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NEW TECHNOLOGIES FOR SUSTAINED PRODUCTIVITY GROWTH: PLANT BREEDING

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Past achievements of plant breeding

Productivity: In the past century, yields of major field crops have risen consistently in developed countries, and also in some parts of some of the developing countries. Most of the gains in yield have occurred during the past 50 years, or even more recently in certain countries. Although on-farm yield gains usually have been linear, in some cases the rate of increase has been reduced in recent years. It is not clear, whether or not such reduced rates of gain will continue.

The gains in on-farm yield are owed in part to changes in management — to increases in application of fertilizers, pesticides, and in use of mechanical aids to planting, cultivation, and harvest. They are owed also to genetic advances — to plant breeding that produces a continuing stream of successively improved cultivars (cultivated varieties). Studies in several field crops indicate that about one-half of the gains in on-farm yield are owed to changes in management and one-half are owed to plant breeding. This ratio varies widely, however, depending on crop, region of adaptation, and access of farmers to tools of management or to improved cultivars.

Analyses of yield gains in some of the major field crops indicate that gains are owed primarily to genetic changes that provide increased tolerance to the important stresses, both abiotic and biotic, that occur in the regions for which the cultivars have been bred, and, to a lesser extent, to changes that promote efficiency of grain production. Cultivars are improved, for example, in drought tolerance, in tolerance to low levels of soil nitrogen, and in resistance and/or tolerance to major disease and insect pests. New cultivars are tougher than the old ones. Conventional plant breeding has produced these changes.

Organization. Plant breeders have worked in both the public and the private sector. Both sectors have been active in plant breeding since the early years of the 20th century.

Public sector breeding has been supported by national governments, by state or provincial governments, and by international research organizations (e.g., the International Rice Research Institute (IRRI)). In earlier years, taxpayers fully supported the breeders in government employ, and donated funds (ultimately from taxpayers in developed countries) supported the international research organizations. In recent years, open-ended government funding has been reduced in amount, and alternative sources of funding have supplemented the public sector breeding programs. The alternative sources include short-term, targeted grants from private and public granting agencies (foundations, etc.), and also from industry.

Private sector breeding is supported by profits from sale of seed of the cultivars developed by a company's breeders, or of cultivars obtained (usually for a fee) from other organizations both private and public. Thus, the farmer who buys the seed supports private sector plant breeding. Private sector breeding predominates (but not exclusively) in maize, soybeans, sorghum, cotton, and fruits and vegetables. It is also active but to a smaller degree in wheat and alfalfa as well as in several other crops.

Potentials for further advance

Genetic yield gains (including increased stability of performance) have been linear for the major field crops and perhaps will continue to be so for at least the next few decades. Virtually all of today's gains in performance are owed to conventional plant breeding and if properly supported it can continue to improve crop yield potential, stability of performance, and increased resistance and/or tolerance to disease and insect attack.

Biotechnology has been added to the plant breeder's toolkit during the past decade or two, and it has already made a few significant contributions, in the form of genetically engineered resistance to insects and to herbicides, with consequent increases in yield, quality, and food safety of grain products, and/or efficiency in production. These one-time gains will be supplemented by additional transgenic contributions in years to come. These will be intended (for example) to provide resistance to additional insect and disease pests, to improve tolerance to some kinds of abiotic stress, and to impart new kinds of herbicide tolerance.

In the medium to long term, knowledge gained from molecular biology will enable breeders to make fundamental (and helpful) adjustments in native genomes of field crop plants (and fruits and vegetables). The "fine tuning" of crop plant genotypes will improve tolerance to abiotic stress (e.g., heat and drought), efficiency of utilization of sunlight, water and soil nutrients, and enable development of more durable kinds of pest resistance than is offered by present form of transgenic resistance. Plant breeding efficiency will be materially enhanced if these projected accomplishments come to pass. This will be the most enduring and significant contribution of biotechnology to plant breeding.

Complications

Several storm clouds are on the horizon, any one of which could materially reduce the potential gains to come from plant breeding in future years.

Public sector plant breeding. Fund totals for public sector plant breeding have neither increased nor decreased significantly during the past 40 years, in contrast to continuing and large increases for private sector breeding. Funding for public sector breeding shows a pattern of reduced funds for cultivar development per se and increased funds for molecular biology applied to crop plants. As a result, cultivar production by the public sector has declined for some crops and/or regions.

In some cases, private sector breeding has replaced public sector efforts, but the private sector cannot satisfy all needs for improved cultivars such as for niche growing regions or "orphan crops". The private sector cannot afford to breed and produce seed for those crops where profit margins (in seed sales) are too low, or cost of breeding exceeds potential for profit because of small market size. So at present, some growers are not served adequately, either by private or public sector plant breeding.

An unfortunate consequence of reductions in cultivar development in the public sector is that there is less and less opportunity to train plant breeders; they will be needed in both public and private sectors, and they can only be effective if they have been trained in the practice as well as the theory of plant breeding. Some public sector breeders are working with private industry to allow students, as "interns," to get experience in practical plant breeding, in the field as well as in the laboratory or on the computer. But in absence of such opportunity, both private sector and public sector plant breeders worry about the future; will there be adequate numbers of well-trained plant breeders?

