Limits to Growth in World Food Production

Ceilings for wheat yields are coming in developed countries.

Neal F. Jensen

Summary. The dramatic increases in wheat yields that began in the mid-1930's in the United States will soon begin to level off. The favorable mix of genetics and technology that has characterized this era must build upon an ever higher yield base for the future. At the same time the residue of factors that can lower wheat yields includes a larger proportion of forces not easily shaped or controlled by man. An example is weather. The result is a natural yield ceiling that is already visible and that will impose a limit on future productivity growth.

Could he return for a day, Robert Malthus would be amazed at how little things have changed in the last two centuries. His controversial discourse of 1798, arguing that the growth of populations occurs geometrically while the growth of food production occurs arithmetically, is still unproved and controversial. But some changes have occurred. For example, while the "passion between the sexes" continues unabated, there have been medical advances which now short-circuit the formerly close relation between the sex act and human births. Other scientific discoveries and technological applications have greatly increased the productivity of food crops and livestock.

The geometrical doubling growth of populations that Malthus postulated has, in fact, occurred, and it suggests that a critical test of his hypothesis is just a generation or so away. World population reached 4 billion people in 1976. Earlier predictions of 7 billion by 2000 are now being modified to reflect the recent slowing in population increase in some parts of the world. Uncertainty surrounds only the "when" of reaching 7 billion—there seems little "if" about it. A further uncertainty surrounds the eventual carrying capacity of the world, which someday might be called the normal population. It is generally conceded that world population cannot stabilize below 12 billion people and may go as high as 25 billion. Studies I made some years ago (*1*) indicated that the range of experts' opinions of the eventual maximum world population included the figure of 50 billion.

Malthus has been somewhat discredited by technology. He did not foresee the Industrial Age and the geometric effect of technology upon economic growth. Technology, backed by cheap energy and vast resources, has enlarged food production capacity so much that today the supply often exceeds the world demand expressed in market terms, although for logistic and economic reasons the food may not get to the hungry people who need it. The result is that food production appears to have fared rather well in Malthusian terms. Indeed, my own data show that wheat yields in New York doubled between 1935 and 1975, just as world population doubled between 1930 and 1976. The current question is, what does technology in agriculture hold for the future of food production? I will attempt to assess the role of technology in the productivity of one crop, wheat, and draw some inferences for the future.

A Century of Wheat Production in New York

The wheat breeding project in my department of the New York State College of Agriculture and Life Sciences at Cornell University has been operating since the early 1900's. The first wheat variety, Honor, was introduced in 1920. Since then 11 additional varieties have been bred (*2*). Today, we grow these 12 varieties annually as a "living museum" nursery on the experiment station fields. This nursery demonstrates visually the changes that have taken place in wheat varieties through breeding. It also provides useful data on the productivity of old and new varieties under modern cultural conditions. By combining this information with the records of wheat production in New York it is possible to measure the impact of technology on productivity (yield per area). Furthermore, it is possible to partition technology and separate the effects of genetics and breeding on productivity from the effects of all other technological factors (such as fertilizer, cultural practices, herbicides, and pesticides).

Figure 1 shows the history of wheat yields in New York State by decades for the past 110 years. Gains were extremely modest from 1866 through the decade ending in 1935. In fact, the cumulative gain (Table 1) for the first 70 years was only 3.1 bushels per acre (bpa) (*3*). The slope of the line from 1936 onward is steeper and continues today essentially as a straight line. The gains in productivity have been substantial, as may be seen from the fact that the 1936–1945 one-decade gain of 4.7 bpa is greater than the total gain of the previous seven decades. The lines for a few other states are shown to indicate that this is a general phenomenon (in fact, it occurs wherever technology has been applied).

Table 2 shows the average yields for the most recent decade, 1966–1975, of all Cornell varieties in the living museum nursery grown under modern conditions. The yields from these experiment station nurseries are higher, of course, than the state average of all production for the same period. These data clearly show the increased productivity of the newer varieties.

Sources of Gains in Wheat Productivity

If we make the reasonable assumption that the 1935 decade-ending mean figure of 19.2 bpa per year was produced by Honor and similar varieties, and the 1975 decade-ending figure of 39.3 was generated by Yorkstar, it becomes possible to make certain statements about wheat productivity. First, we see that produc-

The author is Liberty Hyde Bailey Professor of Plant Breeding in the New York State College of Agriculture and Life Sciences at Cornell University, Ithaca 14853. This article is Paper No. 674 in the Plant Breeding Series.

