to the abundant bioactive phytochemicals in whole grains.

Cardiovascular Disease

Scientists have shown evidence that whole grain intake is associated with a reduced risk of coronary heart disease, cardiovascular disease (*65*). These studies have shown that the ancient varieties as part of the diet shown a significant reduction of total cholesterol, low density lipoprotein (LDL)-cholesterol and blood glucose levels in the bloodstream, reducing cardiovascular risks factors (*65*, *66*).

Other Properties: Antioxidant, Anti-inflammatory, and Anti-microbial

There is a large amount of literature describing the benefits of ancient grains including antioxidant, anti-inflammatory, anti-microbial (*67*, *68*), as well as chronic illnesses risk reduction activity. Polyphenols from the diet are a very important group of natural antioxidant and chemopreventive agents found in different types of food including grains. The mechanisms of the antioxidant and anti-inflammatory effects of the phenolic compounds are generally considered to come from their capacity in capturing free radicals, restoring antioxidant enzyme activities and in regulating cytokine-induced inflammation (*69*). Phenolic properties may also exhibit antimicrobial potential.

Ancient Grains: Food Security and Climate Change

Monoculture and Food Security in the Context of Climate Change

Scientists estimate that 200,000 to 300,000 edible plant species on Earth are known, but only around 200 of these are used to feed the world. Notably, only five members of the cereal family, namely, rice (*Oryza sativa*), bread wheat (*Triticum aestivum* ssp. *aestivum*), maize (*Zea mays*), millets (e.g., *Pennisetum glaucum, Setaria italica, Panicum miliaceum,* and *Eleusine coracana*), and sorghum (*Sorghum bicolor*), provide around 60 % of the plant-based calories humans consume (*70*). Furthermore, only a dozen varieties of this species are grown extensively. For example, the wheat family comprises three main types (*Triticum aestivum*, *Triticum durum,* and *Triticum compactum*), and more than 20 subspecies of each type are represented by hundreds of different accessions. The agricultural revolution in the Fertile Crescent was driven by wild species of wheat, such as einkorn (*Triticum monococcum*) and emmer (*Triticum turgidum* ssp. *dicoccum*), together with spelt *(Triticum aestivum* ssp. *spelta*), which have been used to feed the world for millennia. At present, only common wheat, also called bread wheat (*Triticum aestivum*), is grown widely (representing about 95 % of the wheat produced in the world) (*70*). Concentrating on only a few crops and accessions has contributed to a large loss in biodiversity and increased the vulnerability of these crops to changing ecosystems, making them more susceptible to pests, diseases, and climate change. Consequently, relying on feeding the world population with only a few species is causing difficulties in meeting the current agricultural demand (*71*). In 2021, a National Aeronautics and Space Administration (NASA) study revealed that climate change will affect crop yield as soon as 2030, impacting the yield by 17–24 % (*72*). Ortiz-Bobea et al. (*73*) revealed that slow climate change, which began in the sixties, has impacted global farming productivity by as much as 21%, or the equivalent of seven years of agricultural productivity growth.

A study led by Martin et al. (*74*) revealed that at a global scale, crop diversity continues to decline, and large-scale industrial farms, even in countries located in Asia, Africa, and the Americas, are focusing only on wheat, rice, corn, and soybeans, which represent almost half of the world's agricultural lands. This declining agricultural diversity is a threat to agricultural sustainability because all large industrial farms are susceptible to the same pests or diseases that affect crop yields (*74*). Thus, the combination of declining global crop diversity and decreasing crop yields due to climate change poses a serious threat to food security.