Private sector plant breeding. During the past two decades, consolidations of various kinds have resulted in ownership of plant breeding companies by larger organizations that may have had no previous experience in plant breeding. Often, several medium sized plant breeding companies have been acquired by a single parent organization. These changes in ownership have allowed economies of scale but have also given opportunity for mistakes in management of the breeding operation by administrators without experience in the seed business, as well as the possibility for disruption of operations as a result of reorganization, downsizing, etc.

Consolidations have also brought on fears of monopoly or near-monopoly with resulting overly-high seed prices, although data for market shares indicate that despite current dominance of a small number of companies (as with maize), a sizeable proportion of the market is held by large numbers of small regional companies and a third portion is held by a smaller number of companies of intermediate size. This pattern has existed without major change during the past half century. Predictions on this topic are difficult to make because of the continuing fluidity of ownership in the seed business. Small companies appear, disappear, and are replaced by other newcomers; some grow into large companies, some are purchased and some are sold. This pattern, also, is typical of the past half century.

Biotechnology. Farmers have enthusiastically adopted the first genetically engineered cultivars (for example, with herbicide resistance or resistance to major insect pests), despite the higher prices for such cultivars. But influential segments of the non-farming public have strongly opposed the use of genetic engineering for crop plants. Reasons for opposition include concerns about food safety, environmental damage, and unacceptable power of the private sector over food production. In addition, some sectors have essentially normative objections to any use of biotechnology in plant breeding because it is unprecedented and "unnatural".

These concerns, collectively, have in some cases prevented any use of genetically engineered crops or their products (as in parts of Europe), have delayed or prevented their introduction or use as food in some of the developing countries, and at the least (as in the U.S. where they are allowed) have greatly increased the cost of breeding and introducing genetically engineered cultivars because of the expense in money and time that is required to provided specified data about safety or other characteristics (and consequences) of the new cultivars. Marketing problems and uncertainties abound as well, as various countries set up barriers to import of genetically engineered crops or products made from those crops.

Another potential problem is the high cost of conducting applied research in biotechnology applied to plant breeding. These expenses must be added to the ongoing expenses of conventional plant breeding. Although some aspects of molecular biology already are giving new efficiency to plant breeding (such as use of marker-aided selection to increase speed and precision of moving conventional genes or transgenes from an exotic source to an elite cultivar) much of the science is still at the stage of building a knowledge base and developing improved techniques. The payoff from this research will be long-range and will require consistency of application (and of funding) from either public or private sources if it is to succeed.

Because of a general trend to reduced public funding for agricultural research in general (probably related to the well-fed nature of a public that is many generations removed from the farm) one could imagine that funding of public sector research in biotechnology will not be maintained at the levels needed. One could also imagine that private industry would be unable or unwilling to devote sufficient funds to this research over the long term, thinking in particular of those firms whose management had supposed that biotechnology alone (or nearly alone) would be sufficient at this time to generate a continuing stream of improved cultivars.

Developing countries. On the whole, farmers in developing countries have not been as well supplied by plant breeding from either public (government) or private sector, as have farmers in the industrialized countries. For various reasons, primarily economic and governmental, public sector breeding in many (but not all) developing countries has been under-funded and consequently not productive of improved locally adapted cultivars. The private sector, as well, has not served farmers of developing countries (with a few notable exceptions for some crops in some sectors), because the farmers could not afford to purchase seed or such investment was not wise because of the uncertain nature of the market for the crop.

The international research centers (loosely organized as the Consultative Group on International Agricultural Research, or "CGIAR") have furnished a continuing stream of improved cultivars of some of the major crops for developing countries, such as rice, wheat, maize, cassava, and sorghum. They have been funded from international sources (primarily governmental sources in the industrialized countries) since the 1970s. Their products have had great and beneficial impact in many of the developing countries. But in recent years the funds have been sharply reduced, and those that are granted increasingly come with restrictions that prevent or diminish their use for cultivar development per se.

If this pattern continues, CGIAR assistance (often vital) to plant breeding for the developing countries will be severely curtailed or even stopped, and there is little indication that the developing countries as a whole can or will expand their own public sector breeding activities. Farmers in developing countries will suffer the consequences.

Proper goals of plant breeding. Since "scientific plant breeding" was initiated in the early years of the 20th century, the primary goal of plant breeders — in response to demands of the farmers — has been to develop cultivars that will give higher yields of a desired product and do so dependably, season after season. Public sector and private sector breeders have been united in striving to achieve this objective.

This goal has been brought into question by some sectors, primarily in the social and environmental domains. Rather than to aim for higher yields of staple crops grown in monoculture, one should instead breed crops that can perform well as polycultures, or as perennials (most staple grain crops are annuals), or that serve as erosion-preventing ground cover for crops (like maize or sorghum) that usually are grown with clean cultivation. In general, the goal of plant breeding should be to assist transformation of today's food production system into more environmentally benign systems, rather to simplistically (and harmfully) increase yield per unit area. This new goal would give major assistance to efforts to increase sustainability of food production, both by increasing environmental health and by decreasing any undesirable effects of monoculture high yield production.

Additionally, some critics say that there is no need at all to breed for higher yields of food crops, because food production is already sufficient to feed the world. Just and equitable distribution of food now at hand would solve problems of world hunger. The funds spent on crop breeding could be better spent elsewhere, especially if they were spent to aid in correcting societal problems. This argument, "the world has enough food," also is used to show that genetic engineering to increase yield potential is not needed.

