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RESOURCE DEPLETION, AGRICULTURAL RESEARCH,
AND DEVELOPMENT

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1. Introduction: What are the questions?

The problems that have occupied those doing agricultural development in the last 10 years have essentially been solved, given the framework within which those problems were articulated. In 1974, The Second Report to the Club of Rome carried this warning:

> In ten years food-needy man's back will be even closer to the wall, and in another ten years still closer. Is there really a chance that he will relax his pressure on the ecosystem, or will he continue all over to inflict irreparable damage on nature, which then will retaliate inexorably and mercilessly?1/

Twelve years later, world agricultural production has in aggregate outpaced population growth. The dominant conceptual framework in the 1980s is quite different. This, for example, from D. Gale Johnson:

> Intensity of cultivation increased in response to what might be called population pressure. Consequently, at least after a period of adjustment, instead of declining, food production per capita increased as population increased. . .in a world in which organized research has effectively removed most of the restrictions on production that Ricardo and Malthus attributed to diminishing returns in agriculture.2/

On average, the world's 5 billion people today are better fed than 4 billion people were in 1974. Agricultural production has been growing about ½ of 1% faster than world population.3/

The production increase has been almost wholly in cereal yields per acre. This yield increase, in turn, follows agronomic innovations which require increasing intensity of energy use per hectare. Table 1 shows major world increases in tractor use, fertilizer application, pesticide inputs, and irrigation. The plunge in

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1. Mihaljo Mesarovic and Eduard Pestel, Mankind at the Turning Point, The Second Report to the Club of Rome, New York: E.P. Duton, 1974.

2. D. Gale Johnson, "A New Consensus on the Role of Population Growth in Economic Development," Commentary, Choices, Third Quarter 1986, pp. 28, 29.

3. World population grew 1.75% from 1974 to 1983; a world agricultural production index grew 2.20% annually. WRI, p. 262.

petroleum product prices since 1985 is certain to have accelerated this trend.

In summary, agricultural production is in aggregate sufficient for present and near-future population levels. We should try to understand why food sufficiency remains a problem in some areas, how the finiteness of world petroleum resources will affect future agricultural development, and the implications of long-run sustainability for research agendas.

2. Economic Theory of Renewable and Finite Agricultural Systems with Environmental Externalities

A conventional economic view might frame an optimization problem for maximizing net social value. The value of agricultural consumption is a positive term, the value of resources used as inputs are a cost, as is damage to human health and the environment. It can be helpful to state this in a formal way to clarify the basic logic and the philosophic problems associated with the economic perspective:

$$\max \int_{1987}^{n} \frac{\int_0^Q P_t(Q_t,N_t)\,dQ - C_t(Y_t,R_t,S_t,L_t,K_t) - D_t(X_t)}{e^{rt}}\,dt. \qquad (1)$$

Let us examine the first term in the numerator, $\int P(Q,N)dQ$. It contains several important assumptions. First, it says that value of production is measured monetarily. In Figure 1, the area under the demand curve at Q_1 gives, conceptually, the dollar value of aggregate production. Graphically, the monetary value of agricultural consumption is equal to A + B. In economic theory, this monetary measure of value is directly related to the underlying utility that individual consumers and households gain from their consumption. An important corollary of this first assumption is that participation in agricultural markets enhances social value. An agricultural African household that leaves self-production and consumption for market sales and purchases is increasing our measure of the social value of agricultural output.

A second assumption in Eq. (1) is the irrelevance of equity or distribution of agricultural consumption: a dollar spent on food has the same value whether spent by a Zambian, Czech, or American. A third assumption has aggregate value increasing directly with population. In Figure 1, for example, the second demand curve P_2 is associated with a higher future population level N_2. Consequently, at the same price P*, consumption Q_2 and consumer value are both higher with a higher world population N_2.

We do not mean to endorse these three assumptions, but wish to have them explicit. Obviously, at some future point, population levels and agricultural production and consumption interact.

A useful concept from bioeconomics is the slow approach over time to stable carrying capacity.[4/] In Figure 2, world population eventually decelerates and asymptotically approaches carrying capacity $\overline{N}$. We assume that this world carrying capacity $\overline{N}$ is dependent on sustainable yield for agricultural production.