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Table 1. New York State mean annual wheat yields in bushels per acre for decades ending in the years shown. Records were first kept in 1866.

Decade ending	Yield	Shift	
		Per decade	Cumulative
1875	16.1	(Base) 0	0
1885	17.5	1.4	1.4
1895	18.0	0.5	1.9
1905	17.9	−0.1	1.8
1915	20.1	2.2	3.9
1925	19.3	−0.7	3.2
1935	19.2	−0.1	3.1
1945	23.9	4.7	7.8
1955	27.9	4.0	11.8
1965	33.5	5.6	17.4
1975	39.3	5.8	23.1
	Estimates		
1985	43.3	4.0	27.2
1995	46.3	3.0	30.2
2005	48.3	2.0	32.2
2015	50.0	1.7	33.9

tivity has increased dramatically—the yield has doubled in four decades. Second, we can use the relations between the modern yields of Honor and Yorkstar (Table 2) and the 1935 and 1975 decade mean yields (Table 1) in a simple equation whose solution gives us insight into the source of productivity. Thus, the Yorkstar yield today (58.8) bears the same relation to Honor today (44.1) as the state yield today (39.3) would bear to the hypothetical state yield today (x) if Honor instead of Yorkstar were being grown. The value for x turns out to be 29.5 bpa. That figure falls almost halfway between 19.2 and 39.3 (Fig. 1) and tells us what the expected state average would be today if there had been no advance in wheat breeding after Honor. Of course, Honor gives higher yields today than it did when it was introduced in 1920. This is because of advances in all the other technological or cultural factors, such as fertilizers, herbicides, pesticides, and machinery. Thus, we can partition the total state gain in productivity of 20.1 bpa into a genetic portion of 9.8 (49 percent) and a technological portion of 10.3 (51 percent).

The gain in wheat productivity for the United States as a whole has averaged 0.50 bushel per year over several decades. The New York gain of 20.1 bpa over the 40-year period, 1936–1975, amounts to 0.50 bpa per year, supporting the existence of a general phenomenon.

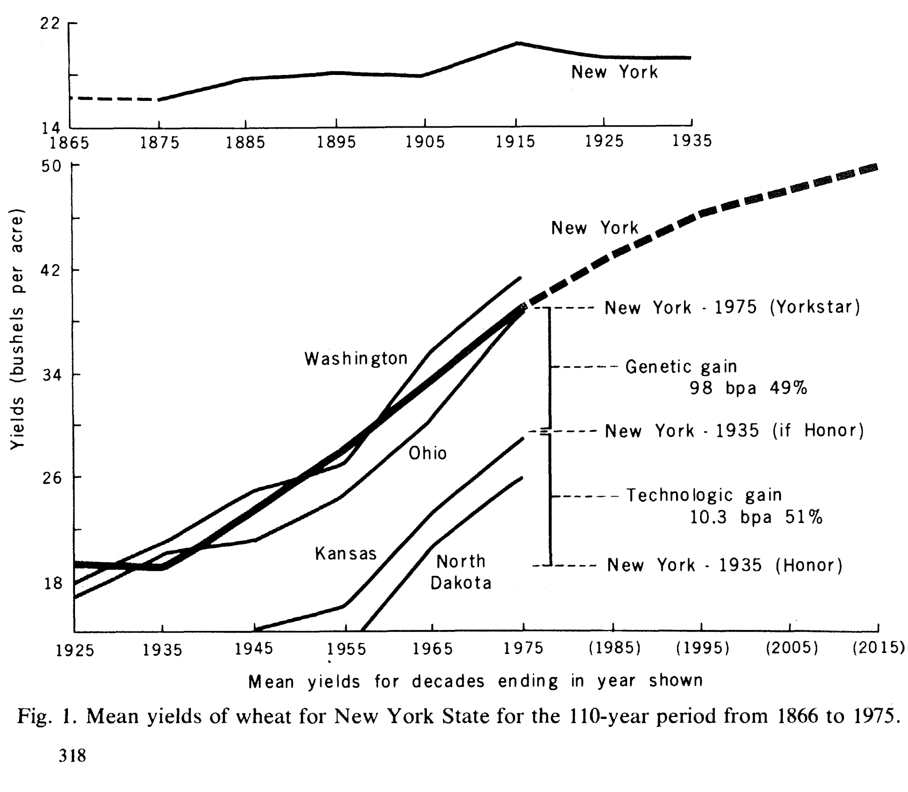

Fig. 1. Mean yields of wheat for New York State for the 110-year period from 1866 to 1975.

