Consultative Group on
International Agricultural Research

Strategies for Sustaining Crop Germplasm Preservation, Enhancement, and Use

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ISSUES IN AGRICULTURE 5

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The Consultative Group on International Agricultural Research (CGIAR) is an informal association of 40 public and private sector donors that supports a network of 18 international agricultural research centers. The Group was established in 1971.

The World Bank, the Food and Agriculture Organization of the United Nations (FAO), and the United Nations Development Programme (UNDP) are cosponsors of the CGIAR. The Chairman of the Group is a senior official of the World Bank which provides the CGIAR system with a Secretariat in Washington DC. The CGIAR is assisted by a Technical Advisory Committee, with a Secretariat at FAO, Rome.

The United States, Japan, and Canada are the leading donor countries, followed closely by several European countries. Developing country members of the CGIAR are China, Brazil, India, Mexico, Nigeria, the Philippines, and the Republic of Korea. The annual CGIAR budget is some $US300 million.

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Strategies for Sustaining Crop Germplasm Preservation, Enhancement, and Use

Garrison Wilkes

Introduction

The idea comes first, then the accomplishment; in the same way genes are the blueprint and plant breeding is the yield improvement that feeds the expanding human populations. Genetically improved cultivated plants and domesticated animals provide an assured food supply, which liberates most humans from the daily quest for food, yet over half of the world's people still live off the production of their own fields. To meet the current demands of an increasing world population an ominous conflict exists between agricultural modernization to optimize production and the preservation of indigenous agriculture along with the genetic diversity found in those areas associated with agricultural origins and development.

Agriculture is an early technology that has remained our most far-reaching impact on the planet. The quest for an assured food supply has done more to decrease biodiversity and physically alter the environment than any other activity in which we engage. Approximately 60 percent of the human population directly or indirectly makes their living from agriculture. Tragically, food production is population driven. As we produce more food, the human population becomes larger and the demand for increased yield creates an open spiral of greater impact on the land.

Germplasm is the source of the genetic potential of living organisms. Among other things, diversified germplasm allows organisms to adapt to changing environmental conditions. No single individual of any species, however, contains all the genetic diversity of that species.

This means that the total genetic potential is represented only in populations made up of many individuals. Such genetic potential is referred to as the **genepool**. The potential represented in a genepool is the foundation for our crop plants in both agriculture and forestry. Germplasm is only maintained in living tissue, most often the embryo of seeds. When the seed dies the germplasm is lost.

The limited number of plants that has historically fed the human population is approximately 1 percent of the flora of the world, and the number that have entered agriculture is a small fraction of that percent. As our human population has grown in number over the last two thousand years, and especially since the development of the science of genetics in this century, we have depended increasingly on a shorter list of the most productive and most easily stored and shipped crops. Today only about 150 plant species (Prescott-Allen and Prescott-Allen 1990) with about one-quarter million local landraces (Wilkes 1989) are important in meeting the calorie needs of humans.

Extinction of a species or a genetic line represents the loss of a unique resource. This type of genetic and environmental impoverishment is irreversible. Throughout the world people increasingly consume food, take medicine, and employ industrial materials that owe their source to genetic resources of biological organisms. Given the needs of the future, genetic resources can be reckoned among society's most valuable raw material. Any reduction in the diversity of resources narrows society's scope to respond to new problems and opportunities (Altieri, Anderson, and Merrick 1987). To the extent that we cannot be certain what needs may arise in the future (new plant diseases or pests, climatic change due to the greenhouse effect, and so forth); it makes sense to keep our options open. **This conservation rationale for future generations of humans applies to the Earth's endowment of useful plants more than to almost any other category of natural resources.**

The Challenge

It is difficult to visualize a challenge more profound in its implications yet less appreciated by the general public than our food production system's dependence on sun, soil, water, and genetic resources (IUCN 1980). Food security and biodiversity will be our most obvious challenges in the decade of the 1990s. How can we supply adequate nutrition to the 5.4 billion humans that exist now and the more than 6 billion that will exist by the year 2000? (United Nations 1989). To put the demands in perspective, in the first 20 years of the next century, one out of every ten humans that **ever** existed will be needing to eat. The food production of a single year will equal that of the entire century 1850-1950, and in the two decades 2000-2020, we will produce and consume as much food as we have since the beginning of agriculture eight to ten thousand years ago! Most of this population increase will take place in the developing countries where demand for food and agricultural products will double. The problems of a precarious food supply and rural poverty are expected to aggravate pressure on scarce land for arable farming, deforestation for new lands will increase, and pushing systems beyond sustainable limits will result in increased habitat destruction. The human population will grow with short-term food increases and not be sustained by long-term "real" increases, so that by the year 2000 the FAO estimates (FAO 1981) there will be at least 600 to 650 million undernourished on the planet, most of them children!

For the developed nations, population increases can be accommodated in part by eating lower on the food chain and consuming grains directly, but the developing world is already doing that. Because new arable land in the developing world will become steadily more scarce, higher yields mean using better agronomy dependent on a combination of more fertilizer, plowing, water lifting energy, and improved plant material. All but the last are agricultural inputs that compete for meager resources available in developing nations. Therefore, breeding for better crop plants will be the central focal point around

which all strategies to increase crop yields will develop. Human knowledge to grow and maintain the crop plants was essential in the early days of agriculture and so it will be in the high human population levels of the 21st century. It will be the positive responses of crops to agricultural systems, inputs, pests, pathogens, and social institutions that will determine the success of our attempt to feed ourselves and yet maintain agricultural systems that are sustainable (CGIAR 1989, 1990; Keystone 1991). **Also agricultural development must not come at the expense of any region or later generation, nor threaten the remaining biodiversity of the planet as we progress toward a sustainable society.**

Evolution under Domestication of Crop Plants

The increase in the Earth's carrying capacity for humans has been made possible by the development of agriculture, which in turn has been dependent on the domestication of plants and their historical distribution well beyond their regions of origin. In the process of domestication, cultivated plants have quite literally crossed a threshold from being wild in the natural vegetation to being totally dependent on human care. In many cases these crops have been so genetically altered that they can no longer disperse their own seed or compete with weeds, that is they can't revert or escape to the wild. We call this selection process domestication.

True domesticates have been so altered that they survive only under cultivation in agriculture or horticulture. One example of a characteristic that has been altered is seed germination. Farmers expect the seed of cultivated plants to germinate immediately after being placed in the soil. Such a characteristic usually would be lethal for a wild plant, which must have mechanisms to ensure germination only at the proper season, hence promoting survival. In cultivated plants survival is keyed to the farmer's commitment for seed bed preparation to

decrease competition with other plants, the sowing of seed, the protection of the plants during growth from pests and pathogens, and finally the collection of fruits, seeds, and other edible parts for human use.

All major cultivated food plants have lost the ability to exist in the wild; in other words they are fully domesticated. These plants have been selected to produce unusually large plant parts, soft edible tissue, thick flesh with intense color, and fruits attached by tough stems. They are so altered genetically that they are dependent on us: to sow them in the proper season, to protect them from competition and predation, to supply them with water and nutrients, and to harvest their propagules in order to repeat the cycle.

In the days of pre-agriculture, humans lived like any other animal in the sense that we daily hunted and gathered our food and on the days there was no success, we went hungry. Our density did not exceed 1 person per 25 square kilometers, and we were sustained on our forage territory. Today our density exceeds 25 persons per square kilometer, and in the urban zones around the world, human density approximates 600 to 1,200 persons per square kilometer with even higher densities in cities such as Mexico City, Rio, or Calcutta. Quite literally we are absolutely dependent on the yields of domesticated plants and animals and there is no turning back to hunting and gathering.

Currently, we have synthetic fibers replacing cotton and linen, and synthetic rubber replacing natural rubber, however, as yet we do not have any synthetic foods replacing our basic crop plants: rice, wheat, corn, barley, sorghum, potato, sweet potato, sugar beet, sugar cane, common bean, soybean, peanut, banana, coconut, and cassava that account for three-quarters of all human energy worldwide. This list is primarily a calorie list and does not recognize the important role of low calorie vegetables and fruits in supplying vitamins, minerals, and protein to human nutrition. Also this list does not include regional foods that locally may supply more than

one-half of the calories consumed; and, in addition, both pasture forages and fiber crops are omitted. Still the point is clear, **worldwide a very short list of food plants makes the critical difference.**

Agricultural Treadmill

The human population has exceeded the carrying capacity for long-term sustainable agriculture without inputs in many parts of the world. Clearly, agriculture cannot continue on the treadmill of always producing more. In 400 human generations, we have progressed from wild food plants to high-yielding domesticates, but we appear at or near the limits. Two generalizations characterize the present world condition:

- **We are now in a state of diminished resources on a per capita basis.**
- **Farming is no longer a subsistence activity where the cultivator eats and depends on the actual harvest, instead the cultivator depends on the money generated by the sale of the crop.**

With subsistence farming there are negative feedback loops that limit production, but cash is a neutral (universal) commodity and cropping for cash has the tendency to be an open, ever expanding, feedback system that is clearly not sustainable on the planet in which we live.

It is my personal contention that when the threshold was crossed from crops for subsistence to crops for sale agricultural became destabilized. Selection for nutritional quality and respect for local habitat carrying capacity or sustainability were shed, and many of the problems we now experience began. This recent change to crops for cash has not been all negative. Cash crops can significantly increase the income and caloric intake of a farmer with a smallholding. But the global exchange economy

that has emerged, based on the principles of comparative advantage and specialization, has increased genetic uniformity at the expense of biodiversity. It also has created the reality of global interdependence based on money and not the quality of life or sustainable land use. The crossing of this threshold has created for us **the imperative to anticipate future needs and better manage the crop plant genepools**, because the natural mechanisms that once worked to create and maintain their diversity are no longer in operation. **Genebanks and an increased cadre of plant breeders need to exist to replace the functions once carried out by the world's subsistence farmers.**

Telescoped Evolution

Charles Darwin called artificial selection, telescoped evolution because what was normally a drawn-out affair in nature was condensed to a short period of time. Plants that are potential candidates for telescoped evolution or domestication must meet three criteria. They must be:

- Capable of thriving in human rearranged environments and often in full sun (heliophytes).

- Yield productive over the short run in terms of land and labor and more recently for inputs: water, fertilizer, and improved seed. Excessive emphasis on yield ultimately leads to dense pure stands (monocultures) and warfare with competitors (insects—insecticides, weeds—herbicides, and fungi—fungicides).