History of Maslin and Polyculture

Maslin is a medieval term for different varieties and species of grains sown in the same field. Archaeological studies have shown that the practice of cultivating maslins dates back at least three millennia, possibly much earlier; indeed, it is suspected that maslins developed when wild cereals were first domesticated in the Fertile Crescent region (*75, 76*). Wild wheat species, such as einkorn, grow naturally in addition to wild varieties of oats, barley, and rye grasses and may have been foraged before the dawn of agriculture. Maslins have been widely developed on several continents, including Europe, Asia, and Africa. A review by a team of scientists in 2022 (*77*) revealed that maslins were traditionally grown in 27 countries, and that the grain mixtures included a large variety of crops, such as oats, rye, rice, barley, millet, and several species of wheat. These grain mixtures tend to be more resistant to pests and climate change, and they can be used to produce different food products, such as bread and ales, and have more elaborate flavors. Note that the components of maslin were consumed as a single crop. A few examples of maslins are: in England, a mixed crop called "dredge corn" was grown, it was a grain mixture that comprised oats and barley and was used for stock feeding, from the era of the middle age to the 1950s; in France, peasants ground the traditional maslin or "méteil" in French of wheat and rye into flour for "le pain de méteil," (bread of mixed grains), currently considered a popular loaf. In Ukraine and its neighboring countries, farmers would grow a mixture of rye and wheat called "surjik" or "surzhyk." Agricultural mechanization was initiated at the beginning of the 18th century (with the first horse-pulled harvesting tool being patented in 1836 in Michigan) and then, accelerated from the 19th century onward. The green revolution initiated by Norman Borlaug led to a combination of technological innovations in crop production and processing, improved breeding, and the rise of scientific agriculture, all of which significantly reduced the practice of maslins. The food industry, increasingly mechanized, preferred cereals that were uniform and would produce a product that was uniform as well, whether it was wheat for bread (white bread was preferred and considered more desirable by the wealthy, compared to brown bread that was reserved for peasants) or barley for ale. Monocultures were both easier to harvest and process mechanically and less likely to cause variations in taste or performance in the field, compared to maslins. Furthermore, 20th-century innovations, such as the widespread availability of artificial nitrogen for fertilizers, have led to exponential growth in single-grain crop yields. Note that at present, maslins cultivation have been abandoned pretty much worldwide (*77*). Globally, since the first green revolution, maslins have been replaced by a rapid-spreading single-grain monoculture. However, there are still a few countries in the world, such as Ethiopia, Eritrea, Georgia, the Greek Islands, parts of India, and a few other countries in Europe, where farmers are still growing maslins. Even today, the European Union lists maslin as a crop category and Poland is the prime producer of maslin for livestock feeding (*78*).

A comeback to the production of maslin could be particularly helpful now, as farmers worldwide struggle with soils degraded by modern monocultures, a growing population, and a changing climate. Maslins have several advantages, including a more reliable yield, a complete nutritional profile, and the ability to grow in marginal soils and survive drought. Note that the grain mixes exhibit a natural resistance to pests (ranging from insects to fungal diseases). There is reason to believe that maslins possess the capacity to increase pathogen resistance through the same mechanisms as those shown by varietal mixtures. In varietal mixtures, plants from a resistant variety can physically block the pathogen (pest or disease) from moving to susceptible plant hosts and also, decrease the overall density of the susceptible hosts (*79*).

Recent Genome Studies on Ancient Grains

On a global scale, the forthcoming food crisis is triggering a wave of genome research on grain alternatives that can withstand changing climates and have high nutritional value. A group of international scientists published the sequence of wild emmer wheat in the journal *Science* in 2017 (*80*), and the full genome of quinoa was published in *Natur*e (*81*). The first draft of the teff genome was published in BMC Genomics in 2014 (*82*), after which other assemblies of different varieties of Ethiopian teff were published in *Nature Communications* in 2020 (*83*) and 2022 (*84*). Genomic studies on spelts were published in 2021 in *Nature* (*85*). The amaranth genome assembly was published in *The Plant Genome* in 2016 (*86*). The first sorghum genome assembly was published in

Nature in 2009 (*87*), and in the last decade, great progress has been made in sorghum genomics, especially breeding (*88*). In 2023, the United Nations declared the International Year of the Millets at the behest of the Government of India. The pearl millet genome was sequenced in 2017 (*89*), and the study was published in *Nature Biotechnology*. These combined efforts to improve our knowledge of the genomic dynamics of ancient grains can provide opportunities to improve the hardiness of modern wheat and other cereals. Notably, significant progress in novel breeding methods and molecular techniques for modern plants and major crops allows the rapid development of such underutilized and forgotten crops. Furthermore, the trait mining and genetic enhancement of these heirloom grains, through the implementation of modern breeding tools, can potentially improve the climate resilience and nutritional value of future cropping systems. Several of these ancient grains are stored in seed vaults worldwide and are a treasure trove for gene mining and the introgression of new traits. Recently, a wheat variety resistant to the Hessian fly was bred by the introgression of genes isolated from ancient wheat varieties stored in the International Center for Agricultural Research in the Dry Areas (ICARDA) (*90*).

Conservation of Ancient Grains in Seedbanks

In some areas of the world, ancient grains have been cultivated over millennia; consequently, some of these ancient varieties are still available e.g., einkorn in France, Italy, Spain, Morocco, and former Yougoslav republic. Emmer is grown in Armenia, Morocco, Spain (Asturias), Albania, Turkey, Switzerland, Germany, Greece, Italy, and the Carpathian Mountains on the border of Czechia.

