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New Crops and the Search for New Food Resources*

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Plants are the basis for the human food supply, either consumed directly or fed to animal intermediaries. In prehistory, in various parts of the world, our forbears brought into cultivation a few hundred species from the hundreds of thousands available and in the process of domestication, transformed them to crop plants through genetic alteration by conscious and unconscious selection. Through a long sequence of trial and error, a relatively few plant species have become the mainstay of present day agriculture. The 30 most important crops consumed directly by humans (in order of production by weight of agricultural product) include sugarcane, rice, wheat, maize, potato, sugar beet, cassava, barley, sweet potato, soybean, banana/plantain, tomato, cottonseed, orange, grape, sorghum, apple, coconut, cabbage, watermelon, onion, rape, yam, oat, peanut, millet, sunflower, rye, mango, and bean. Our sustenance as a species is now based on the production of these species. There are three options available for increasing future crop resources: (1) emphasize genetic improvement and more efficient production of the major crops; (2) reinvestigate little known and underutilized crops; or (3) explore plant biodiversity to discover completely new crops. The first option continues to receive the most attention because of political support from vested interests such as growers and processors so that traditional crops have received the bulk of research support by the public sector and practically all of the private sector support, while their agricultural production has been reinforced by expensive subsidies or tax advantages. Furthermore, new advances in biotechnology have focused on the concept of altering major crops rather than minor ones because it offers the best way to increase returns on investment. Present experience indicates that improvement of major crop yields per unit or area of the major crops continues although the research cost per unit of yield increase has also risen. The consequence of this emphasis on major crops results in a continuing erosion of agricultural biodiversity. The expansion of underutilized or completely new crops offers many potential benefits including production diversification providing a hedge for financial and biological risks, national economic advantages by increasing exports and decreasing imports, improvement of human and livestock diets, creation of new industries based on renewable agricultural resources and substitutions for petroleum-based products, and the spur of economic development in rural areas by creating local, rural-based industries. Although interest in underutilized crops has increased as a result of increasing world globalization because new immigrants continue to prefer their traditional foods, there is no world strategic plan for new crop research , which is presently curtailed by lack of long term support. Similarly, the investigation of completely new crops is virtually ignored and is confined at present to the ornamental and pharmaceutical industries. The long term nature and high risk of exploring, developing, and commercializing completely new crops make it unlikely that the private sector can be successful so that government support and leadership is essential. An optimum strategy for expansion of future food resources will require a balance of effort between the three options described above.

The story of humankind is intimately connected with the search for sustenance and nourishment. An analysis of the food habits of other primates indicates that humans were originally scavengers and collectors of food while our dental structure and digestive biochemistry confirms that humans are omnivorous and well adapted to a varied diet. Our history as a species, from inception of the hominid line a million or so years ago to the present, can be viewed in light of changing technology for obtaining food and to increases in our population, both numerically and spatially, as a consequence of these technological changes. If population is indeed a measure of fitness, we are an extremely successful species, multiplying at an ever increasing and now alarming rate (Table 1).

WORLD POPULATION

The growth in human population, although increasing inexorably, has not been uniform over time, and when plotted on a logarithmic scale (Fig. 1) appears as three surges reflecting stages in our cultural and technological evolution (Deevey 1960). The first surge, from one million to about 10,000 years ago, represents

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technological advances such as progress in tool making, the discovery of fire, and the development of social organization reflecting a change from gathering and scavenging to successful group hunting. This shift in technology caused a rapid increase in the human population and our species dispersed over the entire earth forming associations into communal tribes. However, the expansion of gathering and hunting populations is limited by the fact that human populations must be kept in equilibrium with the carrying capacity of the land. This has been accomplished by a number of adaptive strategies including sexual codes to delay conception and restrict population, constant warfare to maintain territoriality, or even drastic measures such as infanticide for the young or euthanasia for the old. This long phase of human existence as members of hunting societies has had a tremendous influence on our collective psyche. Its influence is felt today in various ways such as the appeal of the chase, the division of labor between men and women, and the social tensions in human interaction ranging from cooperation and community to our predilection for actual or ritualized warfare.

Table 1. World population growth, 1990–2100 (Bongaarts 1995).

	Population (billions)			Increase (%)
Countries	1990	2025	2100	1990–2100
Developing	4.08	7.07	10.20	150
Developed	1.21	1.40	1.50	24
World total	5.30	8.47	11.70	121

The second great change affecting human history is the invention of agriculture, a series of technologies involving plants and animals used for food (Harlan 1992). Cultivated plants and domesticated animals substituted for the bounty of wild species previously harvested by gathering or hunting. About 10,000 years ago, agriculture first appears as a sweeping and sudden change, at least in the time frame of archeologists who have named it the Neolithic Revolution. The precise origins of agriculture are unknown but earliest evidence for it is found in the highlands of Tigris-Euphrates River complex. It led to another momentous population change in the history of humankind, and our destiny as a species again altered irrevocably.