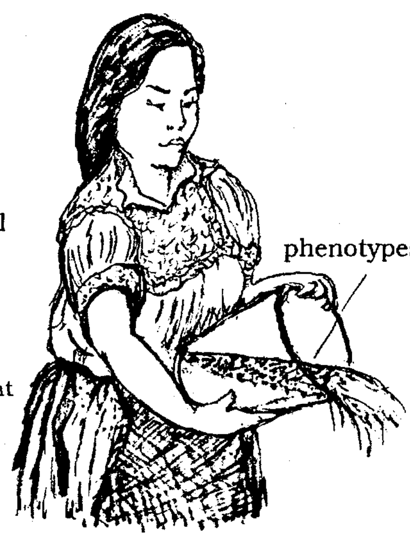
- Genetically plastic and able to hybridize, mutate, and possess a range of genetic mechanisms that promote and maintain variability.

The last criterion is especially important, because it is the one area where we can still make substantial improvements in crop plants (Harlan 1975).

Genepool Selection

The genepool of crop plants and their wild relatives can be thought of as a bucket holding fluid. Under natural selection (normalizing selection mode) the genepool is comparable to a bucket sitting on its bottom. The surface expresses the phenotype, and the volume the genepool. The top surface is small (wild type genes) when expressed as a ratio to the total volume below (recessive multiple alleles). Under artificial selection by humans, the bucket is tipped, and some of the fluid is poured off. The top surface is larger, and the ratio of top area to volume is also greater. Many traits selected under artificial selection are recessive (non-brittle rachis in cereals for example), and once they are fixed, the allelic diversity of the genepool narrows to one. Artificial selection increases the phenotypic diversity (easily observable traits—appearance) but often decreases the allelic diversity (actual genetic reservoir). It is only on hybridization of two diverse forms that the allelic diversity is again broadened in the artificial selection process. This explains why plant breeders value good parents more than high-yielding progeny in their breeding plots.

Natural selection bucket of genes or genepool with limited "wildtype" dominant genes at surface.



Artificial selection pours off many of the genes and the genepool is smaller but the top surface or phenotypes are more extensive.

The Story of Agriculture

The story of agriculture over the last 10,000 years has been essentially the same in at least four independent sites where it began: Central Mexico/Guatemala, Andean South America, the Fertile Crescent in Southwest Asia, and Mid-Northern China (Heiser 1990). First there was human selection for unique traits and a proliferation of phenotypic variance as hidden recessive genes came to the surface through artificial selection and close inbreeding enforced by physical isolation and small population size (when compared to the more widespread wild populations). Second the environment was restructured or rearranged, making it possible for the survival of genetically lethal mutations and more importantly semilethals. In addition the seed was carried into new areas beyond its original native distribution as cultivation expanded, and alleles (diverse forms of a single gene) deep in the volume of the genepool bucket (hidden variation) rose to the surface, because they conveyed adaptation factors for the new conditions.

The expanded cultivation following domestication brought the crop into the territory of wild relatives with which they were not genetically protected by isolating mechanisms, and inevitably hybridization occurred to produce a wealth of variation that has driven the selection process ever since (Simmonds 1976). Examples are the hexaploid bread wheats (6x) that can be thought of as three plants in one. Maize hybridized with teosinte, its closest relative, but unlike wheat kept the same chromosome number. Through back and forth or introgressive hybridization, genetic exchanges have occurred so that part of the teosinte genome is in maize and vice versa (CIMMYT 1988). Because of introgressive hybridization, teosinte is a "little second plant" in the maize genepool (plant within a plant). Regionally distinct forms of cultivated rice hybridized and resulted in explosive bursts of variation (Chang 1985). Potatoes are a polyploid like wheat. Almost all major crop plants have developed a mechanism of one form or another to expand the gene

base and this has countered the tendency of artificial selection to narrow it (Wilkes 1989).

History of Plant Breeding

Historically, plant breeding as a human activity can be viewed as developing through three phases and we are currently on the threshold of the fourth. The earliest domesticated crops were probably not much more productive that the wild progenitors, but the act of cultivation was a radical break with the past as artificial selection was applied to small isolated populations. This was the first stage of plant breeding or human control over crop plant evolution. All the major world food crops were developed in this first stage (Hawkes 1983).

The second stage of plant breeding came with the discovery of the New World or Columbian Exchange that followed the circumnavigation of the world. A rapid diffusion of crops, livestock, and farming techniques coupled with emigration resulted in tremendous genetic recombination as distinct and far-flung crops or distinct landraces were brought together and hybridized in farmers' fields. This era also saw the development of colonial empires in the tropics and cash plantation crops such as coffee, cotton, rubber, and sugar cane. Many of these cash crops, such as coffee, were moved from the Old World to the New, where free of their diseases, they became more productive; or the reverse, New World to the Old, such as rubber. These plantation crops were the first modern cash crops. Now all field crops, with the possible exception of kitchen gardens, are cash crops.

The third stage of plant breeding and improvement began with the rediscovery of Gregor Mendel's classic experiments on the heredity of garden peas at the beginning of this century. For the first time the plant breeding community had a set of principles by which to proceed with the crop improvement process. Products of this era are hybrid corn, changes in the photoperiod response of soybeans, and the dwarf stature wheat and rice from the

Centro Internacional de Mejoramiento de Maiz y Trigo (CIMMYT) and the International Rice Research Institute (IRRI) respectively. These late 1960s Green Revolution cereals (dwarf stature wheat and rice) and the genes they hold now enter the food supply of 2 billion people and are directly responsible for feeding more than 800 million people by their increased yields.

The fourth era of plant breeding, genetic engineering, promises to have an impact equal to that of computers in the way we go about managing and structuring the productivity of the world around us. Traditional plant breeding is, in fact, genetic engineering, but this term is now being limited to biotechnologies such as *in vitro* cell culture, and recombinant DNA techniques. These biotechnologies can speed the breeding because genetic material is introduced directly into cell cultures (splicing), completely sidestepping the genetic recombination through the usual sexual processes or when cell cytoplasm is altered as in protoplast fusion. And, of course, all of these changes depend on cloning technologies where hundreds of identical plants are grown from units as small as a single cell. Already potatoes developed at the Centro Internacional de la Papa (CIP) using these techniques are having a significant impact worldwide and superior clones of cassava are leaving the Centro Internacional de Agricultura Tropical (CIAT) for Africa and Asia.

The advent of these technologies has ramifications that affect our current state regarding plant germplasm. Because these advances are produced using unnatural means they can become intellectual property and thus are potentially protected by the laws of ownership. The specter of patent protection has polarized the public views of germplasm as either public good (common heritage) or private good (rewards for value added). On a broad brush, the developed world has the skill to enter the biotechnology game, but because the developing world mostly lacks the resources (personnel, institutions, and finances) it is fearful of what these new technologies hold for it in the future (Juma 1989). Much of this fear is reflected in an International Undertaking on Genetic

Resources of FAO (Witt 1985). This has been good because it has focused attention on why plant genetic resources have been undervalued, but unfortunately the discussions and solutions sought have been more political and have not led to an accelerated implementation of strategies necessary to conserve and use crop diversity (Wilkes 1988). These strategies center on five scientifically based issues: 1) genetic erosion, 2) genetic wipeout, 3) genetic vulnerability, 4) genebanks, and 5) training for plant breeding.

Genetic Erosion

The technological bind of improved varieties is that they have a tendency to eliminate the resource which they are based on and from which they have been derived. Current elite varieties yield better than the varieties they displace. Once a displaced variety is no longer planted, its genes are lost to future generations unless it is conserved. Primitive forms also are lost because of bad land use planning, environmental degradation, and urbanization. Elite varieties also have a second force: they create market expectations. Once a highly uniform variety captures a large fraction of the market share, other varieties are bred to mimic or have the same attributes as this leading variety. This further eliminates diversity within the crop and even across crops. The market place also has the potential to influence and form a market focus for a single variety. These marketing forces of 'volume sales' and specialized handling of specific varieties actually have promoted the decrease in the total number of crop plants that enter commerce. Long-distance transport focuses on a limited number of commodities and on only certain crop varieties, with the result that local producers and small unique variety suppliers are forced out. In developing and developed countries the deep well for the genepool in landraces and in folk- or farmer-maintained varieties, which has been the foundation of the past breeding process, is disappearing. When a tree falls in the forest there is a crash;

when the seed of a unique variety is no longer planted it is a silent loss. Like soil erosion, it is gone with no drama of disappearing; genetic erosion leaves a void and a diminished genepool.

Genetic Wipeout

The wholesale loss of plant genetic resources is called by some, "genetic wipeout," a somewhat emotive term but useful in drawing attention to the problem. Genetic erosion is a slow gradual process based on the independent individual decisions of farmers while genetic wipeout is the rapid and one stroke destruction of genetic resources, usually by institutional failure. Social disruptions such as political instability or crop failure and famine due to natural disasters can eliminate genetic resources rapidly and have done so repeatedly in the past. Quite literally the genetic heritage of a millennium in a particular valley can disappear in a single bowl of porridge if the seeds are all cooked and eaten instead of some being saved as seed stock. Equally dramatic is the discarding of a genetic collection because a curator retires and the collection is no longer of use to the institution. This is especially tragic if a comparable collection can no longer be recollected because of genetic erosion in the countryside. The processes of genetic erosion and genetic wipeout are not mutually exclusive but are, in fact, two ends of a spectrum interlocked by the demands of an increasing human population under which biodiversity impoverishment increases daily.

Genetic Vulnerability

To be vulnerable is to be at risk. One of the attributes of humans that sets us apart is the ability to learn from the past, to anticipate the future, and to be aware of risk. Another attribute is our ability to adapt and modify our behavior to minimize risk and decrease our vulnerability. We have been so efficient at food production that we tend

to forget how much of the natural ecosystem we have rearranged and also forget there is vulnerability in that agroecosystem until a crisis—drought, crop disease, or pests—reminds us, that we are dependent on a food supply to sustain life (NAS 1972).

What is meant by genetic vulnerability? "Genetic" is clear, determined by genes, but "vulnerability" is more open to interpretation. The dictionary definition for vulnerability is "unprotected from danger." Thus genetic vulnerability means the extent to which crops are unprotected from danger by the genes they carry or in some cases lack them altogether. The danger is usually considered to be the potential damage from unsuspected pathogens and pests. These may be new strains or biotypes of a species already known to be able to attack "susceptible" varieties, or they may be pathogens and pest species that are encountering a new host species or variety for the first time.