In addition, there are more than 1,750 gene banks worldwide, ranging from national, regional, and international organizations, that conserve approximately 7.4 million samples of crop seeds. The Svalbard Global Seed Vault in Norway, created in 2008, holds duplicates of more than 1.2 million seed samples of nearly 6,000 plant species from 98 gene banks around the world (*91*). This is the world's largest and most diverse crop collection. As part of humanity's collective efforts to ensure food security and biodiversity amid climate change and other environmental disasters, as of 2022, more than 20,000 new seed samples from 10 global gene banks have been deposited in the Svalbard Global Seed Vault, which is also known as the "doomsday vault." Ancient wheat was deposited at the Leibniz Institute of Plant Genetics and Crop Research (IPK), including samples of wheat collected from the Austrian Alpine region in the 1920s, one of the oldest collections at IPK. The vault houses samples of more than 150,000 different types of rice species and 200,000 different types of wheat species. In 2020, the Cherokee Nation became the first indigenous group in North America to deposit the seeds of nine heirloom food crops that predate European colonization (*92*).

Agronomists, botanists, and geneticists, such as Nikolai Vavilov, have pioneered seed collection and conservation. In the 1920s, he began collecting and storing as many seeds, grains, fruits, nuts, and tubers as he could find in Leningrad, thus, creating one of the first seed collections. He also collected the data on his trips to five different continents, eventually carrying out 115 expeditions to 64 countries, including the Fertile Crescent (Israel, Palestine, and Turkey), and collected over 380,000 samples (*93*). The variety of seeds he amassed was stunning. Among them was "Hourani" or "biblical wheat," an indigenous durum variety originally found in storage vases of Masada fortress, stored 2,000 years ago by King Herod the Great, discovered by the famous Israeli archeologist Yigael Yadin (*94*).

Notably, the Vavilov Research Institute donated seeds and other specimens to Svalbard, several of which were collected during Vavilov's early trips. To date, there are only 98 depositors in Svalbard, a low percentage compared to the 1750 genebanks that exist in the world. Another major seedbank is run by the United States Department of Agriculture's National Plant Germplasm System (*95*). More than 600,000 accessions from over 16,000 plant species are stored within the USDA-NPGS, consisting of nearly 27,000 grass samples (Figure 4).

The CGIAR Genebank platform (*96*, *97*) is a partnership between 11 genebanks, among them ICARDA, ICRISAT, IRRI, CIMMYT and Africa Rice are organizations that are preserving numerous cereal grains, legumes and millets germplasms accessions. This platform is the largest and most widely shared collection of genetic diversity available under the International Treaty for Plant Genetic Resources for Food and Agriculture (*11*).

ICARDA is one of the largest seed banks in the world (*97*). It was originally housed in Lebanon, but when the Lebanese civil war started in the 1980s, it was moved to Syria, before being shifted back to Lebanon (shortly after the Syrian civil war that started in 2012). This seed vault has a unique collection of over 140,000 varieties of legumes, barley, wheat, and other crops developed and maintained by local farmers in the Fertile Crescent region since the beginning of agriculture (Middle East) and gathered by scientists. More than 75 % of ICARDA's collection consists of local varieties or landraces.

Figure 4. Picture of the National Small Grain Collection seed bank at USDA-ARS, Idaho. Photo Courtesy of Harold E. Bockelman, Supervisory Agronomist/Curator, National Small Grains Collection, U.S. Department of Agriculture, Agricultural Research Service.

The ICRISAT Genebank (*97*) was established in 1979 in India and is serving as a world repository for the germplasm of 11 crops including sorghum, pearl millet, chickpea, pigeonpea, groundnut, finger millet, foxtail millet, little millet, kodo millet, proso millet and barnyard millet.

This genebank is one of the largest international genebanks with 129,091 germplasm accessions originating from 144 countries.

The International Rice Research Institute (IRRI) Genebank (97) is the largest collection of rice genetic diversity in the world with more than 132,000 available accessions, including cultivated species of rice and wild relatives of rice. This genebank is the largest collection of rice genetic diversity in the world.

The International Maize and Wheat Improvement Center (CIMMYT) germplasm bank (97) contains approximately 150,000 unique collections of wheat seed and its ancestors and is the largest unified collection in the world for a single crop. For maize, the germplasm bank contains more than 28,000 samples, including the world's largest collection of maize landraces, representing nearly 90% of maize diversity in the Americas.