Finally, as a corollary of certain concerns about use of biotechnology for plant breeding (biotechnology gives too much power to the private sector), some groups believe that private sector plant breeding must be curtailed or even eliminated, because of the innate inability of profit-seeking industry to strive for socially just or environmentally beneficial goals in plant breeding. For this reason, they believe that it is wrong for industry to finance public sector plant breeding research (whether with unrestricted grants, or as targeted research, or as contract research) because this undesirably warps the direction of public sector breeding research and may even turn out false and biased results.

They also believe it is fundamentally wrong for farmers to have to pay for seeds, because farmers have always saved their own seed and were not dependent on profit-seeking industry. They are particularly concerned about the application of intellectual property rights (such as patents or "plant variety protection") to seeds and breeding materials, because products of nature have always belonged to the public at large and not to individuals or corporations — it is morally indefensible to claim ownership over items that belong to the public at large.

The problem of intellectual property rights becomes even more contentious and difficult to resolve with the fairly recent entry of the public sector into this area; universities and public sector plant breeders are now obtaining intellectual property rights of various sorts on their biological and intellectual products of plant breeding research, and use them as sources of income via licensing or other financial arrangements, to support the breeding programs.

Predictions/Recommendations

Mark Twain is supposed to have said that "Prophecy is a good line of business but it is full of risks." This statement certainly applies to the future of plant breeding. But I will predict that plant breeding will continue to provide improved cultivars for farmers who want them, cultivars bred to satisfy their needs as nearly as possible. Biotechnology will continue to give useful aids to existing kinds of conventional breeding in constantly increasing amount, but at a slower pace than was envisioned ten or 15 years ago, before concerns about its safety and desirability were brought to the attention of the general public. Patience and caution will be essential, for those who wish to use it in plant breeding.

The nature of both public sector and private sector plant breeding seems to be changing, with public sector plant breeding acquiring some of the characteristics of the private sector, and the private sector performing some functions of the public sector. For example, some university crop breeding programs receive significant portions of their funding from check-off funds (as from wheat commodity organizations) or from royalties (as from seed company sales of public sector vegetable cultivars). In a certain sense, the farmers or the seed companies employ the public sector breeders to do breeding that otherwise would not be done. And some of the large private seed firms have made products of their genomics research available for use by the public sector, or are considering such actions. Presumably, due consideration of the options has provided the conclusion that the firm will profit more in the long run by stimulating further wide-ranging research based on its initial work, than by sequestering the knowledge for use by only their own researchers. Intellectual or biological products that the firm can use for cultivar improvement are more likely to come from such wide-scale basic research than from their more narrowly-based in-house research.

For developing countries, it seems likely that private sector breeding will increase in amount, sometimes coupled with the public sector research organizations. Both small local companies and large international companies will enable this change, sometimes in collaboration with each other. The extent and speed of such development will depend on the economic health and stability of commercial agriculture in each country. Stable markets and prices that justify input expenditures must be in place before farmers, using their own good judgment, will purchase seed as compared to growing less productive but "free" saved seed. Hybrid seeds (such as of maize, rice or sorghum) are most likely to succeed as products of private sector breeding because their nature prevents farmers from saving seed illegally (in countries with intellectual property rights legislation). But in some economic and environmental situations (such as where climate prevents production of sound seed for replanting even though it is salable as a commodity) private sector seed breeding and sales of self-pollinated crops will be profitable for both farmers and seed companies.

But many farmers in many parts of the developing world will remain outside the potential private sector market, and unless society changes its attitude toward support of the CGIAR centers, or of local government public sector seed programs, these farmers will be on their own. There is the possibility that they themselves, with help from professional breeders, can set up their own "participatory plant breeding" networks of farmer breeders, avoiding dependence on outside capital or outside funding. Work to this end is in progress; time will show how successful it can be.

Similarly, for “environmental plant breeding”, continuation and expansion of current efforts in this direction will be needed to show both the market demand for such products and also whether they are better than other products or other methods for solving present day problems in environmental health (erosion, nitrates in ground water, etc.). This is long-range “public goods” research that clearly has to be done in the public domain (although it need not be restricted to that area), and public funds had ought to be appropriated to support it.

And finally, the movement to “hire plant breeding” from the public sector (check-offs, royalties) is probably a good way for underserved agricultural producers to “buy” the cultivars they need, if the private sector is not providing them. Such research could be a useful supplement to the more fundamental research at the universities or other public institutions and can help to “keep their feet on the ground.” It also can provide good training grounds for future plant breeders whose primary goal is development of successful cultivars. This can help to fulfill a need that will continue to grow, with or without continuing contributions from biotechnology.