The fact is epidemics hit the hardest if the host species is highly and uniformly susceptible and also present in dense stands of individuals. The host species may be either genetically very diverse overall (as varieties or a individuals), or genetically uniform overall, **but if it is genetically uniform for susceptibility, then epidemics may result**. Such was the case for the single gene in the Texas male sterility cytoplasm of maize (1970 U.S. corn blight epidemic), which conditioned a highly susceptible reaction. No matter what genetic background that gene is in, an epidemic with race T of the corn blight pathogen will occur, given the right environmental conditions. In this case the gene giving susceptibility was an "agronomic gene." There was no "breakdown" of a resistance gene. No matter what the genetic basis of susceptibility the three major hazards are pathogens (fungi, viruses, and so forth), pests (insects, nematodes, and so forth), and abiotic stresses.

The key point about epidemics is that they are promoted by dense stands of individuals containing the same gene (or genes) conditioning susceptibility, regardless of their overall genetic uniformity or diversity. The magnitude of the epidemic will be conditional to the geographic distribution of the gene (or genes) for susceptibility and the number of humans dependent upon the susceptible variety as a food source. Genetic vulnerability is the potentially dangerous condition of "thin ice" of having a narrow genetic base. Never before have there been such widespread monocultures (dense uniform stands of billions of identical or nearly identical plants) covering thousands of hectares. The narrowness of the genetic base is responsible for, on the one hand, the predictability of higher yields, and on the other hand, the greater risk of crop failure.

Crop specialization and genetic uniformity do not create vulnerability. What they foster are the rapid inroads over vast areas if a vulnerability does develop. Genetic vulnerability is in fact a market phenomenon because farmers make the choice of which variety is best for them. If a widely planted high-yielding elite line crashes under the stress of a severe drought, the impact is large because the variety responding to the stress accounted for a sizeable percentage of the crop acreage. Neither the genetic uniformity of the variety nor the vast acreage caused the drought. Given the drought and the susceptibility of the variety to drought stress, the impact of vulnerability was magnified. Given a normal year the improved variety results in magnified yield, which is the desired outcome, and the reason certain varieties are so widely planted. Some widely planted and genetically uniform varieties have remained durable for decades and other varieties have folded the year they were released.

This push for genetic uniformity over vast areas has increased the potential for genetic vulnerability as plant breeding of important commodities has become inter-

nationalized first from the International Agricultural Research Centers such as CIMMYT, IRRI, and CIP and now from private seed companies that sell seed around the world. Currently, the potential for a crop failure hinged to genetic vulnerability is considerable, and there is significant reason for concern. Genetic diversity in time (the sequential replacement of cultivars) is the chief substitute today for genetic diversity within cultivars (or among crop species) and it requires a bountiful support for dynamic plant breeding activities.

Genebanks and Germplasm

Genebanks are an institutional solution to genetic erosion and genetic wipeout. Although a degree of *in situ* conservation can preserve parts of the genepools of crop plants, to date this mode of conservation has not been implemented broadly enough to be as successful as *ex situ* genebanks. To be successful genebanks must have four distinct functions in addition to preservation of seeds and clones to counter loss due to genetic erosion. They must:

(1) Be linked to exploration of undercollected zones to increase and maintain representation of the genepool as samples in the genebank.

(2) Maintain the genetic integrity of samples, storage over time, and regenerate stocks periodically.

(3) Evaluate and document to maintain a useful data base to guide management and use of the holdings.

(4) Be linked to active evaluation, prebreeding, and early breeding for enhancement so that genebank materials will be in a useful form for the plant community.

Unless there are more plant breeders working with genebank materials to mix and evaluate the genes, agriculture with elite varieties will undermine itself and fail.

IARCs and Their Crop Responsibilities

Institute	Year Established	Location	Crop Responsibility
International Rice Research Institute (IRRI)	1960	Philippines	Rice
International Maize and Wheat Improvement Center (CIMMYT)	1966	Mexico	Wheat, maize, triticale
International Center for Tropical Agriculture (CIAT)	1967	Colombia	Beans, cassava, rice, tropical pastures
International Institute of Tropical Agriculture (IITA)	1967	Nigeria	Cassava, maize, plantain, cowpea, soybean, yams
International Potato Center (CIP)	1970	Peru	Potato, sweet potato
West Africa Rice Development Association (WARDA)	1970	Cote d'Ivoire	Rice
Asian Vegetable Research and Development Center (AVRDC)	1971	Taiwan	Selected tropical and subtropical vegetables
International Crops Research Institute for the Semi-Arid Tropics (ICRISAT)	1972	India	Sorghum, pearl and finger millet, chickpea, pigeonpea, groundnut
International Livestock Centre for Africa (ILCA)	1974	Ethiopia	Browses, grasses, legumes
International Center for Agricultural Research in the Dry Areas (ICARDA)	1975	Syria	Barley, lentil, faba bean, durum wheat, bread wheat, chickpea
International Centre for Research in Agroforestry (ICRAF)	1977	Kenya	Multipurpose trees
International Network for the Improvement of Banana and Plantain (INIBAP)	1984	France	Banana and plantain

Seed is the most common mode of genebank preservation. Seeds age in even the best genebank and ultimately die sooner or later depending on the species. Periodically the seed must be planted, populations maintained through controlled pollinations, and new fresh seed stock returned to the genebank. A seed genebank is generally the easiest to establish and does not incur a significant cost or management crisis until years later when the need for scientifically based regeneration develops.

To better understand genebanks requires an appreciation of the kinds of genetic materials that can be saved as seed. For convenience, germplasm can be organized in six distinct categories (Wilkes 1977) based on their station or advancement in the agroecosystem.

- *Varieties or cultivars in current use*, often very advanced elite varieties.

- *Obsolete cultivars*, often the elite varieties of 20 to 50 years ago and usually found in the parentage of current cultivars.

- *Primitive cultivars* or landraces of traditional agriculture.

- *Wild and weedy taxa* near relatives of crop plants.

- *Special genetic stocks*, including induced mutants.

- *Coadapted genetic stocks*, in which two forms of a crop, two distinct crops, or a crop and symbiont such as a crop and its unrelated weed or nodule-forming bacterial are grown together.

Varieties or cultivars in current use have generally undergone a vigorous selection process by plant breeders for plant type, response to input, predictability of yield and are more or less homogeneous genetically. The released varieties possess a "highly tuned" set of elite

genes but a considerably narrowed gene base against the foundation parents from which they have come. Ultimately these foundation stocks trace back to landraces in diverse parts of the world. The released advanced varieties most favored by farmers are the ones most widely and frequently used as partners in current breeding programs for the next cycle of varieties. On average, varieties are replaced every 5 to 10 years, so they have a commercial lifetime of maybe 7 years. Some released varieties are knocked down by either pests or pathogens the year they are released, so there are no guarantees on the durability of new varieties.

Obsolete cultivars are advanced cultivars from the most recent past that have been displaced by a newer release. Often specifically selected older materials appear in the pedigree of a wide variety of releases. Some obsolete varieties are more useful as parents than they were as varieties at the time of their release. The Wheat Genebank at CIMMYT is holding a large collection of obsolete varieties that can be computer searched through a pedigree chart data base. Both special genetic stocks and induced mutational stocks, which are used in the breeding process. are comparable to obsolete varieties in the amount of genetic variation they possess.

Primitive cultivars or landraces are the real treasure house because they are the largest depository of genes for a crop. They are also the largest unknown because they are usually heterogeneous genetically and few data exist on their morphological, biochemical, and genetic traits, or their responses to pests or environmental stresses.

Landraces are a rich source for new traits but usually exhibit narrow local adaption. Landraces seldom, if ever, make acceptable broadly adapted varieties. Generally, landraces perform poorly under high inputs of fertilizer, water, and intensive cultivation and are replaced by the new elite seed. On the other hand, there is a fairly wide variation in the ability of landraces to survive fluctuating environments, to withstand cold, drought, insect damage, and other such variables. After all, most

landraces represent accumulated mutational events integrated and balanced in the real world over centuries. It is with the genes landraces possess that modern plant breeding has formed the current elite varieties.

The *wild relatives* and weedy taxa are poorly represented in genebank collections and the most difficult to regenerate. This is because these ancestral forms and wild relatives closely related to the no longer extant ancestral taxa do not come from cultivated fields but come from unique and often highly specific wild habitats. These taxa self sow their seed and exhibit genetic adaptation in an often very narrowly defined environment for day length, soil, and water relationship. They possess many dominant wild type alleles and carry rare recessive alleles at very low frequencies. It is almost impossible to regenerate the genetic integrity of the wild collected seed because the site of regeneration does not match the site of collection. There are regeneration site selection forces and it is difficult to regenerate a population of sufficient size to capture rare alleles with confidence. In most genebanks the wild and weedy forms are simply a form of wild populations and not a broad enough net to capture the genetic diversity of these unique genetic systems that have genes compatible with but not found in the crop plant.

To compound the problem most plant breeders have limited interest in the wild and weedy relatives and their biology is not as well known as the crops. Most of the wild relatives (and there are certainly exceptions such as wheat, barley, and maize relatives) have only been collected along roadsides and the full extent of their populations is not fully known. These plants, which are neither cultivated nor of interest to most herbarium taxonomists, have been understudied. Certainly they should be in genebank collections and it is important to conserve them *ex situ* as seed. The strongest case for *in situ* conservation can be made for wild relatives in their native habitat.

The *special genetic stocks* are usually carefully constructed genotypes such as seed lacking a specific

chromosome or chromosome markers with recessive alleles on the chromosomes that are the tools of the plant breeder. These stocks make up a small fraction of the total genebank but they have been useful in the past and certainly have utility for the future. Many have been constructed through long selection processes and these tester stocks belong in the collections.

The last category is seldom found in genebanks and comprises materials that the future with biotechnology tools will want to exploit in new and novel ways. **These are two genetic systems that express mutual coadaption or coevolution.** This can be two varieties of the same crop with the same growth habitat, height, planting, and so forth, but one is long season the other short; two distinct crops again with the same growth pattern (maize and sorghum grown together in Honduras where with sufficient water there will be both a maize and sorghum harvest and in dry years only sorghum). The most extreme pattern of these coadapted systems is a crop and its nodule-forming bacteria or unique pollinator insect. The tropics have numerous examples of these coadapted systems in relay planting, double cropping, and perennial agricultural systems that haven't been adequately captured in genebank collections. Some of these coevolutionary patterns are not even known to us and the hope is that *in situ* conservation will preserve them until we better understand how they work and can include them in genebanks.