General Limits to Growth

The legacy of Malthus is that we cannot escape the question of limits to growth, whether it be growth of populations, economics, or food productivity. The question is particularly apt today as we see around us many constraints on economic growth—indeed, on living—related to our formerly "free" or inexpensive basic resources of land, water, air, minerals, and energy. Historically, the full costs of economic growth often have not been assessed or recognized within the same time frame. The result has been that we live in a world of continual corrective action for past transgressions against our life-support system. At the same time, our concern, insofar as we are wise enough, extends into the future. Today, solutions that may be technologically feasible may not be otherwise feasible. These are not solely economic matters—an environmental impact statement, for example, is basically a political instrument.

Table 2. Ten-year (1966 to 1975) mean yields in bushels per acre per year of all Cornell wheat varieties in the living museum nursery, Ithaca, New York.

Variety	Year of release	Yield	Height (cm)
Honor	1920	44.1	116
Forward	1920	47.8	112
Valprize	1930	44.2	116
Yorkwin	1936	48.4	115
Nured	1938	46.0	114
Cornell 595	1942	52.1	112
Genesee	1950	52.5	111
Avon	1959	53.8	108
Yorkstar	1968	58.8	95
Arrow	1971	57.3	94
Ticonderoga	1973	64.7	85

In agriculture, too, we have long operated under this generally accepted concept of unlimited growth. I think it is fair to assume that the technology of the future will not be as "free-wheeling" as the technology of the past. The constraints we now see on economic growth will also place limits on the way technology itself will evolve in the future. The farmer will not escape this. In fact, during the past few years the farmer has been caught in a whirlwind of bannings, withdrawals, and substitutes affecting fertilizers, herbicides, pesticides, livestock medicines and feeds, and many other supplies and operations.

Productivity Versus Production: What Is Ahead?

Productivity and production, although related, are terms with vastly different meanings. Productivity is yield per area or the yield potential under a given set of environmental parameters. Production, however, is productivity realized, the sum of all harvested areas times their yields. Scientists work to increase wheat productivity. These increases make possible increased production, but the relation is not a direct one since many factors influence the actual production of wheat from year to year. For example, I referred to the doubling of wheat productivity in New York between 1935 and 1975 (from 19.2 to 39.3 bpa). The average yearly production of wheat for these two decades separated by 40 years, however, increased only 39 percent (from 4,868,300 to 6,778,200 bushels). The reason for this is that farmers reduced their wheat acreage from an average of 255,300 acres per year for the earlier decade to only 172,000 acres per year 40 years later.

The world food problem often translates into a scenario where we pose the question of maximum production to meet a crisis. How much wheat could New York (a state whose highest acreage was 790,000 in 1880 when 15,010,000 bushels were produced) produce today in all-out production (*4*)? The answer would surely be disappointing. In my opinion it would be difficult today to find one half of the acreage available in 1880 for wheat—given the sizable irreversible losses to urbanization and the competing pressures for alternative uses even in a crisis. Even with a doubled productivity rate it would be difficult to attain the record of wheat production established a century ago.

What is the outlook for continued growth in productivity in wheat? The picture I have painted shows four decades of uninterrupted growth at a steady rate. The productivity can be attributed equally to genetic and other technological gain. The genetic gain potential still before us is undoubtedly large (*5*). The technological gain potential must also be considered sizable but is more speculative because technological directions will evolve from a mix of pressures and information yet to be discovered (how can one know the unknown?).

It has come as a shock to me to realize that my answer to the question posed in the previous paragraph is gloomier than the circumstances would suggest. It is the point of this article that, despite the favorable evidence presented, we are approaching the end of an epoch of research and of increases in wheat productivity. Our picture of the future is blurred because our viewpoint is within the time segment represented by the upward slope of the productivity line in Fig. 1. It is self-evident that this slope cannot be sustained indefinitely. In fact, I believe the line will begin leveling off and this will be evident for the decade ending in 1985. I emphasize here that productivity will continue to grow, but at a slower rate. After a few decades of gradual slowing, the productivity line for New York wheat will assume a slope very much like the 1865 to 1935 segment, except, of course, at a higher yield level. It seems unlikely that any future combination of genetics, technology, or unknown factors will be able to generate a sustained rise in productivity from these high levels. Thus the entire past and future of wheat productivity in New York under rain-fed conditions can be expressed as a zigzag line embodying the single dramatic upward slope that began in the mid-1930's.