New Technologies for Sustained Productivity Growth:
Plant Breeding

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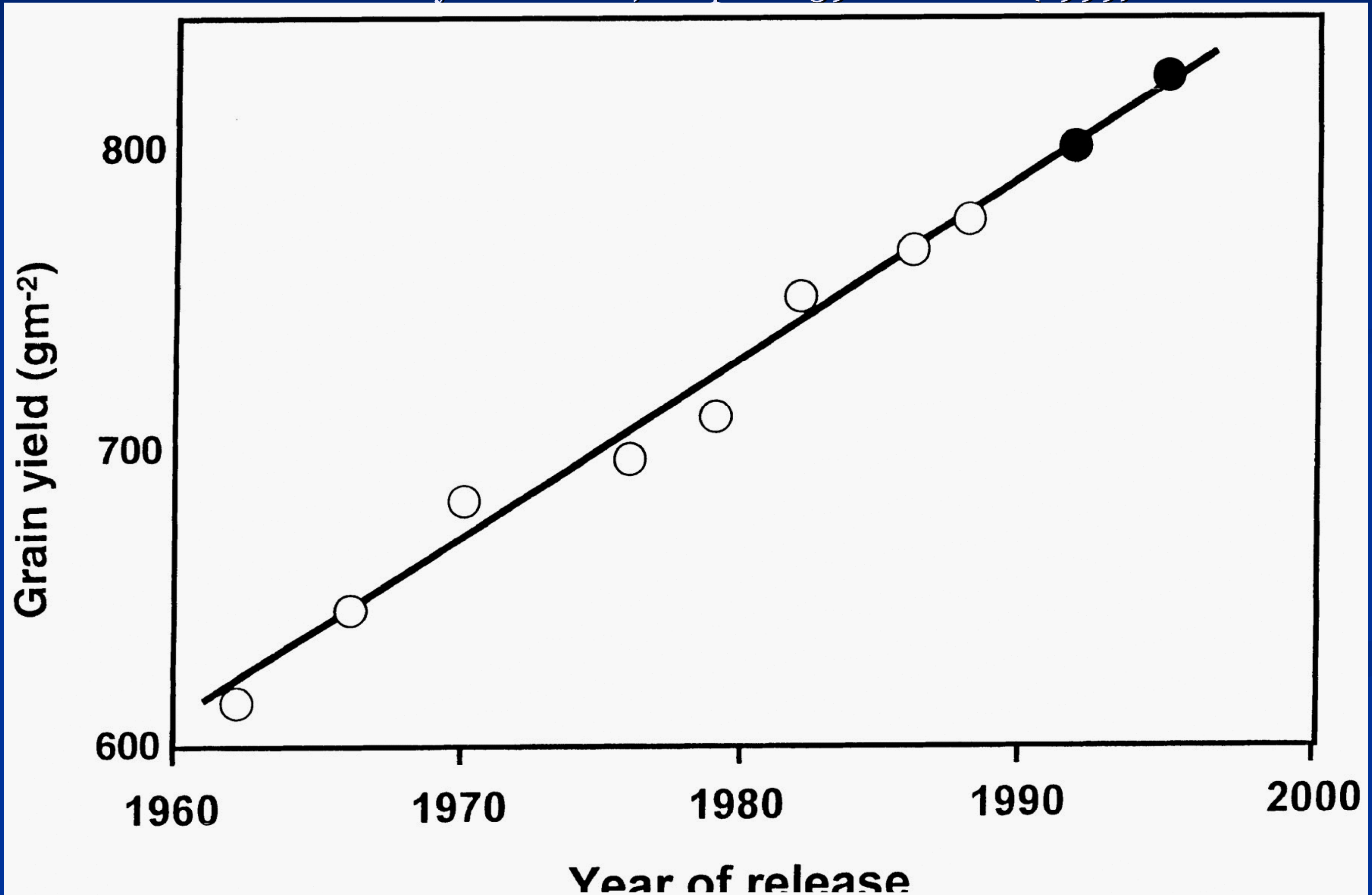
Past Achievements: Productivity