The third surge in population, brought about by the scientific-industrial revolution, is barely 200 years old, and is with us now. This scientific and technological revolution enormously increased food productivity and efficiency, but the increase in population arose as a consequence of advances in sanitation and medical care that reduced mortality rates, especially in the young. The birth rate fell as populations, no longer needed in a mechanized and more efficient agriculture, exited the rural economy for an urban existence, but not fast enough to compensate for the decline in death rate. The birth rate decline lag in the demographic transformation from high birth and death rate to low birth and death rates has resulted in a huge increase in the growth of human population in poor areas of the world. Equilibrium has been achieved in North America, Europe, and Japan, but not in the rest of Asia or Africa with important consequences for the human condition in the next 100 years (Bongaarts 1995).

THE DISCOVERY OF AGRICULTURE

The ubiquitous association of agriculture and humans makes it tempting to ascribe a single locus and a diffusion pattern. But the evidence suggests that agriculture has resulted from independent but similar discoveries throughout many parts of the world. For example, we find each great ancient civilization based on grain, a nutritious, compact, and versatile source of food (wheat in the Near East, rice in Asia, maize in the Americas, and sorghum and millets in Africa) a demonstration of the technological brotherhood of humans. Although widespread over the earth, the discovery of agriculture was by no means universal. For example, the aborigines of Australia or the

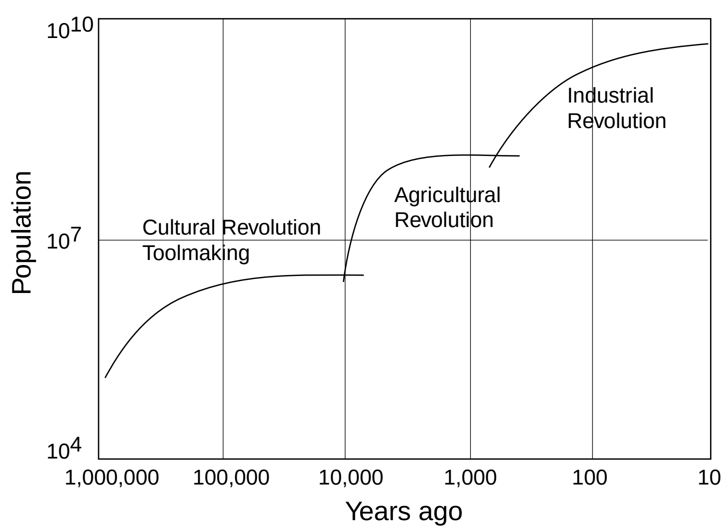

Fig. 1. The growth of human populations reveals population surges based on advances in technology (Deevey 1960).

Inuit cultures of the far north never entered this phase and remained as true gathering and hunting societies. What is remarkable about agriculture is the perspicacity of each population in ferreting out desirable food species and transforming them into new entities: crops and domestic animals, a process known as domestication.

Domestication involves two distinct events. One is to identify potentially useful species and the other is to actually transform them into dependable servants. The choice of appropriate species seems obvious when it is completed but so are all acts of genius. The virtue of the original unimproved selected species may not have been so obvious. Cassava, for example, is poisonous, and many crop are unpalatable or inedible without the cooking process. The change from wild plant to crop is accomplished by no less than a genetic transformation achieved through selection of genetic variants that intensify desirable traits and eliminate undesirable characteristics. Selection (differential reproduction) led inexorably to evolutionary changes as some weedy food plants were converted to domestic crops dependent upon humans to complete their life cycles. The traits desirable from a human perspective, such as nonshattering and loss of seed dormancy, are often those which limit survival of the plant. Cultivated plants, unlike weeds, are usually unadapted to exist without the benefit of human interference. The development of crops resulted in a loss of independence of both humans and plants. As in the case of the dairy farmer and his herd, it is not clear who serves whom the most. Many crops, maize, for example, have been so altered that they no longer exist outside of cultivation, and a direct connection to their progenitors has been all but obliterated.

The success of domestication assured the expansion of agriculture. Examples of fundamental alterations in crops are changes that ensure dependable cultivation and increase harvestability and alterations that increase productivity, usually by altering the proportion of the plant that is economically useful (harvest index) rather than an increase in true biological efficiency.