The rate of productivity increase will become slower and will eventually become level for several reasons. First, improvements to the wheat plant through plant breeding become part of the productivity base. Continued incorporation of an improved character into new varieties results in a sideways movement in productivity rather than a new upward swing. Plant height is a good example. The heavy wheat head is positioned at the very tip of a slender, reedlike stem. It is like the handle of a lever whose fulcrum is the base of the wheat plant. The ability of the wheat head to remain standing until ripe for harvest through seasonal hazards such as wind and rain storms is dependent on three factors: (i) the firmness of the root attachment to the soil, (ii) the length of the culm (leverage), and (iii) the actual strength of the culm. Reduced height is a powerful way to increase resistance to lodging or falling over. With reduced height and increased lodging resistance, productivity can increase because the crop escapes the severe losses in quantity and quality which accompany downed grain. Also, the full effect of technological inputs, such as increments of fertilizer, can be realized. Table 2 shows the significant height reductions realized in the variety sequence of Genesee, Avon, Yorkstar, Arrow, and Ticonderoga. We believe a further reduction of 6 inches (15 centimeters) or so is possible for nonirrigated New York wheat. Thus, height reduction represents a plant improvement whose impact already has been built into the productivity base of wheat.

Second, technology, other than genetic, already has identified and removed or modified as many bottlenecks to productivity as possible, given our present state of the art. For the future, technology will be under a tight rein of accountability to society for its impact on health, safety, environmental, and ecological concerns. These and energy considerations may sometimes dictate that possible solutions are not feasible. The predictable result is a slowing of productivity growth.

Third, as the factors which are bottlenecks to production of wheat are eliminated or modified through breeding and other technology the eventual residue will consist of forces over which man has less and less control. A good illustration is climate and weather. In Fig. 1, although the slopes of the Kansas and North Dakota lines are similar to New York's, the level of production for both states is lower than that for New York. This is principally due to climate and weather, reflecting moisture available to the crops in the different areas. Climate, or weather, will play an ever important role in future crop production. While one may think of ways to increase production, particularly in a developing country, it is not so simple in a developed country where technology has long interacted within the competitive needs of society. In fact, with time it is easy to see factors conducive to shrinking agricultural production. For example, western U.S. irrigated agriculture faces gradual elimination as the pressures for higher priority water needs become evident.

Coming: Absolute Yield Ceilings

A productivity line with an undeviatingly upward slope as shown here must be a short-range phenomenon. To gain the perspective of the long run it is necessary to understand the nature of a yield ceiling. A ceiling has two faces, one relative, the other absolute. I think it fair to say that almost all productivity increases of the past have been made in the relative area; that is, the ceiling has been there but it has been possible to gradually raise it by bumping against it as we have discovered successive new inputs and favorable mixtures of technology. In technical terms the yield ceiling at a given time is the product of interaction between genotype (variety) and environment. Scientists have raised productivity by successfully modifying both the genotype and the environment. Nevertheless, somewhere down the road ahead of us lies the absolute ceiling, still somewhat flexible, with swings from year to year but basically buffered and resistant to upward change by the outside forces man has not yet mastered. What are these forces? I have mentioned weather. Others are the loss of land and irrigation water to urban (people) demands. Another is economic—simply, it will cost too much to try and extract the last increment of possible yield. Agriculture is a high-risk enterprise where major economic costs are committed at the front end of the season and the whole enterprise is at hazard to many unknown forces of the season, including the market. In North Dakota during the drought years of the 1930's, decisions to harvest wheat fields in the fall often were made simply on the judgment as to whether the value of the wheat exceeded the remaining operations of binding (twine) and threshing—all previous costs of raising the crop already had been committed and were beyond recovery. As we approach the absolute yield ceiling for rain-fed wheat I believe we will see also the development of an altered strategy of production based on optimum rather than maximum returns. The input costs of the maximum strategy based on the hope of a bumper crop each year will have to be adjusted to a more moderate approach based on average pragmatic expectations and more in tune with the conservation of energy and resources of the future.