In Situ Germplasm Conservation

The need for *in situ* conservation is really a relatively recent event. One hundred years ago humans were packed less densely, communication was localized, and our demands on our surroundings less harsh. All useful plants and animals were maintained in the open world of fields and forest (Vavilov 1935). Only recently have we engaged in *ex situ* conservation of crop plant seed in cold storage seed banks or *in situ* preserves. Before the world was so restructured by our activities these functions took

care of themselves (Altieri, Anderson, and Merrick 1987; Oldfield and Alcorn 1991).

In situ conservation in perpetuity can take two somewhat distinct but overlapping pathways:

- *Entire Biomes* — the entire preservation of vast tracts with the *in situ* conservation of animals and plants. This is a continuum from vast tracts of wilderness, totally devoid of humans, to unique habitats with considerable management and protection by humans. This level of preservation will be extremely important in slowing the species extinction rate but will have little impact on regenerating degraded habitats or habitats that humans exploit as a resource base. Conservation at the biome level works to get humans out of the picture and does not promote humans at the pivot point of the system.

- *Specific Sites* — preservation of those useful plants and animals in a dynamic interaction that does not lead necessarily to a decreased carrying capacity of the human population. This also is a continuum from the tracts necessary to sustain a hunting-gathering society, to shifting-milpa agriculture, to cultivated fields where the local crop landrace hybridized with a field margin, weedy, wild relative. The essential elements are that the plants and animals are found useful by humans and the human density does not increase to the point where the resource base is degraded. In truth these idealized systems will not be easy to achieve by *in situ* conservation but will deaccelerate their disappearance and give us more time to understand and appreciate how these systems evolved. Considerable potential exists for creative institutional arrangements including tourism for *in situ* conservation, especially for historical sites and in the developing countries.

Levels Of *In Situ* Management

So as not to lose sight of the full context of genetic resources, and the role of *in situ* conservation, I've broken the whole into four major groupings. These four are listed in terms of decreasing intensity of human management in the context of *in situ* preservation (Plucknett and others 1987; Alcorn 1991).

• Cultivated plants and domesticated animals	Living historic farms and sites rich in historical significance to the national heritage
• Wild relatives of domesticated plants and animals	Evolutionary gardens and gardens of chaos in centers of crop diversity and origin — often showing peasant farming at best, *in situ* monitoring of wild populations; this level might also include "hot spots" for pests and pathogens of selected crop plants.
• Wild species used directly	These are the "extended kitchens" of many peasant farmers that extend into the forest; the species may be wild but their survival managed.
• Wild species currently not used by people	Maybe they are still unrecognized.

Because of the large number of accessions in the major crop collections (2 million), there is no way that an *in situ* system could be employed for all. In essence such a mandate would freeze all landrace in the genetic landscape of peasant farmers, placing much too high a social cost on peasant farmers. But a limited number of selected landraces in key sites would be both feasible, practicable, and appropriate. These key sites would be especially useful if they were located in "hot spots" where

the diseases, pests, and pathogens of the crop were also evolving under the pressures of natural and artificial selection. These would remain evolutionary gardens for continued dynamic genetic change (Hoyt 1988).

These selected *in situ* stations would highlight the issue of genetic resources because of their location and educational function. To be effective, such *in situ* conservation of landraces needs to be coupled with both tourism and research. A visit to the Mayan ruins at Chichen Itza along with a reconstruction of a milpa carefully researched by the Mexican Escuela Nacional de Agricultura would impress affluent tourists about the primacy of plants. The same could be done for potato and other tubers in the Peruvian highland agriculture at Inca Ayacucho. In the Old World, village India at the fertility temple sites around Khajuraho would be an excellent site.

The elements these *in situ* programs have in common is a living connection to the past. Living plants on display are a shared heritage from the past for all people. These are the crops that feed us and support our cities and our ability to live at high density. In making the connection between the past and present we make our identity to the past. Mexico can be proud of maize, its contribution to the world community; India its contribution of sugar cane and rice; China its contribution of soybeans, rice, and tea; and the list goes on for about 500 significant food plants that support a human population of 5.4 billion. Yet the most significant service of *in situ* landrace preservation is not the heritage from the past, or the pride of the present, but the sense of direction. The living farms with their heritage germplasm of *in situ* landraces wouldn't preserve the genetic landscape as much as they would instill pride in the plant domestication accomplishments of the indigenous peoples in the past. These farms wouldn't focus on just one crop but the mix of different crops and the cropping pattern. This is what *in situ* can do best, whether it be the crop and its wild

relatives hybridizing or the interaction of two genotypes of the same crop or two distinct crops interacting in the same field.

The second case for *in situ* conservation is evolutionary gardens. These are the great natural resource bases from which our useful crops have developed. These are the fields where the crop and its weedy wild relatives on the margin continue to hybridize and where there is the dynamic evolution through introgressive hybridization or changes in ploidy level. Teosinte in Mexico is a classic example of such a relationship. These systems are analogous to a still where the boiling of the mixture is hybridization and where the distillation by both artificial selection (the crop) and natural selection (the wild relative) results in a dynamic generation of genetic refinements in the plants. *In situ* preservation of these sites would allow this system to continue for future evolution of the crop genetic system under full selection pressure of both pests and pathogens (Wilkes 1971).

We know so little about the domestication process, which has taken place in the last 10,000 years, the prehistory, for most of the major crops. These *in situ* zones of crop origin are windows on the past that are being closed by changes in land use. Until a few years ago it was possible to find in the Nordic countries two distinct barleys, one early, the other late, with identical stature planted together in the same fields. Presumably these are in the Nordic Genebank but the knowledge of which two accessions go together is lost! Also there is a pea and barley combination that has been lost. In Mexico we still have the corn/bean/squash coadapted systems in place but they will not remain given the current economic priorities.

Future generations might thank us immensely for "holding the line" and preserving 500 of these systems worldwide for future study. Right now, when seed from these locations (weed and crop) go into *ex situ* genebanks,

many times the two are not cross-referenced. One of the few collectors who has been very sensitive to this problem is Professor Angel Kato-Y in Mexico (Kato-Y 1976).

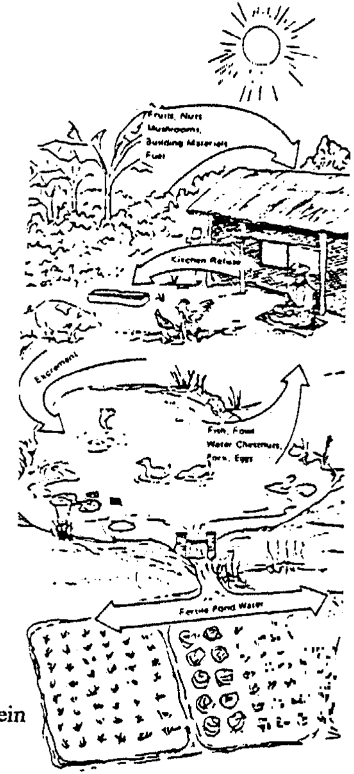
Now we come to the other side of the evolutionary gardens where the focus isn't on a single crop but on all the plants that the indigenous inhabitants use in the landscape. This is an evolutionary sequence also because some of the plants are full domesticates, some are incipient domesticates, others are gathered regularly, and some only occasionally. To find a society at stability using the vast knowledge of their surroundings is the ethnobotanist's dream. This way of life only exists in a non-cash society and so most have disappeared and the rest are disappearing. The information potential here is tremendous.

These are the "Gardens of Chaos" of Edgar Anderson (Anderson 1952) where the agricultural extension officer considers it his moral responsibility to set the garden in straight rows and generally clean up the act. Edgar Anderson correctly saw everything as being in its place and balanced like a miniature ecosystem where relationships were defined by webs rather than straight rows. Often these gardens have no clear line where native vegetation begins and indeed the wild plants are managed for useful products. Books can list the species used but they have a hard time drawing in all the lines of connection that is the web of these self-sustaining peoples and their plant and animal cohabitants of the "hearth." The evolution here is of the entire habitat and only *in situ* will capture this for genetic conservation.

I think the strongest case for *in situ* conservation of useful plants in a self-sufficient peasant society is as a teaching tool to reestablish the primacy of plants to an industrial model/style of thinking urban dweller (you have seen one corn plant you have seen them all), who is entrained on the supermarket. These decisionmakers have forgotten that civilization depends on an assured food supply. They have forgotten or never really knew that yields and harvest are fraught with the variance of weather, pests, and pathogens. *In situ* preservation of

Row Crops and Garden Crops

	Field Crop Seed Agriculture	Dooryard Vegetative Culture
Yield to Work Expanded	High	Low
Area of World	Temperate	Tropical
Plant Life Cycle	Seasonal	12 months and more
Biomass	Monoculture Small	Diversified Large
Stratification	Open to sun	Sun and shade mixed
Mineral Cycle	Prairie soils Bare ground Open	Lateritic soils Harvest and planting same operation More nearly closed Use of detritus
Predator Control	Physical	Biological
Seasonal Peaking Periods	More pronounced Harvest storage problems	Less pronounced Continuous harvest
Plants Used	Many with high protein yield	Fewer with high protein yield



self-sustaining agroecosystems is one of the best way's to demonstrate that environmental impoverishment is irreversible. There is a saying I like that sums up this issue: "The law locks up he who steals the goose from off the common, but lets loose he who steals the common from the goose."

We can't stop population growth and the simplification of ecosystems to planted monocultures but we don't have to have these conditions everywhere. *In situ* preserves are thresholds to what the world once was and hopefully they can be models to how it might be in the future. This doesn't mean that we all will go back to hunting and gathering. It means that by preserving some of the remaining human sustaining biological systems in place we will have models that work to guide us in the quest for sustainable agriculture. Dwarf stature wheat begot the idea of dwarf stature rice. Likewise gardens of chaos begot relay planting of crops now successfully deployed in Asia. The multilines with the same stature but differing maturities, pest resistance, or stress-tolerance are all modeled in gardens of chaos. Coadapted different taxa are ideas that biotechnology talks about in cell fusion across taxa lines yet these systems already exist in many village dooryard agroecosystems. These *in situ* "extended kitchens" have considerable information and their preservation is best justified if they are well-studied. Unfortunately, they are disappearing because much of the agricultural research work is following maximum yields and increasing dependence on the products of plant breeding (Wilkes 1971, 1991).