Africa Rice's genebank (97) contains almost 22,000 accessions, 85% of which originated in Africa. In addition to the two cultivated rice species, these include the five African crop wild relatives. Long-term conservation is carried out at its new genebank in M'bé, Côte d'Ivoire.

Partners Genebanks from the CGIAR genebank platform (ICRISAT, ICARDA, CIMMYT, Africa Rice and IRRI) have sent copies of their collection to the Svalbard Global Seed Vault over the past few years.

These large genebanks harbor thousands of ancient or heirloom varieties and are a source of priceless genetic resources, to ensure food security for humanity in the future. Notably, in the context of global warming, gene and seed banks can prove to be crucial in the future, as we do not know the challenges we will face in the future, or the types of bacteria, viruses, insects, and fungi that can harm our crops.

Conclusion

Ancient grains consist of large arrays of seeds that include cereals and pseudocereals. They have been produced to feed humanity since the beginning of agriculture but were largely ignored by Western countries after the Green Revolution (for economic reasons). At present, the production of these grains is being revived, owing to the realization by Western countries that rely on a small number of crops can compromise food security, especially in the scenario of global warming. In addition, in the last decade, there has been momentum toward eating healthier whole grains, and ancient grains are part of that momentum. Whole grains are more nutritious and their daily consumption have undeniable health benefits. A recent survey by the Wheat Grain Council indicated that more than 60 % of shoppers consume whole grains as part of their daily diet. This regain of interest in ancient grains and native seeds has triggered more studies on how the world is preserving seed biodiversity and stimulating scientific advances.

Notably, there are lessons to be learned from the indigenous population across the world (370 million indigenous people occupy 22 % of the global land area, as of 2023), where the preservation of traditional forms of farming knowledge and practices helps maintain biodiversity, enhance food security, and protect the world's natural resources. Native seeds and the conservation of seed diversity represent a way for smallholder farmers worldwide to ensure food sovereignty and agricultural autonomy. Their farming practices render both ancient and modern visions that entail careful planting, preservation, and respect for the environment and the place of cultivation. Thus, improving social relationships by promoting knowledge exchange between farmers, through daily activities and seed fairs, is crucial for these populations. This also promotes food sovereignty, as the farmers produce what they consume and can save seeds for the next planting while selling the surplus. Additionally, this approach guarantees agricultural autonomy; by saving seeds, farmers do not need to buy the mandatory technological packages involved in planting modern commodities or large plantations. Thus, this is a sustainable farming practice, as it does not deplete the natural resources, but rather respects them. Furthermore, any intervention in seed management must consider local interactions and rules, to support women's empowerment, instead of increasing gender inequality.

However, modern countries preserve seeds in large vaults, called seed and gene banks These seed and gene banks harbor extensive collections of ancient or heirloom varieties worldwide and are a source of invaluable genetic assets, crucial for ensuring food security for humanity in the future. These seed vaults hold the key to our survival because they are a backup for nature. In recent years, genetic research and breeding on "ancient grains" have intensified, as there is a progressive universal awareness that ancient grains are our best opportunity to ensure food security in the future. Beyond the use of ancient grains, the whole system of modern farming practices needs to be revisited and enhanced, to ensure the sustainability of farming practices and reduce the vulnerability of the ancient grains to climate change.

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Mention of trade names or commercial products in this publication is solely for the purpose of providing specific information and does not imply recommendation or endorsement by the USDA. The USDA is an equal opportunity employer and provider.

Appendix

Table A1. Abbreviations

Whole Grain Council	WGC
Compound annual growth rate	CAGR
Food and Agriculture Organization	FAO
Asociación Nacional de Mujeres Rurales e Indígenas	ANAMURI
World Trade Organization	WTO
Antigliadin antibodies	AGA
Celiac disease	CD
National Aeronautics and Space Administration	NASA
Consortium of International Agricultural Research Center	CGIAR
International Center for Agricultural Research in the Dry Areas	ICARDA
International Crop Research Institute for the Semi-Arid Tropics	ICRISAT
International Rice Research Institute	IRRI
International Maize and Wheat Improvement Center	CIMMYT
International Food Policy Research Institute	IFPRI

Table A1. (Continued). Abbreviations

Leibniz Institute of Plant Genetics and Crop Research	IPK
United Nations	UN
United States Department of Agricultures National Plant Germplasm System	USDA-NPGS

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