The end result of the agricultural revolution has been a fundamental change in the human condition. The interaction of humans, crops, and domestic animals has resulted in fused genetic destinies. An abundance of food causes changes in selection pressure and alterations of human evolution equivalent to those wrought by the domestication of plant and animal species. Agriculture, by creating not only a dependable food supply but a surplus to be stored, permitted civilization to develop. In the process this new system pushed out the hunter and the nomad and rapidly expanded to all usable land, filling it with people even beyond its capacity! As agriculture produced more food, it instilled the quest for fertility—of corn, of cattle, of soil, of women. The present population explosion has its roots in that phenomenon. The social ramifications of the Neolithic Revolution remain. They include the implication of territoriality and land ownership, our feelings regarding fertility and population, and our attitude regarding community.

FOOD RESOURCES

Vital to our agricultural systems is the choice of servant species to sustain us. The options are prodigious. Thus, there may be 350,000 plant species of which it is estimated about 80,000 are edible. However, at present only about 150 species are actively cultivated, and of these, 30 produce 95% of human calories and proteins (Menini 1998). About half of our food derives from only four plant species (rice, maize, wheat, and potato) and three animal species (cattle, swine, and poultry). Most marine food is still largely harvested from the sea, but this technology is now changing. It needs to be stressed that anonymous and unsung farmers and herdsmen in prehistory, not agricultural scientists, made the choices of most of our current agricultural species. Despite the tremendous advance made by the scientific revolution, the discovery or creation of new crops is a rare and unusual event. We are, in fact, dependent upon Stone Age crops and animals.

It is reasonable to pose the question whether the resource of food species that we now depend upon is sufficient and adequate for the future. Have our forebears made, in fact, the best choices of servant species? Are we hostage to the solutions of the past or can we begin anew? One is awed by the conservatism of the human species seemingly held captive by the resource base of the past. One might intuitively expect, in light of increasing population pressure, that we would be expanding the number of species to sustain and nourish us. The fact of the matter is that the trend for our food economy has been the other way, with fewer and fewer species accounting for more and more of our food. The agricultural history of the United States chronicles the rise and fall of introduced species, but through a process of introduction, trial, and error, it is now based on a very narrow group of food crops with almost 80% of annual row crop area planted to maize, soybean, and wheat.

Many crops have been developed over time in various parts of the world. Food crops may be classified on the basis of their economic importance as follows:

Major crops are cultivated worldwide in adapted areas with high economic value and are associated with high genetic input. They include grains, forages, oilseeds and grain legumes, tuber crops, fruits, vegetables, and sugar crops (Table 2).

Specialty crops are niche crops that, while economically important, have small markets that can be filled by a relatively few growers. Included are a number of horticultural species including fruit, vegetable, and spice crops.

Underutilized crops were once more widely grown but are now falling into disuse for various agronomic, genetic, economic, or cultural factors. In general, they are characterized by much less genetic improvement than the major crops but they are being lost because they are less competitive. Examples include cereals such as emmer and spelt; pseudocereals such as buckwheat; and oilseeds such as sesame and safflower.

Neglected crops, traditionally grown in their centers of origin and where they are important for the subsistence of local communities, are maintained by socio-cultural preferences and traditional uses. These crops remain inadequately characterized and, until recently, have been largely ignored by agricultural researchers and genetic conservation. Yet they may represent our most valuable potential resource for the future. In some cases, their lack of exploitation is an historical accident. Examples include the Andean root and tuber crops, and the minor millets such as *Panicum*, *Paspalum*, and *Digitaria* species.

New crops include those recently developed from wild species whose virtues are newly discovered, formerly collected or wild-crafted species, or synthesized crops created from interspecific or intergeneric crosses. They represent only a handful of cultivated species and very few are included as new foods. Totally new crops from wild species are mainly associated with industrial crops such as *Limnanthes alba* (meadowfoam), a source of unique seed oils, or *Taxus brevifoli*a, a source of Taxol, a valuable anticarcinogen. Kiwifruit (*Actinidia deliciosa*), now an important world fruit, is an example of a new crop developed in New Zealand from a crop only previously gathered in China. Newly synthesized crops include triticale, developed from intergeneric crosses between wheat and rye, and two crops derived from interspecific crosses in *Brassica*: harukan, a heading crucifer, and oo, a fodder rape.

Genetically transformed crops include those modified by recombinant DNA technology. Gene splicing is now an established technique with over 50 transgenic crops field tested in the United States. Rates of adoption by farmers for transgenic cotton, soybean, and maize have been very high from the first releases in l996. In 1998 there were about 2.8 million hectares of transgenic cotton, mostly *Bt* (54% of the total), 8.0 million hectares of transgenic soybean, all herbicide resistant (28% of the total), and 6.9 million hectares of transgenic maize, mostly *Bt* (21% of the total).