Genebanks and Storage

To be stored safely for a long time, living seeds and the genes they hold must be at a low moisture content. A large number of seed crops may be stored for up to 25 years or more at refrigerated temperatures just above the freezing point. These are called "active storage conditions." Longer storage periods are maintained at subfreezing temperatures. At temperatures of -18/20ºC safe storage

for 50 years or more is the norm. These are called "base storage conditions." At the temperatures of liquid nitrogen, super dry seed (approximately 6 percent moisture and in some cases as low as 3 percent) is expected to remain viable for up to 500 years, and certainly periods of 100 years is a reasonable time frame. The number of national and institutional genebanks with refrigerated active collection storage conditions exceeds one hundred. The number of genebanks with base collection storage facilities is less than forty.

Not all genebanks have gotten around to actually regenerating their collections with rejuvenated fresh seed. **Creating new genebanks does not correct the problem. It is only when genes increase the diversity in farmers' fields through the characterization, evaluation, and prebreeding process of growing the seed and searching for useful traits that we can say the technology of genebanks is really dependable enough to replace the older system of farmer held seed.** The concept of genebanks looks good on paper, but so far only the banks of the International Agricultural Research Centers, numerous developed country, and only a few developing country programs have the system in place and have a proven record of moving the genes back into farmers' fields (Table 1).

Approximately 75 to 90 percent of the variation in the major crops and less than 50 percent for many minor crops is found in genebanks (Plucknett and others 1987; Cohen and others 1991). The largest genepool is found in the silently shrinking landraces and folk varieties of indigenous and peasant agriculture. Increasingly, the centers of genetic diversity for crop plants have become the mega-genebank storage facilities and not the countryside. Genebanks are filled with seeds on the hopes that they will be useful, however, until these banks undertake the evaluation of their holdings I prefer to call them storage facilities. Worldwide there are far more storage facilities than genebanks at the present time. Using my concept of working genebanks with regeneration and evaluation capabilities few models can be found

Availability of Genebank Accessions to Potential Users, USA[1]

Center	Crop: Facility*	Accessions	Accessions able to be regenerated per year	Accessions sufficient for distribution	Location available for regeneration
NPGS	Barley:				
	NSSL	721		436	2
	NSGC	26,168	5,000	22,175	
	Maize:				
	NSSL	21,671		1,865	2-7
	NCRPIS	8,783	450	7,000	
	Potato:				
	NSSL	3,262		86	1
	IRI	4,272	300	4,000	
	Rice:				
	NSSL	942		205	1
	NSGC	16,010	5,000	13,899	
	Tomato:				
	NSSL	1,984		1,202	1
	NERPIS	5,615	300	5,500	
	Wheat:				
	NSSL	1,597		619	2
	NSGC	42,478	5,000	36,932	
	Totals				
	NSSL	29,674		4,413 (14.9%)	
	Regional	103,326	16,050	89,506 (86.2%)	

Table 1. Percentage of accessions from the National Seed Storage Laboratory (NSSL), Fort Collins, Colorado, and regional plant introduction conservation facilities available for distribution after regeneration. Values shown are numbers (of accessions or locations) and percents of totals.

Notes: *Acronyms for regional plant introduction and collection facilities are as follows: NSGC—National Small Grains Collection; NCRPIS—North Central Regional Plant Introduction Station; IRI—Inter-Regional Potato Introduction Project; NERPIS—Northeast Regional Plant Introduction Station. Values for NSSL indicate number of unique accessions not yet in the regional plant introduction facilities.

[1]Numbers from Cohen and others 1991. The United States is used here illustratively because it is a coordinated multicrop system. The collection in Gatersleben, Germany, for instance, could have been used.

outside the IARCs and the developed nations. The IARCs have the envious record of regenerating, evaluating, using, and maintaining their collections (Table 2).

Looking at Tables 1 and 2, any genebank that can distribute 85 to 90 percent of its holdings at any given moment is fully functional. Always there will be shortfalls for difficult to regenerate and/or widely called for seed and hopefully these can be supplied within a year or two. Remember also there are differences in field space and human effort due to pollination system differences. Not all crops are the same. To regenerate a mostly self-pollinating crop like wheat takes little space and only a few plants to regenerate an accession. To regenerate an outcrossing plant like maize requires at least 256 plants and handmade chain pollinations (different male and female plants) of at least 100 plants to catch all the alleles in the accession with a frequency of higher than 5 percent. Genebanks that can provide only 50 to 85 percent of their accessions at any given time are in need of upgrading. Genebanks that can provide less than 50 percent of their holding are in serious trouble. Many genebanks around the world are in this last category. The good part is that there is still time to upgrade the situation with many national collections before germplasm is lost.

Realizing our dependence on landrace genetic resources creates a sense of humility, which in the arrogance of our accomplishments, we have often ignored. In the words of Sir Otto Frankel: "To an unprecedented degree, this decade of vast consequence for the future of our planet is in the hands of perhaps two or three generations...no longer can we claim evolutionary innocence...we have acquired evolutionary responsibility" (Frankel 1974). Sir Otto has been very blunt. If we know what we are destroying through negligence and inaction, then we are morally responsible. Plant breeders, conservationists, and international policymakers need to start pulling in the same direction to save our crop plant genetic heritage (Kloppenburg 1988; Frankel 1989).

Availability of IARC's Genebank Accessions to Potential Users[1]

Center	Crop	Accessions	Accessions able to be regenerated per year	Accessions sufficient for distribution	Location available for regeneration
AVRDC	Mungbean	5,273	1,000	3,200	2-5
	Pepper	3,471	250	1,000	2-5
	Soybean	12,303	1,000	8,000	2-5
	Tomato	3,814	350	3,000	2-5
	Total	24,861		15,200 (61%)	
CIAT	*Phaseolus* (bean)	25,000	1,800	20,000	3
	Tropical pastures	21,000	1,800	14,000	3
	Cassava	4,500	*In vitro*	*In vitro*	
	Total	50,500		34,000 (74%)	
CIMMYT	Barley	7,200	2,000	6,480	3
	Bread wheat	48,600	8,000	43,740	3-7
	Durum wheat	15,300	3,000	13,770	3-7
	Primitive wheat	4,320	4,000	3,888	3
	Triticale	11,700	3,000	10,530	3
	Wild relatives	2,700	500	2,430	3
	Total	89,820		80,838 (90%)	
	Maize	13,346	250	10,910	4-8
	Teosintes (annual and perennial)	93	*In situ*		
	Tripsacum spp.	90	Clonal		1
	Total	13,529		10,910 (81%)	
CIP	Potato (Clonal, *in vitro*, seed)	4,500	3,500 clones 300 seeds	3,500 seeds 650 clones	4-9
	Sweet potato (clonal, *in vitro*, seed)	5,507	2,000 clones 300 seeds	50 clones	1
	Total	10,007		4,200 (40%)	

Availability of IARC's Accessions (cont'd.)

Center	Crop	Accessions	Accessions able to be regenerated per year	Accessions sufficient for distribution	Location available for regeneration
ICARDA	Food legumes	17,900	2,000	10,740	1
	Total cereals	43,700	3,000	26,220	1
	Forage legumes	22,000	2,000	13,200	1
	Total	83,600		50,160 (60%)	
ICRISAT	Groundnut	12,841	1,500	12,500	10-15
	Pearl millet	21,919	2,000	21,800	10-15
	Pigeonpea	11,482	1,300	11,300	10-15
	Other millets	7,082	1,000	7,000	10-15
	Sorghum	32,890	2,600	32,600	10-15
	Chickpea	15,995	1,400	15,600	10-15
	Total	102,209		100,800 (99%)	
IITA	*Musa*	412	412	412	2-7
	Oryza species	12,500	4,500	9,000	3
	Vigna unguiculata	15,200	4,000	9,439	3
	Wild *Vigna*	1,450	1,000	1,000	
	Total	29,562		19,851 (67%)	
IRRI	Rice	86,000	10,000	77,400 (90%)**	2
WARDA	Rice	5,430	1,000	3,000 (55%)	3-16

Table 2. Percentage of accessions from crop germplasm collections available for distribution following regeneration. Values shown are numbers (of accessions or locations) and percents of totals; accessions usually available as seed except where noted.

Notes: *AVRDC—Asian Vegetable Research and Development Center; CIAT—Centro Internacional de Agricultura Tropical; CIMMYT—International Center for the Improvement of Maize and Wheat; CIP—International Potato Center; ICARDA—International Center for Agricultural Research in the Dry Areas; ICRISAT—International Crops Research Institute for the Semi-Arid Tropics; IITA—International Institute of Tropical Agriculture; IRRI—International Rice Research Institute; and WARDA—West Africa Rice Development Association.

**Of its total 86,000 accessions, IRRI has successfully canned 43,500 accessions for medium- and long-term storage.

[1]Numbers from Cohen and others 1991.

There is a very strong case for the plant breeding community in the IARCs to take on a leadership role in training and doing evaluation prebreeding and moving genes from the bank to the breeders' plots. There are few other institutions other than IARCs as well positioned (including universities) to fill this obvious void in the plant breeding process. The world goal should be a cadre of plant breeders at the national and local levels in the ratio of 1 to 10^6 human population. To achieve this level means a tenfold increase in the skill of producing new plant varieties.

Genebanks Slow Down Crop Evolution

Genebanks have additional disadvantages other than their aging seed. Essentially they store seed and in that sense they draw genes out of circulation. For the seed to be useful requires documentation and evaluation, activities that very few genebanks are performing fully. Information management within genebanks is as important as the physical arrangements for safekeeping of the seed. Genebanks slow down crop plant evolution, so both hybridizing and segregating populations of a breeding process become a necessary adjunct to the well-functioning genebank. Genebanks pass on the genes; they don't breed finished varieties. Until we improve our expectations and funding of genebanks and their linkages to breeding, they will continue to function short of being truly useful to the plant breeding process.

I emphasize the importance of germplasm for crop plants, because it is the area where I expect the greatest advances in the next two decades, and the greatest potential we stand to lose if management of plant genetic resources does not improve. For genetic advance for any crop there are two resources: (a) the gene or genes that control specific traits, and (b) the knowledge of how to exploit that trait in the total genetic background of the finished variety for farmers' fields. This loss of knowledge disturbs me because much of the international talk about germplasm loss centers around genetic erosion

and genetic wipeout and rarely stresses the equally important decrease in the number of plant breeders around the world. Compounding the trend is the privatization of plant breeding and the rush to biotechnology that is drawing funds away from germplasm management in the public sector.