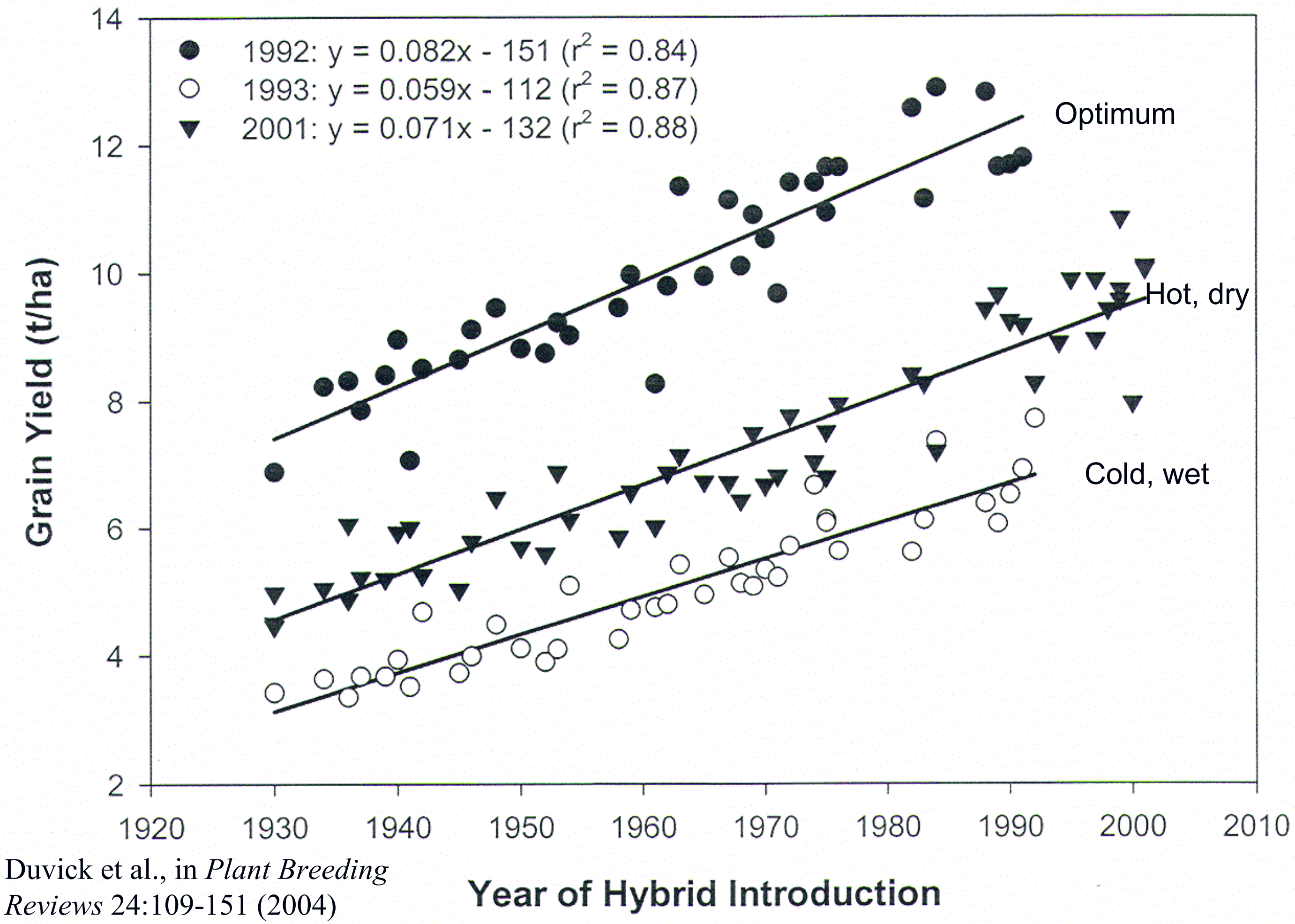
- Linear gains in yield for most field crops
  - 50% to management (e.g., fertilizers)
  - 50% to genetics (e.g., higher yield cultivars)
- Genetic yield gains are caused by:
  - Increased tolerance to abiotic and biotic stress (e.g., drought tolerance, disease resistance)
  - Increased efficiency of grain production (e.g., small tassels, short plants)
  - Conventional breeding did it all

Genetic gain in wheat: Mexico (CIMMYT)

Reynolds et al., Crop Sci. 39:1611-1621 (1999)



Increased Maize Yield in Good Years and Bad



Duvick et al., in *Plant Breeding Reviews* 24:109-151 (2004)

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Past Achievements: Organizational

- Public sector (a): National, state, province
  - supported by tax payers*
- Public sector (b): IARCs (IRRI, etc.)
  - supported by tax payers indirectly **
- Private sector
  - supported by farmers***

- *Now supported by combination of restricted grants, royalties and the original sources
- **Now supported by combination of restricted grants, collaborations and the original sources
- ***Still supported by farmers

Potentials for Further Advance

- Genetic yield gains can continue at same pace for at least several more decades
  - Conventional plant breeding will continue as the essential foundation
- Biotechnology, via transgenics, can continue to add defensive traits
  - Must move beyond vertical (short-term) resistance to horizontal (durable) resistance

Potentials for Further Advance

- In long-term, molecular biology insights can enable skillful, non-transgenic, improvement of native genomes
  - This will improve speed and precision of breeding for increased tolerance to biotic and abiotic stress, and therefore
  - Will increase yield and dependability
- This will be the most significant and long-lasting contribution of biotechnology