In Figure 1, total cost of agricultural output at population level N_1 could be equal to total revenue P^*Q_1. Graphically, total cost is area B. Economists define consumer surplus as the excess of consumer value over cost. This is area A. In summary: consumer value is A + B, cost to consumers is B, and consumer surplus is A. Note that the higher population demand curve P_2 would give a greater consumer surplus at the same price P*.

In the second term in the numerator in Eq. (1), the cost term is C(Y,R,S,L,K). It is written to emphasize that average cost per unit production (C) is influenced by yield per hectare (Y), research expenditures (R), and the available supply of petroleum resources (S). Of course, labor (L) and capital (K) are at least as important, but we want to focus here on resource and environmental dimensions. Table 1 has shown yield increases for cereals to be sizable: 2.5% annually. Many authors attribute this increase to research, education, and extension efforts. In the U.S., for example, Braha and Tweeten argue that the domestic productivity growth of 1.8% annually is due to growth in farmers' education, and public expenditure on research and extension in agricultural production.[5/] In an American context, they conclude the economic rate of return has been about 50% on each dollar invested.

In a development context, Barker and Herdt summarize rice research studies, and report a median rate of return of about 60% on each dollar invested in

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4. Colin Clark's Mathematical Bioeconomics (New York: Wiley, 1976) is probably the best known explication of this relationship in an economic context.

5. Habtu Braha and Luther Tweeten, "Evaluating Past and Prospective Future Payoffs from Public Investments to Increase Agricultural Productivity," Oklahoma State University Agricultural Experiment Station Technical Bulletin T-163, Sept. 1986.

research.[6] As we shall see in the next section, the data imply that research has attained yield gains by developing responsiveness to energy intensive inputs.

The third term in the numerator, D(X), reflects the damage attributable to the production process. The individual variables in the X vector include pesticide residues affecting agricultural workers and consumers, groundwater problems, and the possibility of climate change. We must recognize that fossil fuel combustion and petroleum-based chemicals both contribute to the two major types of climate change being studied. One, termed the greenhouse effect, leads to predictions of global warming. The other, ozone depletion, refers to reduced ozone screening of hazardous solar radiation. This, in turn, increases skin cancer rates.

The denominator of Eq. (1) also carries an important embodied assumption. The term e^{rt} discounts future periods from the perspective of today's decision-making. If r is an interest rate of 10%, for example, it means that a billion dollar damage incurred in 20 years is simply 14% as important today. In mathematical terms, the discount factor in the denominator of Eq. (1) defines the weights by which we, in 1987, reduce the significance to us of events affecting future generations.

There are many alternative ways to define Eq. (1) formally. We could accommodate many of the problems just discussed. But we particularly wish to turn to the subject of energy use and agriculture.

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6. Randolph Barker and Robert W. Herdt with Beth Rose, The Rice Economy of Asia, Washington, DC: Resources for the Future, 1985, p. 203.

3. Energy Intensive Agriculture and Third World Cars

Development economists have not considered resource availability or cost as major factors affecting agricultural development. Neither Hayami and Ruttan, nor de Janvry, nor Barker and Herdt, nor Mellor and Gavian consider it a problem.[7]

However, Table 2 shows the considerable energy intensity embodied in modern agricultural practices in the United States. As estimated by Pimentel,[8] 6.9 billion calories are required per hectare for a yield of 7,000 kg per hectare. (In U.S. measures, this is 11.2 MBtu energy per acre to produce 112 bushels per acre.[9])

Note the importance of fertilizer. Nitrogen fertilizer is the single largest category of energy use. It should not be supposed that the U.S. is unique in fertilizer usage, however, since many countries, including China and Japan, use more fertilizer per hectare. Increasingly, synthetic fertilizers are replacing organic fertilizer in developing countries.

Figure 3, from Barker and Herdt (p. 52), shows the differential response of old and new technologies for rice production as they respond to fertilizer. The high technology method makes extensive use of fertilizer, tractors, modern varieties, irrigation, and uses somewhat more labor per hectare. High technology yields are more than twice low technology yields. While there exists biologically deter-

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7. Yujiro Hayami and Vernon W. Ruttan, Agricultural Development, Baltimore: Johns Hopkins, 1985; Alain de Janvry, The Agrarian Question and Reformism in Latin America, Baltimore: Johns Hopkins; Barker and Herdt, *op. cit.*; J.W. Mellor and S. Gavian, "Famine: Causes, Prevention, and Relief," Science, 30 January 1987, vol. 235, pp. 539-545.