Knowing what is in the world collections has been the major stumbling block to their use. A great deal of new and novel genetic variation is locked up for the major crops in the approximately 2 million genebank accessions worldwide (Marshall 1990). To be blunt, this variation is useless until we plant the seed and use it for crop improvement (Goodman 1990). If the function is solely storage the germplasm will never be evaluated and its potential will not be discovered. To evaluate samples means to look at plants in the field and discover traits or potential for crop improvement, not just counting the number of seed held and their vigor of germination. I would like to see germplasm being worked. To accomplish this goal the one hundred significant genebanks around the world need to add a minimum of a thousand evaluation/prebreeding plant breeders. Half of these genebanks are in developing nations; no single factor could increase food self-sufficiency more than an increase in regional plant breeding staff in the tropics and an infrastructure to support their proven elite seed. Only a few developing nations have an adequate cadre of plant breeders and interestingly those nations are food sufficient.

Clearly, plant breeders are going to have to establish the efficacy of genebanks (Brown and others 1989). To do this there have to be more plant breeders and they must be linked to major genebanks. The number of plant breeding graduate students has decreased in recent years as the universities expanded into the new directions of biotechnology. This opens an excellent opportunity in my mind for the IARCs to expand their training role. I have yet to find a replacement for the insights of a practicing plant breeder who knows the crop well. When the number of working plant breeders decreases so will the amount of insight and the pace of crop improvement

will suffer. A development period of approximately 10 to 15 years exists between finding new useful germplasm and a finished variety in a farmer's field. The truth is the pace of finding new useful germplasm has already fallen off but is not evident because elite materials bred a decade ago are only now reaching the varietal release stage. What is not being done now will become evident at the end of the decade when there will be even more people and a greater demand for food.

The Use of Germplasm Resources

If a new crop-threatening hazard (disease, insect, and so on) appears for which genetic resistance is unavailable in the breeders own germplasm, the breeder is forced to look elsewhere for the needed genes. In this event an active collection, if available, will be screened. Numerous examples are on record of sought-after genes being identified in active collections especially in cereals and legumes. An important source of improved germplasm in the major crop species can be found in university and national research plots or international screening nurseries and trials conducted by IARCs. Advanced lines and varieties undergoing evaluation in such trials are heavily utilized by many breeders as parents in new crosses. They do so because of the accumulated performance and evaluation data available to them that help to identify germplasm with the greatest potential value. The best of this germplasm eventually is made a part of base and active collections. Performance data on unfamiliar material, when available, are more useful to breeders than descriptor data because they provide productivity and adaptation information that is particularly sought by breeders in choosing parental materials. Almost no performance data are available on the germplasm held in the world network of genebanks.

Proportionally the heaviest use of active collections is made by breeders of plant species that have little or no history of breeding improvement but for which collected material is available. Generally, these are in the tropical

pulses, some root crops, vegetables, and some industrial crops. For these crops the breeder who has initiated an improvement program has no alternative but to use exotic (unknown) collected material for local evaluation and selection.

Exotic germplasm is most often utilized in the pursuit of long-range breeding goals. Some, but not all, of the exotic germplasm comes from active germplasm collections. Exotic germplasm reaches the large programs via national, regional, and international evaluation networks and frequently by personal contacts of the scientists.

Breeders point out that without better passport and descriptor data, they have no rational entry into the active collections and are forced to screen accessions more or less blindly in their search for useful material (Peeters and Williams 1984). Surely efficiency can be increased by better management and evaluation of collections and to achieve this the world cadre of plant breeds needs to increase and be actively involved.

General agreement exists among breeders that genetic resources systems both nationally and internationally should include comprehensive programs of enhancement. They believe that enhancement may be one of the keys to maximizing future collection utilization by breeders. In general, genes identified in primitive materials exhibit considerable specific local adaptation (negative linkages) and need to be introgressed or repeatedly backcrossed to improved genotypes. Useful genes from these sources generally are used only when combined in genetic backgrounds that are more acceptable to breeders ("free of the negative baggage"). Public sector breeders conduct enhancement or prebreeding research moving desired genes into elite material but, unfortunately, this work is a relatively small part of their total breeding effort due to financial constraints, clientele pressure for new improved cultivars, and the time required to achieve useful results. This is sadly not going to change until the importance of enhancement is recognized and the service appropriately rewarded. The world community is ap-

proximately 750 to 1,000 public sector enhancement plant breeders short. Enhancement research is pursued in the private sector also, but to a much smaller extent. The successful products of such private research usually are kept as proprietary products and are available to the public breeders only after their release as genetic components of new commercial cultivars.

Germplasm for Varietal Development

Most cereal breeders do not make heavy use of germplasm of landraces and wild and weedy relatives existing in active collections for reasons as previously noted (Duvick 1984; Peeters and Galwey 1988). This is particularly true for breeders of species in which breeding improvement is well-established and has been underway for a long time. Breeders tend to be reluctant to use unadapted exotic germplasm for crossing purposes—particularly if they continue to make acceptable breeding progress without its use. This is sad because the potential for significant advances using new exotic material is foregone in favor of the slow advance. Better breeding for enhancement is a way around this bottleneck to genetic advancement.

It is instructive to examine some of the specific traits that give new varieties their higher yield potential. The new maize hybrids are greatly improved in root strength (resistance to root-lodging), in resistance to stalk-rot fungi, in resistance to heat and drought, in ability to withstand poor nitrogen nutrition, in resistance to pests and pathogens, and in ability to withstand the deleterious effects of crowding due to dense planting.

Breeders of the other cereals have shown that similar genetic improvements can be made. All crops have improved ratios of grain to straw. This causes proportionately less photosynthate to go into stems and leaves. All crops have better resistance to lodging, better drought resistance, and more capacity to handle excess (or deficiency) of soil nutrients such as nitrogen (the cereals) or

iron (sorghum, soybeans). The cereal crops are all greatly improved in resistance to premature death, a syndrome of unknown cause that results in poor grain development and/or stalk rot. Additionally, continual updating of resistance to new races (biotypes) of pathogens, insects, and nematode pests has been of vital importance to many crops. Varietal turnover in some advanced regions of crops production (Yaqui Valley, Mexico—wheat 5 tons/ hectare) are as short as 3 years while other regions (Punjab, Pakistan—wheat 1.7 tons/hectare) are much slower (12 years) to experience varietal improvement (Brennan and Byerlee 1991). This is an opportunity cost that could be reversed by increasing the number of plant breeders doing local adaption breeding for national or regional programs.

Training for Plant Breeding

Worldwide the ratio of total population to plant breeders is increasing. The needs are such that the reverse should be the case. In actuality, because the world population has increased, training of plant breeders has remained constant (actually a small decline) in the United States (Collins and Phillips 1991) and appears to parallel the condition worldwide over the decade (1980-89). Of this total, approximately 40 percent of the United States' Ph.D. degrees awarded were to foreign students. Most of the United States' current elite crop varieties trace back to the product of breeders trained during the period 1930-75. This also applies to a remarkable degree to the developing world.

Unfortunately in the United States, many smaller university plant breeding programs have shown a nearly 10 percent decrease over the 1980-89 period (Collins and Phillips 1991) as administrative shifts toward molecular and biotechnology programs have competed for limited funds. I have made the case elsewhere (Wilkes 1989) that the "productivity ratio" of public sector plant breeding full-time equivalents (FTE) is one to a million people fed. These FTE, approximately 500 plant breeders in number,

are active in bringing on new varieties and hybrids to feed a population of a half billion. The number of FTE in the private sector seed companies is estimated to be a very comparable number and interestingly the total number of FTE plant breeders in U.S. universities in 1989 engaged in 440 breeding programs was 458.6 individuals a little lower than the numbers in 1980 (Collins and Phillips 1991). In the United States, these numbers lead me to generalize that research and development of plant genetic resources (academic programs, public sector plant breeding, and programs of private seed companies) involves a breeder to population ratio of 1 to 500,000. Using this number there are obviously some regions of the world with serious deficiencies.

The work of trained plant breeders around the world is one of the major reasons that the predicted famine of the 1970s never happened. One of the major developments in international agricultural research was the emphasis in this period by Rockefeller and Ford Foundations on training plant breeders for developing countries. These plant breeders are not being replaced by a second wave as well-trained. Funds to train for plant breeding skills are hard to come by and 90 percent of developing nations can't afford university tuition at academic institutions in the North. Even an advanced country, like Mexico, with a very well-developed agricultural research matrix, cannot afford to send nationals out for 3 to 5 years of Ph.D. training. Mexico has had to go to a program of short post-doc training for their Mexican trained key personnel. This is tragic because many of the leading plant breeders in the North have former students trained in the 1950s to 1970s around the world who have kept in touch and the mutual flow of germplasm has been significant. Even when the political situation has been cold, personal contact and mutual respect has resulted in a free and open exchange of South-South and North-South unimproved and elite material. This invisible infrastructure of goodwill has been one of the most powerful forces in plant breeding in the 1960s and 1970s. Plant breeding is a human activity and without communication and exchange of seed the process comes to a dead stop. That such a small cadre of

plant breeders have been so effective in doubling the world's food supply is a tribute to genetics and the art of plant breeding.

Plant Breeding Needs

The establishment was quick to rally round the concept of genebanks when the concern was genetic erosion, however, it has been very slow to realize that effective preservation of germplasm is only half the job (Williams 1991). Nor could breeders be left to see to this; they were too busy with their own tasks. The plant genetic resources found in genebanks are the "insurance" for future elite varieties only if they are used in the breeding process (a policy is underwritten). **The importance and effective use of plant diversity in a productive and sustainable agriculture is one of the least appreciated and poorly managed aspects of genebanking.** Public sector research and development planners lack policies and management plans in this area and the general public is unaware of a lack of direction. Currently the major genebanks hold approximately 2 million accessions (about half of these are thought to be duplicates) worldwide. Trevor Williams has presented evidence that in fact the number of distinct and useful accessions is around a half million (Williams 1989, 1991). Yet these 500,000 accessions are useless until we grow out and use this variation for crop improvement; nor can they be considered valuable until they are used!

This is an instant on and off modern world and there are those that think that germplasm in genebanks could be used like a parts catalog. All that has to happen is to evaluate all the traits for the accessions and enter this mass of information in a computer. Then all you do is "dial a trait"—plug into the database to find the desired trait—and then plug it in the plant. This plug-in idea is rather popular with the media accounts for the promise of biotechnology also. The real truth is that genetic factors that permit local adaptation and yield, the genetic margin of difference for the farmer of one variety or hybrid

over another, is practically never due to a single gene. About the only magic bullet single gene traits have been those for disease resistance and most of these become obsolete before a decade has passed.

Progress in plant breeding of the major grain crops can be expressed quite simply as yield per unit area. Considering all of the major advances, there is no doubt that changes in farming practices such as increased use of nitrogen fertilizer, better weed control and more timely planting and harvesting, and pest control have had important effects on crop productivity. But the single most important input has been that of breeding in the production of improved hybrids and varieties (Duvick 1986).