What is the reason for this diminution of diversity in our food crops? One would expect that there would be many species among the 350,000 available to us, to have equal or better attributes than those we now consume. I propose four explanations:

1. The crops chosen were not random ones but represent thousands of years of trial and error. They have

Table 2. The 30 major food crops, 1995 (megatonnes).

Cereals	wheat (554), rice (551), maize (515), barley (143), sorghum (54), oat (29), millet (27), rye (23)
Oilseeds and Legumes	soybean (126), cottonseed (58), coconut (47), rapeseed/canola (35), peanut (29), sunflower (27)
Vegetables	tomato (84), cabbage (46), watermelon (40), onion (37), bean (18)
Fruits	banana/plantain (85), orange (57), grape (55), apple (50), mango (19)
Tubers	potato (285), cassava (164), sweetpotato (136), yam (33)
Sugar crops	sugarcane (1168), sugarbeet (265)

survived because of unique attributes that cannot be denied. Wheat, an ancient crop of Southwest Asia, is a complex interspecific hybrid, adapted to bright sunny weather and cool climates for early growth. Its unique properties are based on a combination of seed proteins (gliadin and glutenin) that make possible varied bakery products such as bread, pastry, and pasta. Maize, an ancient crop of Central America, is a C-4 plant that is amazingly productive. Its nutritional deficiencies (low lysine) can be overcome by complementing animal rations with the protein of grain legumes. Rice, a native of China, is especially adapted to grow in wet climates. Potato, adapted to cool climates, has very high potential yields, well-balanced protein, and high versatility in storage and processing.

2. Our major crops have received an increasing amount of grower and scientific attention that has overcome or compensated for many of their deficiencies and increased their adaptation. Value-added processing has increased their economic importance. Thus, maize, grown principally as a source of poultry and swine feed, is now widely used as a source of starch, a sweetener replacing cane or beet sugar, and as a source of ethanol. Soybean oil is used to produce many products including margarines, shortening, and salad dressing, and the resulting protein-rich meal is used in animal feed. Soybean is also the source of many food products including miso (soy paste), shoyu (soy sauce), tofu (soy curd), soy milk (extracted fluid), tempeh (fermented cake-like product), cooked immature beans (edamame), sprouts, and is the source of textured protein for meat substitutes.
3. Our important crops have become part of our social fabric as well as our religious and cultural heritage. We have become addicted to them and, in various culinary forms, they have become mainstays of our diet. A meal without rice is unacceptable in Asia (and much of South America), as is a meal without bread or potato in Europe or North America. It is very difficult to change basic food habits.
4. Finally, the political influence of the growers of basic food grains has encouraged governments to protect them with subsidies and to support them indirectly with basic research funds and marketing assistance. This is especially true in Japan where rice cultivation is even found in urban areas, an indefensible practice from an economic standpoint. It is true in the United States, where maize growers had long been protected by subsidy, and which now, even in light of a planned phased elimination, continues still in the form of support for the ethanol industry.

A STRATEGY FOR EXPANDING NEW FOOD RESOURCES

A legitimate case can be made for expanding crop diversity and for reversing the trend toward monocultures in many parts of world agriculture (Janick et al. 1996). There are, of course, extremely successful examples of new food crops developed from underutilized species of which soybean and canola are the best examples. The soybean has contributed more than $500 billion to the US economy from 1925 to 1985 and canola (low erucic acid rapeseed) has become a major crop of Canada, recently valued at a billion dollars per year by virtue of its healthfulness as a cooking oil based on a significant fraction of long-chain monoenoic fatty acids. New crops advocates suggest that successful new introductions offer alternative means to increase farm income by diversifying products, hedging risks, expanding markets, increasing exports, decreasing imports, improving human and livestock diets, and creating new industries based on renewable agricultural resources. Diversification could spur economic development in rural areas by creating local, rural based industries such as processing and packaging and by providing general economic stability. Furthermore, an expansion of alternate crops could serve the strategic interests of nations by providing domestic sources for imported materials and by providing substitutes for petroleum based products. Diversification would also serve as a form of world food security and would make agronomic sense because reliance on few species poses special hazards and risks due to biotic hazards. The southern maize leaf blight epidemic of l970 arose because the common male sterile (T) cytoplasm of practically all hybrids grown in the United States was susceptible to an outbreak of a new strain of *Helminthosporium maydis*, a fungal pathogen, that caused a billion dollar loss in a single year. Finally, the use of new species are also important for potential sources of new industrial products of industrial compounds, new foods, and new medicinals.