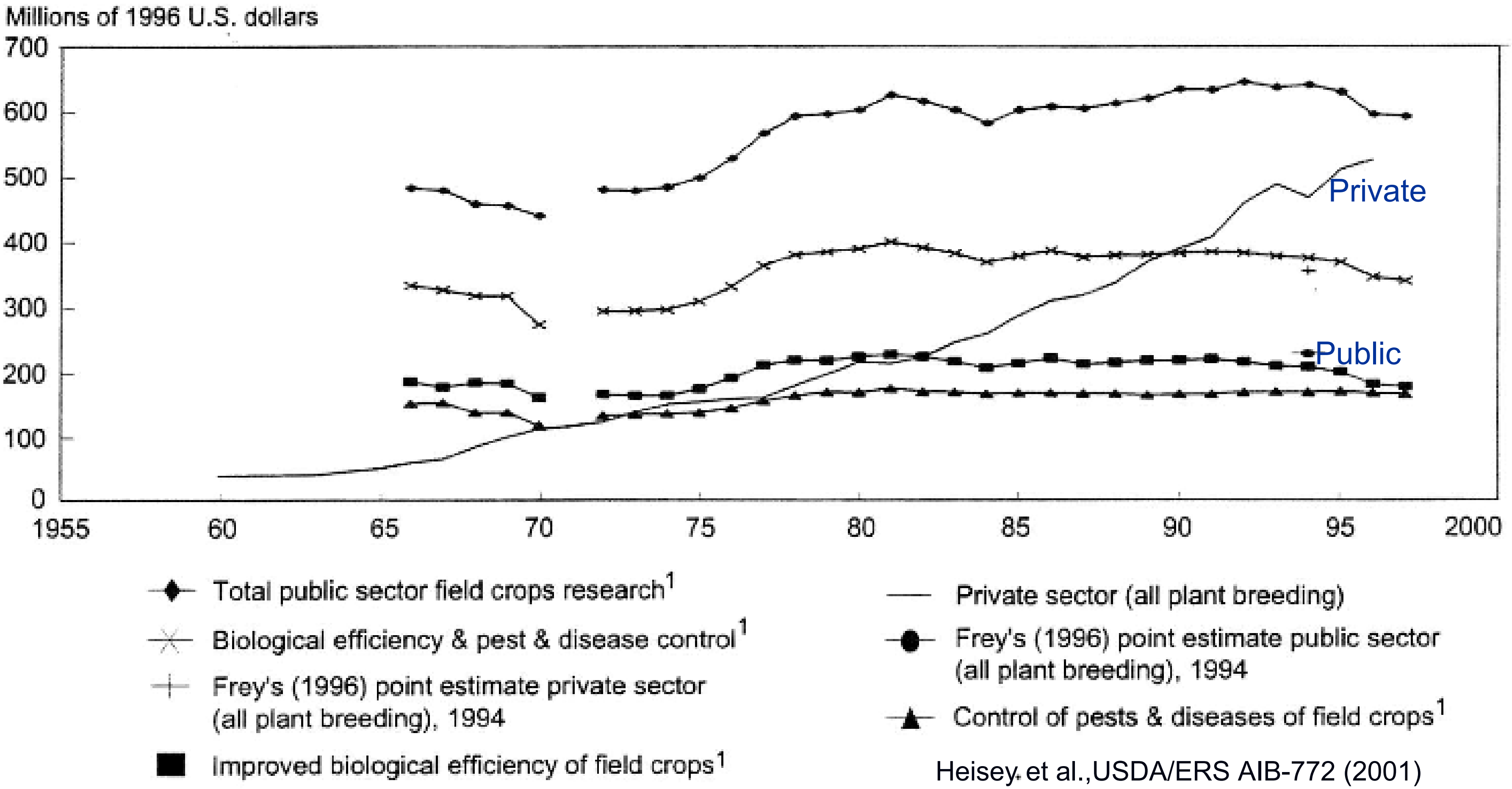
Complications: Public sector

- Funding amounts (U.S.) constant over the years, but increasingly less for cultivar development, more for biotechnology
- Consequently, less work in cultivar development than previously, in some crops and/or regions
- Reduced ability to train plant breeders to meet future needs.

Public and Private Expenditures in Plant Breeding, US

Figure 3

Real public and private sector expenditures on plant breeding, U.S. agricultural research deflator



Heisey et al.,USDA/ERS AIB-772 (2001)

[1] Data not available for 1971.

Complications: Private sector

- Consolidations: advantages and disadvantages
  - Economies of scale
  - Disruptions in management and organization
- Fears of monopoly
  - the norm for past 50 years
- Fluid ownership situation
  - the norm for past 50 years

Complications: Biotechnology

- Transgenic crops enthusiastically adopted by farmers, when allowed to do so
- Strong and effective opposition by some segments of society
  - Chief concerns: food safety, environmental health, concentration of power in private sector
- Consequent bans of transgenic crops or their products in some countries

Complications: Biotechnology (cont'd)

- High cost of research
  - Long-term until major payoff
- Can public sector funding stay the course?
  - Disaffection of public with agriculture and farmers
- Can private sector funding stay the course?
  - Cannot stop conventional research so need extra profits to pay for biotechnology research.
  - How much higher can seed prices go?

Complications: Developing Countries

- Farmers in developing countries are not well supplied by plant breeding (some exceptions)
  - Public sector generally poorly supported
  - Private sector usually absent because no markets for commercial seed sales
  - IARCs have made major contribution of improved cultivars for some crops, but
- IARC funding now reduced drastically
  - Directed away from plant breeding
  - Directed toward rural socio-economic development

Reduced Funds, IARCs

- *"Expenditures on agricultural research in the public sector, including the International Agricultural Research Centers (IARCs) have stagnated and in some cases, declined sharply in recent years."* (Maredia and Byerlee, Agricultural Economics 22:1-16. 2000)

Complications: Alternative Goals for Plant Breeding

“Plant breeding’s primary goal should be to enhance environmental well-being”

- Breed for best performance in polycultures
  - Higher total yield
  - Better stability of performance
- Breed for perennial habit
  - Less plowing, less erosion
- Breed ground-cover crops
  - Prevent erosion in row crops

Complications: Alternative Goals for Plant Breeding (cont'd)

"Plant breeding's primary goal should be to enhance socio-economic well-being"

- Biotechnology will be bad for the poor and disadvantaged
  - Biotechnology is the tool of the private sector
  - Biotechnology will increase power of corporations
- Intellectual property rights for seeds is wrong
  - "Farmers' rights" should prevail
- Higher yields from plant breeding are not needed
  - Sufficient production already, if it is justly and equitably distributed.