Repeated studies for each of four major crops (maize, wheat, soybeans, and sorghum) have shown that about 50 percent of yield gains over the past 50 years in the United States were due to varietal improvement. Presumably the same would hold for other parts of the world. The rate of yield gain attributable to breeding has been estimated at about 1 percent per year. Gains have usually been linear and up to now show no sign of decreasing but there is some fear that a flattening (logistic curve) might be ahead.

The plant breeding community is the primary provider of new varieties, yet if breeders don't supply varieties that find favor with farmers, they have no product. Therefore, to satisfy farmers, two concerns are always addressed by the breeder in any released variety: yield and predictability. Selection for superior genotype is primary in creating high-yielding varieties. Yield has many facets—the obvious tons/hectare, or farm gate value, cost of inputs, but also very important qualities such as nutritional, taste, texture, and so on and the long-term sustainability with current farming practices. Predictability means that the heritability must be high, and to achieve this standard there is a considerable pressure for genetic uniformity. Genetic uniformity can be either in the form of homozygosity (often recessive) or

the hybrid of inbred parents (hybrid maize). The kinds of uniformity desired in maize, for example, are: (1) rapid and uniform germination of seeds; (2) nearly simultaneous flowering; (3) nearly simultaneous maturation of harvestable product; (4) stature that promotes mechanical harvest (ear height); (5) product uniformity for taste, flavor, and chemical composition; and of course (6) year-to-year stability of yield. This last point demands special mention because in the last 25 years plant breeders have developed selection techniques for buffered systems that yield well over a range of conditions across a wide range of habitats.

The gains or increased yield capacity of the newest varieties and hybrids are exhibited, not only when inputs are optimal (high levels of soil fertility, plentiful water, and in the absence of disease and insect pests) but also when fertility, pest, and environmental conditions are unfavorable (Duvick 1986). The increased "toughness" of new hybrids and varieties is a fairly well-kept secret, at least outside plant breeding circles. It is generally claimed by nonplant breeders interested in criticizing the current state of food production that new hybrids and varieties are "weak" and disease-prone, and that they must be given plentiful supplies of water, fertilizer, and pesticides in order to do well.

The facts are that modern varieties must be much tougher than their predecessors in order to survive modern cultural conditions. In maize for example, today's crowded growing conditions (due to high seeding rates to maximize yield) increase opportunities for individual plants to suffer water and nutrient shortages, and reduced available sunlight. For all crops, monocropping facilitates the epidemic increases of disease, insect, and nematode pests and the pathogens and pests are generally more virulent over time. The older varieties cannot stand present growing conditions and exhibit female sterility, insufficient root growth, develop weak, lodging-prone stems, and become more prone to disease and insect attack (Duvick 1986).

The adoption of these highly uniform, yet superior, hybrids and varieties means that plant breeders must bring on, in continuing fashion, new varieties with new resistances or tolerances. Varieties typically are replaced by new ones every 5 to 10 years (Brennan and Byerlee 1991). Those societies that grow modern plant varieties have, therefore, an indispensable need for modern strategically planned plant breeding programs. **Once steps are taken toward planting modern crop varieties, there is no alternative but to support energetic, well-planned, and well-executed plant breeding programs.**

Differences between Primitive Populations and Modern Varieties

Two major differences exist between the processes of early domestication of our crop plants and current breeding practices. First the early development of the crop in the area where it originated or diversified usually occurred in the presence of coevolving pests and pathogens. Second the genepools during the early evolution of the crop exhibited considerable variation because of hybridization with wild related species and also because of genetic recombination between primitive cultivars. Today few breeding programs use primitive cultivars in the breeding process and most rely rather on a limited number of proven elite lines long ago derived from the primitive forms (Wilkes 1989).

In peasant farming cultures excessive genetic uniformity was virtually never present, no matter whether the crop was annual or perennial, self-pollinated or cross-pollinated. Although self-pollinated annuals in general consisted of small populations of homozygous individuals they usually contained a large range of different homozygous genotypes and thus, as a population, were highly heterogeneous. Naturally cross-pollinating crop species invariably were maintained in an outcrossed condition and were both heterogeneous and heterozygous; and perennial plants, whether increased via seed or

clonal multiplication, also were maintained as genetically heterogeneous populations of heterozygous individuals.

Genetic heterogeneity did not provide absolute insurance against epidemic pest attacks nor against environmentally caused yield losses. Species-specific genetic uniformity is sometimes sufficient in itself to support epidemics of disease or insect pests. Thus Dutch elm disease devastated the entire species of American elms in the United States in the 1960s.

Nevertheless, it is certain that the large amount of heterogeneity in primitive forms in peasant agriculture did and still does greatly reduce the danger of loss to epidemics within the same crops. This advantage appears to be no longer present for those countries that grow highly uniform modern crop varieties, at least not in the same way as is seen in peasant varieties.

Varietal Mixtures

It is not simply the number of crop species and of individual varieties that made landrace crop fields more diverse. Spatially and temporally crops were intermixed in ways that reduced their vulnerability to pests and diseases and increased their efficiency in using water, nitrogen, and light. Some of these intermixes were intercropping, overcropping, sequential (relay) planting, and adjacent patches or mosaics. Elements of this strategy are found in modern day multiline mixtures and relay planting with distinctly different genotypes (for example the early and late forms of the crop). Similarly mixes of resistant and vulnerable cultivars have demonstrated yield stabilities that are many times that of large plantings of single varieties. The mixtures appear to keep insect pest populations from overrunning the susceptible varieties because of their patchiness. Such human designed agricultural systems that mimic more natural ecosystems appear to be more stable. Much of this research has been pioneered by Professor M.S. Wolfe

at the Cambridge Plant Breeding Institute, United Kingdom in the 1970s and 1980s (Wolfe 1985, 1988).

There is a continuum from a multiline in which the individual lines differ only by identified resistance genes, to line mixtures whose individual members are segregates from common parents (not isogenic), to optimal variety mixtures that appear to be the best option to supply heterogeneity for disease resistance (Browning 1988; Simmonds 1988; Wolfe 1988).

A growing body of literature supports the concept that a field made up of heterogeneous elements yields at least as well as their separate components, be they pyramided disease resistance genes in different multilines (the clean crop multilines of Borlaug 1958) or multilines that stabilize the inroads of the pathogen at low, nondamaging levels without stacked disease resistance genes (dirty crop multilines of Browning and Frey 1969); varietal mixtures (Wolfe 1985); or species mixes such as wheat and oats, wheat and barley, maize, beans, and squash, or barley and peas. In fact, on average the mean yield of the mixture exceeds the mean yield of the components when extended over a number of years (Wolfe 1985). Modern agricultural practices traditionally have used large inputs of fertilizers, herbicides, fungicides, and insecticides to optimize the field conditions in an attempt to stabilize yields. General indications are that additional applications of these inputs have levelled off relative to yield (Duvick 1986). They are no longer as cost-effective as they once were, and even more importantly massive applications are becoming socially unacceptable. All of these factors point to the attractiveness of varietal mixtures that can compensate for biotic stress through their dampening effect on the spread of diseases. In addition, varietal mixtures will require no new demands on plant breeding programs because currently available varieties are, in most cases, adequate for mixture development.

Mixtures present an evolutionary dilemma for pathogens but no absolute assurance of durability. As in

monocultures, diversification of varieties in mixtures (diversification of varieties over time in monocultures) and differences in resistance genes among varieties are the most reasonable answers to forestall the genetic vulnerability problem. In industrialized agriculture, monoculture has rapidly become an accepted tradition encouraged by the industrial users of agricultural products. The value of heterogeneous crops is often more readily accepted by the farming community than by those who serve it. The reason is simple: the advantages of the heterogeneous crops system benefit the farmer, but the changes needed, at least in industrialized agriculture, have to be introduced by the agricultural service industry and society in general.

Plant Breeding in Developing and Developed Countries

In the developing world, high-yielding varieties (HYV) for the major crops have come into dominance just within the last 15 to 25 years. The immediate effect of these introductions is to make available novel genes for resistance to widespread diseases for which landraces may have been susceptible. Simultaneously rapid losses of indigenous diversity are occurring. As a few hybrids from the same breeding programs come to dominate a developing country's production, increased vulnerability is almost certain to emerge. It is very doubtful whether all breeding programs in developing countries can react as rapidly to future epidemics as the U.S. maize breeders did between 1970 and 1972.

A classic example of a genetically vulnerable variety without replacement is the wheat 'Sonalika' in South Asia. Farmers will stay with their chosen varieties with remarkable persistence as long as the variety performs well in their hands. This is exactly what has happened with 'Sonalika' where it has been removed from the recommended variety list because of known serious disease susceptibility (Dalrymple 1986), but continues to be

planted over vast acreages because it is so early, possesses amber grain, and fits the multicropping schedule. 'Sonalika,' which was released in 1967, has for more than a decade been known to be susceptible to a new race of leaf rust (and therefore needs to be replaced) but has not had the plant breeding attention to generate a suitable replacement. Farmers cannot abandon this susceptible variety (Sonalika accounted for 40 percent of wheat acreage in 1988) because there isn't a satisfactory replacement. Plant breeding at the local and regional levels continues to fail these farmers.

For the past 25 years, leadership in wheat and rice breeding for developing countries has come from CIMMYT and IRRI. There is a strong possibility that with limited funds these institutes will devote a smaller proportion of their efforts to variety development in the future. The national breeding programs in developing countries are, in general, not as well-funded nor as effective as the breeding programs in the IARCs. There are significant policy questions, therefore, as to whether adequate breeding efforts worldwide will indeed be devoted to bringing on new wheat and rice varieties at frequent intervals for the developing world. This question is of particular significance if the IARCs move away from maintenance breeding in favor of more "upstream" activities such as biotechnology or politically favored activities such as elite HYVs for marginal environments.

Those countries with a high proportion of area sown to the HYVs are on a treadmill. They cannot turn back to cultivation of the indigenous peasant varieties without serious delay due to the time that would be needed for re-education of the farming population and restocking of seed of indigenous varieties. They cannot continue to plant the presently used HYVs indefinitely because new pest races inevitably will appear, causing disastrous epidemics in the aging varieties. This latter problem is particularly acute in the tropical and subtropical areas with no cold season (and often little dry season) to annually set back the pest populations.