In Fig. 1 and Table 1 I have provided some estimates that show one scenario for wheat production in New York. These estimates have been arrived at by considering the range of possibilities as they seem today. For example, I believe the present level of production of approximately 40 bpa is high enough to raise the possibility of a 10-year yield average that does not exceed it (*6*)—just as in the earlier decades of little change in productivity. On the other hand, I must believe my research data which show Ticonderoga, Houser, and newer wheat lines to be higher yielding than those now in production. At the other extreme, what might be the ultimate yield ceiling under rain-fed conditions in New York? Sixty bushels per acre average for the state? If this is possible it still remains a goal beyond my vision today. From these and other considerations I have projected a level of approximately 50 bpa and have allowed four decades to reach it. Bear in mind that the level must be maintained over a 10-year period. At this point the increase in productivity will become essentially a horizontal straight line when drawn through the fluctuating annual points.

This represents a 27 percent increase in wheat production per acre over our last decade level of 39.3 bpa—a handsome increase, indeed. (Remember that the actual production of wheat in New York in 2015 will depend on many other factors; in fact, New York might not be growing wheat at all.) This prospect must be balanced by the knowledge that the (world's) people production will be between 7 and 8 billion, essentially a 100 percent increase.

Conclusions

In conclusion, I am aware that the favorable data on wheat productivity I have presented for New York through 1975 do not support my gloomy conclusions and prognosis for the future. Nevertheless, I strongly believe that my interpretation of an approaching yield ceiling is valid and that the Malthusian divergence of food production and people production rates will widen. I am not writing of the end of productivity gains—these will continue for an unknown time—but of a slowing in the rate. At the same time, agricultural production will inevitably decline so long as the urbanization and life-support pressure of people on the environment remains unchecked. We must remember, however, that a favorable or desired trend in population stabilization must be sustained for something like 70 years for the entire population to reach equilibrium throughout its age structure.

Foreign affairs of the future will be deeply affected by the outcome of the food-people problem. What I have presented here can be but a small input into the global mix and I hesitate to draw any conclusions because of the kaleidoscopic nature of the world food situation. For example, there are countries that have yet to reach the point at which agricultural yields "take-off," and others that will never reach that point. Nevertheless, I suggest to those whose business it is to make projections on the world stage that absolute limitations to food production loom in the future. We have been surprised at the rapidity with which the energy crisis, the depletion of fossil fuel supplies, came upon us. It would be tragic indeed for this to be repeated with food. The bicentennial of Malthus's paper will be in 1998. Let us hope that by that date the problem, if not the solution, will be much clearer.

References and Notes

1. N. F. Jensen, in *Man and the Ecosystem* (proceedings of 1968 symposiums and seminars), R. M. Klein, W. W. Christensen, F. O. Sargent, Eds. (Univ. of Vermont Press, Burlington, 1971), pp. 11–25.
2. The newest variety, Houser, is not included in Table 2.
3. The conversion factor for bushels per acre to kilograms per hectare is 68.2.
4. In a crisis it is assumed that national resolve would provide suitable incentives needed for maximum production.
5. The U.S. Department of Agriculture's World Collection of Small Grains, for example, contains more than 37,000 wheats—each a potential parent.
6. In fact, yield estimates for 1976 and 1977 are slightly below the previous 10-year average and the prospects for the record low acreage 1978 crop are not promising. As a counter to this, it is well to remember that the strength of superior new varieties is their capability to make disproportionate yield gains in favorable seasons.

The Environment Today

Russell E. Train

In recent years there is very little that has been left unsaid about environmental problems and needs. This is not the same as saying we know all the answers. Our scientific knowledge, in particular, about natural systems and their interreaction remains inadequate. What we do not know still far exceeds what we do know.

What we do know is that the natural systems of the earth appear to be in considerable trouble—a statement that should be taken in the context that I am not by nature a pessimist. A sense of hopelessness would have made the very real environmental progress of the 1970's an impossibility. A major factor in explaining the extraordinary upsurge of public concern over environmental problems in the late 1960's and early 1970's was not simply the growing realization of the seriousness of the problems but a vital new sense that we really did not have to put up with them, that our society had the capability to make significant changes for the better. It appears to be a phenomenon of human history that, no matter how severe a problem may be in fact, it seldom becomes a passionate public cause until there is a widely held conviction that it can be solved.

The author is president of the World Wildlife Fund–U.S., 1601 Connecticut Avenue, NW, Washington, D.C. 20009. The original version of this article was presented as a lecture at the Tyler Ecology Symposium, Los Angeles, 31 March 1978.

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