Higher yields not needed

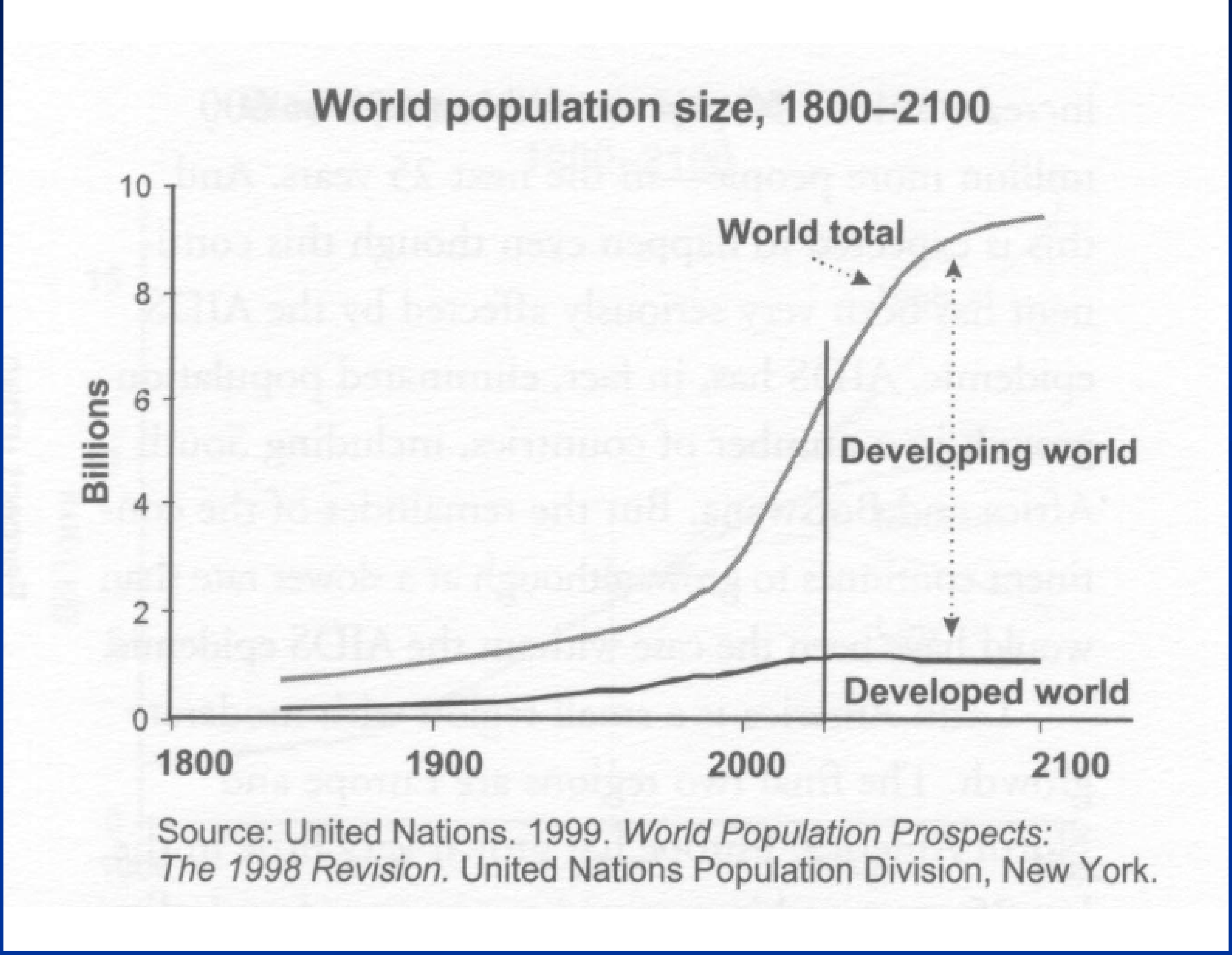
- *“Not only is there enough food in the world, but as long as we are only talking about food — how best to produce it — we’ll never end hunger or create the communities and food safety we want.”*
- *“Hunger is not caused by a scarcity of food but a scarcity of democracy.”*