At least 5 to 10 years of targeted efforts are needed to put strong breeding programs into place or to improve ineffective breeding programs. Those countries with undersized or ineffective programs that are now depending upon the IARCs for new HYVs have no time to waste. They must begin as soon as possible to strengthen their national breeding programs up to the size and efficiency that will serve their countries properly. Clearly there is a significant lack of skilled breeders at the national level to achieve these goals.

Part of the strategy is for developing countries to work cooperatively with surrounding countries with similar climatic conditions and cultural practices. The pooling of several small programs can, in theory, reach the same goals by providing a sufficient base for bringing out improved varieties at frequent intervals. Unfortunately, histories of planned, government-led intercountry cooperation have few success stories. Remarkable skills in management and diplomacy are needed to make such cooperation productive.

Worldwide cooperation and collaboration in plant breeding are now needed more than ever before. The history of development of successful new varieties shows, without exception, that the varieties could not have been developed if breeders around the world had not freely exchanged germplasm and information. With higher proportions of the crop area being sown to highly bred varieties (and conversely, with smaller and smaller areas being planted to indigenous farmer varieties), the need for an active worldwide plant breeding collaboration is stronger than ever.

The developing countries are now a significant factor in genetic vulnerability. Both hybrids and HYVs have come into dominance within the last two decades. The immediate effect of these developments has been increased production and rapid losses of local landraces that the elite germplasm has displaced in farmers' fields, and essentially the same genetic backgrounds can now be found in the agricultures of both developed and

developing countries. This translates into a wider net to pick up pests and pathogens in the context of varietal invasion, new encounter vulnerability, and pathogen invasion. **Because a few elite materials have come to dominate the basic cereals and legume crops worldwide, increasing vulnerability is almost certain to emerge.**

The burden of genetic vulnerability up until now has been placed primarily on the shoulders of plant breeders because elements exist in the technology of plant breeding that can be designed to minimize the impact of genetic vulnerability. Farmers have always been alert to variations in a crop and have taken advantage of unplanned, fortuitous genetic variants that appeared long before these evolutionary processes had the names of mutation, introgressive hybridization, and polyploidy. Artificial selection is a powerful tool of plant breeders both in controlled crossing or peasant farmer opportunism with landraces. Almost always selection can be employed to overcome the expression of genetic susceptibility once it appears and is recognized.

The trouble with genetic vulnerability in modern elite varieties is that uniform monocultures are so widespread and the impact so magnified that it doesn't matter if the plant breeders can correct the problem. That it has happened at all is sufficient to disrupt the world food supply. Collectively, plant breeders have a very important influence on the amount of genetic uniformity to be found in commercial crop varieties, however, demands of the industry and limitations of research resources ultimately define how diverse these varieties really are. Genetic uniformity in and of itself is not necessarily undesirable (if deployed wisely) and is necessary for much of our present agricultural markets (Plucknett and others 1987), however, to disperse a uniform variety very extensively is to spread a wide net for pests and pathogens.

The price of the emphasis on maximum productivity is vigilance, based on a thorough knowledge of current

varieties, and the ability to trace any new infection with great care. Ultimately, varieties under development should originate from parentage wider than the varieties they displace. For most breeders, however, there are few incentives to go any further for breeding parents than the very small number of elite materials at the top of the pyramid. Individual breeders watch with vigilance for outbreaks of pests and pathogens, but there is no overall management strategy to quickly bring genes from the lower levels of "gene in reserve" for most of the major crops, and there is no strategy at all for keeping the reserve ranks filled with planned diversity of genotypes for resistance to pest, weather, or soil problems. This strategy must surely be at the very core of genebank policies and management.

Nowhere is the impact more serious than the extension of the high-yielding grain belt germplasm into microhabitats and marginal lands of the tropics (CIMMYT 1987). This has cast a larger net to capture pests and pathogens. These habitats are often without the pronounced dieback seasons of the major temperate grain belts when severe cold (U.S. corn belt), severe drought (Punjab, wheat), or flooding (South East Asia, rice) push back the pest and pathogen populations. Presently with wheat being harvested over most of the year somewhere in the world, the potential to capture pests and pathogens has increased.

Instead of promoting commercial wheat seed in Iran and Turkey forming a continuous carpet from the Punjab into Europe, or commercial seed for Nepal and Thailand forming a continuous carpet from the Punjab to China, there ought to be a mosaic of diversity so there will not be a connecting bridge of genetic uniformity to promote the march of a pest or pathogen. The idea of a genetic "firebreak" using bands of diverse germplasm to slow down the march of a potential vulnerability needs to be in place. Clearly, an integrated, genetic-based, crop management strategy is needed to mitigate unwanted increases in genetic vulnerability of widely grown elite plant materials.

One of the best strategies for all vulnerabilities is periodic reassessment. When susceptibility is ignored it creates vulnerability, but susceptibility reassessed generates options.

Future Needs and Priorities

If plant breeders breed from only adapted elite material as many commercial companies tend to do, and aim only for the short run, narrow germplasm bases result, thus increasing the potential for genetic vulnerability. A certain amount of long-range breeding aimed at increasing genetic diversity must always be present. However, it is difficult to determine the minimum number of plant breeders necessary to insure this goal of providing sufficient genetic diversity in reserve. If the total number of individuals committed to breeding decreases, the amount of germplasm actively used by breeders also may decrease unless some way is devised of increasing output per breeder, particularly with regard to enhancement or breeding for broadening the useful germplasm base. Much potentially useful germplasm is lost due to lack of personnel. An inordinate amount of public responsibility must be assumed by a few individuals who prepare genebank or landrace materials for further breeding work. The degree to which these few can prebreed and efficiently create, evaluate, release, and store valuable germplasm is limited. Furthermore as breeders retire and administrators change their emphasis, valuable breeding pools and germplasm collections often are discarded, a tragic loss for the public at large.

Changing patterns of susceptibility of major crops to diseases will always result in surprises. The measure of success is how appropriate our preparedness and timely our responses are to the vulnerability. **Investing** by the IARCs in improved minor crops for the zones between major grain belts should be a priority to protect their yield advancement with maize, wheat, and rice. **Improvement in the evaluation** of germplasm in genebanks and the development of alternate maternal parents (cytoplasm)

should broaden the backup varieties to current elite materials. To do this we need plant breeders not only at the IARCs, but also at the regional level dealing with local adaptation. Improvement of crop varieties depends on new and diverse germplasm resources, and also the human skill to see promise in segregating populations early on in the breeding process. There exists an obvious need for **more plant breeders** worldwide to hybridize crops and generate genetic diversity than exist presently. **The return to a more diverse genetic mosaic will be an important strategy to reduce genetic vulnerability within and between crops.**

Agriculture, Germplasm Conservation, and Strategies for the Future

The challenge as we approach the next century will be to design agricultural management strategies and institutional arrangements that can successfully ameliorate the negative environmental effects of agricultural and urban intensification primarily in the grain belts.

The uniformity of major crops and the fact that they have largely displaced indigenous landraces is a given of the present agricultural consumer context. Subsistence farmers are a decreasing minority. Most farmers sell some or all of their harvest for cash and are, therefore, yield over cost-of-inputs driven. They need to use the best varieties available to them. Genetic vulnerability is inherent in the use of uniform elite germplasm. New varieties are continually brought up from breeders' plots to replace older ones. However, the lack of a broad-scale management strategy to anticipate expected problems and minimize their impact exhibits tunnel vision about how biological systems organize themselves and an insensitivity to the plant breeding establishment's public responsibility. Positive actions to deal with **genetic erosion, genetic wipeout**, and **genetic vulnerability** at both national and international levels must involve the following initiatives:

- *Create new programs* to identify genetic erosion and vulnerability—variety surveys and collaboration in international efforts to monitor the use and geographic distribution of elite germplasm.

- *Develop appropriate genepools* (especially in the public sector) introgressed by exotic derived germplasm to support the commercial breeder with diverse useful materials.

- *Increase training* in the maintenance of plant genetic resources both nationally and internationally. Active genebanks should be linked to prebreeding and in moving genes from the collections into enhanced materials but not finished varieties. The future will be best protected from genetic vulnerability if worldwide cooperative networks of crop specific prebreeding develop.

- *Conduct basic and applied research* in order to more efficiently and effectively measure genetic distance between varieties and improve evaluation techniques, especially relating to the nature of resistance to pests and pathogens and pest and plant interaction; in conjunction with early detection of changes in the virulence of pests and pathogens as well as shifts in the varietal picture.

- *Educate and inform* the food industry, farmers, seed suppliers, plant breeders, and others about the relationship of genetic and spatial diversity with regard to the potential for crop vulnerability so they can develop effective management strategies such as parallel breeding, genes in reserve, enhancement breeding for gene pools, wide crosses and biotechnology; and alternative management strategies to monocultures such as crop rotation, tillage practices, crop mixtures, multilines for resistance, pyramided resistance factors, manipulations of pest parasites, pest trap crops, insecticides and fungicides, and better monitoring.

Summary and Charge for Change

The quest for an assured food supply has done more to decrease biodiversity and alter the landscape and environment than any other activity in which we engage. Because food production is population driven, the demands for increased productivity mean that the ability of natural systems to conserve genetic resources has been diminished (genetic erosion) to the point that we are now dependent on genebanks to preserve the genetic estate. There is a large amount of germplasm now held in the genebanks of national programs and the IARCs. The wide dispersion of these holdings is desirable but the lack of the ability to fully use the collections has limited the effectiveness of many national programs, both within the country and in exchanges between countries and regions. Better germplasm is the fastest and least expensive input for increasing crop plant productivity. Many national genebanks need to become more active in the search for new useful genetic materials to be used in the breeding process. To compound the problem only a very few crop varieties now occupy the major acreage worldwide and these highly uniform monocultures exhibit considerable potential for genetic vulnerability.

More than ever before, international efforts are required to help slow genetic erosion, establish and encourage internationally responsible and proactive genebanks, and help prevent epidemics in the developing countries where the greatest threats of genetic vulnerability and germplasm erosion now exist. Because of their major role in insuring global food stability, the donor community and the IARCs can no longer continue to neglect the issues posed by the decreasing number of plant breeders relative to human population and genetic vulnerability. The current haphazard, uncoordinated, and unsystematic approaches to the problem reflect dangerous and inappropriate national and global priorities.

The new strategies should be more adaptive and employ less preventive maintenance breeding to sustain

the yields required by an expanding human population. We can no longer afford to ignore the continued loss of biodiversity in agriculture. If society took seriously genetic erosion and genetic vulnerability, we would have better management practices in place than our presently dangerously reckless pattern of casual neglect.

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