The long time required for the genetic improvement of wild species, and the high risk involved, makes it unlikely that a rescreening of wild germplasm would be a profitable activity for uncovering new food crops.

In general, a search through wild species only makes sense for medicinal crops. Problems in this area relate to tensions between the governments in the countries where these plants are found and private drug companies, who in any case have shown little incentive to explore botanicals because they are not patentable. It seems clear that this effort will require cooperation between the public and private sector and the countries which claim these untapped germplasm resources.

The reinvestigation of neglected and underutilized crops is a better strategy to obtain new food crops. Recent work with pearl millet (*Pennisetum glaucum*) in the United States suggests that a number of grains could have wider appeal worldwide, especially for special situations such as for arid areas, or for double cropping (e.g. following summer wheat where the season may not be long enough for soybeans). Furthermore, the globalization of our economy has increased interest in ethnic foods, opening up an expanded market for new products.

Many neglected and underutilized crops are locally well adapted and constitute an important part of the local diet, culture, and economy; require relatively low inputs; and contribute to high agricultural sustainability. However, traditional agricultural research in developed countries has hitherto paid little attention to or ignored these crops and, consequently, they have attracted little research funding despite the fact that they are adapted to a wide range of growing conditions, contribute to food security, especially under stress conditions, and are important for a nutritional well-balance diet. Although these traditional crops often are low yielding and cannot compete economically with improved cultivars of major crops, many of these crop species have the potential of becoming economically viable.

A major factor hampering the development of these traditional crops is the lack of genetic improvement and narrow genetic diversity for important agronomic traits. Further constraints are the lack of knowledge on the taxonomy, reproductive biology, and the genetics of agronomic and quality traits. However, because these crops represent the greatest resource for meeting new food needs in the next century, publicly funded research is required. The development of the Consultative Group on International Agricultural Research (CGIAR) Centers and other associated groups have carried out research efforts in this area. These include the International Potato Center (CIP) that supports work in tuber crops; the International Crops Research Institute for the Semi-Arid Tropics (ICRISAT) and the International Centre for Agricultural Research in Dry Areas (ICARDA) which carries out work on crops of the dry semiarid tropics such as sorghum, pearl millet, pigeon peas, chickpeas, and lentils; and the Asian Vegetable Research and Development Center (AVRDC) which carries out work in tropical vegetable improvement. Unfortunately, funding for publicly supported research, both nationally and internationally, is no longer increasing, and in many cases is declining at the same time that the cost of doing research is soaring. This has prevented a serious, long term, world strategic plan for the type of research effort that would increase biodiversity. With a shortage of funds, international research efforts have understandably emphasized only those few major food crops grown in the tropics and subtropics that lead to food security: rice, wheat, maize, sorghum, banana and plantain.

At the present time, there are two competing strategies for meeting the food needs of the future. One is to increase food diversity by exploiting the potential in underexploited and neglected crops. However, genetic improvement requires a long-term, sustained effort. Unfortunately, there are no financial incentives either in the public or private sector to accomplish this feat. Only emphasis on world cooperation will be able to maximize this effort.

The other competing strategy is to seek further improvement of our present major crops emphasizing the new technology of molecular biology now fortified by genomics. For example, it has been successfully demonstrated that oil quantity and quality is amenable to change. The proponents of molecular biology stress the likelihood of altering our present oil crops (soybean or canola) to duplicate other oils. It should be possible, for example, to genetically engineer soybeans to produce oils very close to olive oil, sunflower oil, or canola, and vice versa. Clearly the incentives to do this are powerful. The present protection of intellectual property rights through patents will encourage the private sector to pursue this goal.

The current success of genetically transformed crops in the United States (*Bt* maize and cotton, and herbicide resistant soybean) provides a rationale for this approach. However, because of the enormous expense of this endeavor, the multinational research companies are reluctant to move outside of any but the most important crops. Thus, the trend toward reducing genetic diversity in agriculture is constantly being reinforced.

The coming controversy will be to decide which strategy leads to a more productive and sustainable agriculture. It should not be overlooked that molecular biology may also contribute to the genetic improvement of underutilized and neglected species by overcoming bottlenecks, but the problem is that many of these crops are not inherently productive. Thus, traditional plant breeding is still essential. I expect all these avenues to be pursued, but if I were a betting person, I would not wager against the molecular biological approach because the tide of history is in its favor. In my opinion, a way must be found to pursue both options. The only way to do this is to foster true cooperation between the public and private sector, between national and international research organizations, and among universities and other researchers. The challenge of increasing food resources to meet a doubling of the population before the end of the next century depends on such an approach.

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