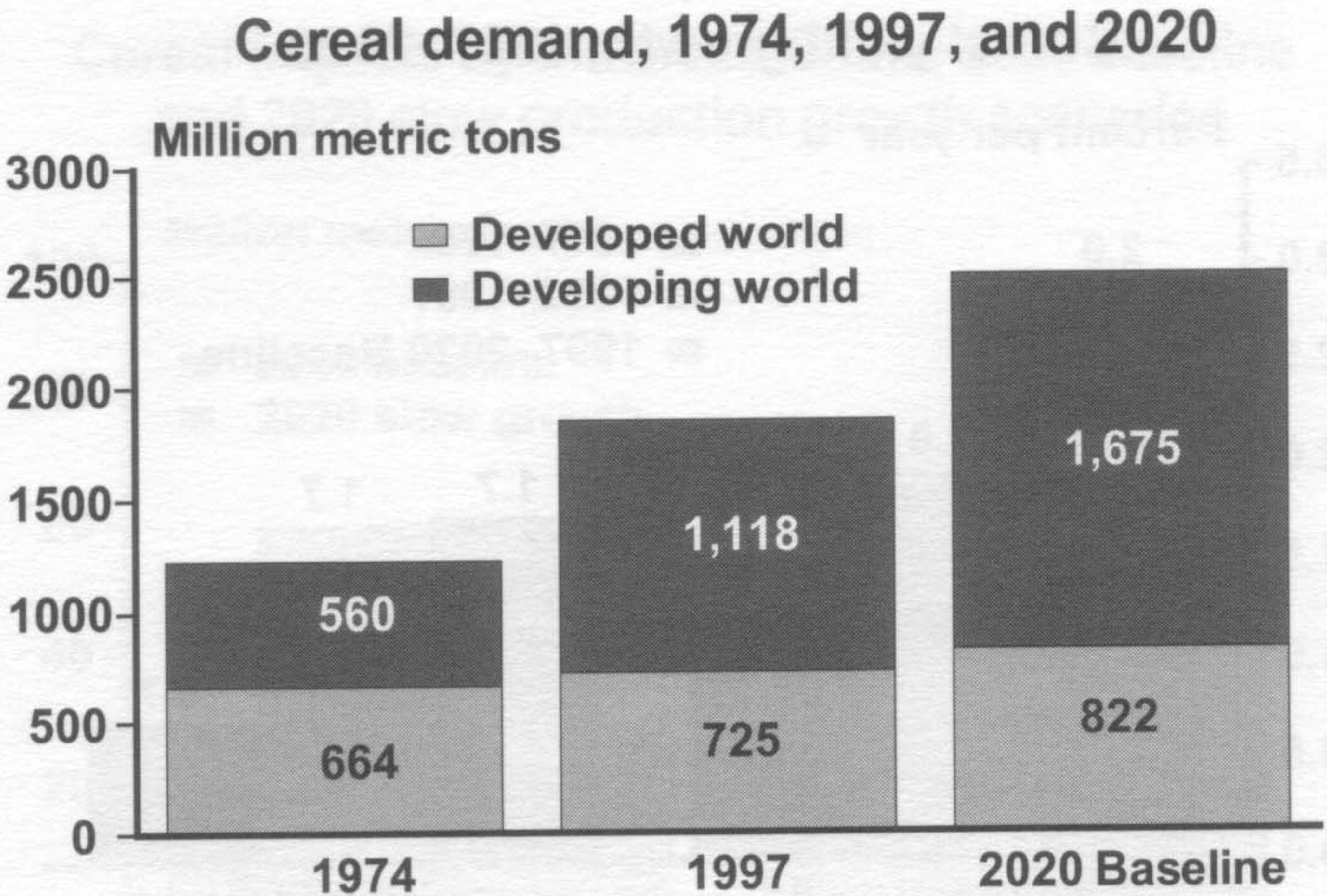
Frances Moore Lappe, *The Des Moines Register*, July 24,

Higher yields not needed

- *"The biotechnology industry claims it holds the answer to world hunger: high technology to increase production. But according to the United Nations Food and Agriculture Organization (FAO), this badly misstates the problem. There is no shortage of food in the world. Per capita food production has never been higher."* Advertisement in New York Times, October 11, 1999, by *Turning Point Project, a coalition of more than 60 non-profit organizations.*

Global Population Trends





Source: Rosegrant et al. 2001. *Global Food Projections to 2020: Emerging Trends and Alternative Futures.* International Food Policy Research Institute, Washington, DC.

Commentary: Genetic Engineering

- “In reality, anxieties about genetically engineered crops are social rather than scientific. … Outrage at [concentration of wealth] rather than perception of serious objective risks, underlies much anti-GM activism.“

  John Postgate, book review, in TLS August 1, 2003

Predictions

- Plant breeding will continue to produce improved cultivars
- Biotechnology will be used increasingly, albeit at slower pace than expected
- Plant breeding of the future will seamlessly integrate conventional and molecular breeding
    - but probably will have a fancy new name, e.g., "biological enhancement"

Predictions

- Public and private sector plant breeding will come to resemble each other in some ways
  - Public sector, supported by check-off funds and/or royalties will breed for producers not adequately supplied by the private sector
  - Private sector will donate some of its basic research findings to public use

Predictions

- Private sector breeding for developing countries will increase in amount
  - Will grow in step with development of profitable commercial agriculture
  - Hybrid crops (maize, sorghum, rice)
  - Self-pollinated crops in regions where sound seed production is difficult or not possible
  - Small local companies and large international companies (and sometimes the public sector) will share the markets

Recommendations

- Public sector should be funded to do research in “environmental breeding”
  - Breed new crops for use in environmentally friendly and also profitable reinvented production systems (polycultures, etc.)
  - Breed current crops for use in environmentally friendly and also profitable modifications of current production systems (monocultures, etc.)

Recommendations

- Encourage development of "participatory plant breeding" where needed (and wanted)
  - The farmer pays
- Encourage "breeding for hire" by public sector, for crops/regions not adequately supplied by private sector
  - The farmer pays

Recommendations

- Increase efforts to maintain and increase genetic diversity of crop plants
  - Germplasm collection, conservation and characterization (“seed banks”)
  - Public sector breeders for niche crops and regions
  - Germplasm Enhancement of Maize (GEM) program, a collaboration of public and private sectors

In Conclusion

- Plant breeding can and will continue to help feed the world but adjustments will be needed to adapt its support and operations to current and future societal needs and norms
- Plant breeding — "planned evolution" — has itself evolved, and will continue to evolve in the years to come

A final comment …

"The laws governing inheritance are for the most part unknown. No one can say why the same peculiarity in different individuals of the same species … is sometimes inherited and sometimes not so … "

Charles Darwin (1859) "The Origin of Species"