8. David Pimentel and Carl W. Hall, Food and Energy Resources, Orlando, FL: Academic Press, 1984 and Pimentel, Handbook of Energy Utilization in Agriculture, Boca Raton, FL: CRC Press, 1980.

9. One hectare is 2.47 acres, 252 M calories equal one MBtu, a liter is .26 gallons, and 1,000 kilograms equal 1.1 U.S. tons.

mined yield maxima for optimal use of solar energy, cropland, water, and temperature, actual yields in leading countries have reached only one-third to one-half of the biological maxima.[10] We should expect in the near future that yields and energy intensity will continue to grow.

There is an important resource problem in anticipating future growth in energy intensive technologies. The future price and availability of oil will depend upon growth in third world use of automobiles and air travel. In the U.S., transportation uses more than two-thirds of petroleum consumption. For the third world, the same fraction probably applies: two-thirds of petroleum is used for automobiles, trucks, and airplanes.

Agricultural production itself uses a modest 1% of the U.S. total annual energy consumption of 75 Q.[11] With world energy consumption at 300 Q, global agricultural energy consumption is probably much smaller than 3 Q.

However, the supply relationships for energy use in agriculture depend upon non-agricultural consumption of energy. The question is particularly important for petroleum. In 1987, proven world reserves are 700 billion barrels and world consumption will be 20-25 billion barrels. In addition to proven reserves, recent geological estimates of as-yet undiscovered oil are about 450 billion barrels.[12] Clearly, at a use level of 20-25 billion barrels annually, conventional oil at 1.2 trillion barrels would last about 50 years.

There is a major problem, however. Per capita oil use in the U.S. is 24 barrels

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10. Barker and Herdt, pp. 215-217. This is the basis for the logistic yield function in the Appendix.

11. A Q is a quadrillon Btu, or 252 trillion kcal. The 1% estimate is by Heady and Christiansen, in Pimentel and Hall, 1984, p. 237. International data are published in U.S. Energy Information Administration, International Energy Annual. Energy used to process, transport, refrigerate, and cook food is much greater than the conventional energy used in on-farm production. For corn, farm production is only one-seventh of the total energy requirement.

12. Proven reserve data are published in year-end issues of the Oil and Gas Journal. Geological estimates of yet undiscovered oil and gas are from Charles D. Masters, "World Petroleum Resources: A Perspective," U.S. Geological Survey Open-File Report 85-248, Reston, VA, 1985.

per year; most of this is burned in transportation. If the current world population of 5 billion attains the same consumption level, global use will be 120 billion barrels annually. Alternatively, if the global population doubles while per capita use attains 1/2 the current U.S. level, the same 120 billion barrel annual figure results. The ratio now of remaining resources to annual use would be 9 years. The continued availability of oil at current prices for the high U.S. consumption rate seems to require that developing countries abstain from similar consumption, or higher population, or both.

The changes in world attitudes about oil availability over the last 15 years are due to fluctuations in market structure rather than changes in estimates of resource availability. In 1982, global oil prices reached $34 per barrel, and concern about exhaustion was high. At that time, remaining resources were about 1.3 trillion barrels. Five years later, 100 billion barrels have been consumed, bringing remaining resources to about 1.2 trillion barrels. But, since prices are $15-$20 per barrel, there is no concern about availability.

The rapid short run fluctuations in market power and monopoly pricing should not be confused with the gradual depletion of conventional oil.

Many agricultural energy inputs can use other energy forms besides oil. Table 2, for example, shows that nitrogen fertilizer is usually derived from natural gas as an ammonia feedstock. (Technically, ammonia can also be made from oil and coal at a higher cost.)

The remaining resource picture is comparable for natural gas. In Table 3, it is evident that present world consumption levels permit, arithmetically speaking, 121 years of consumption. However, if world use attained the American per capita level, the number becomes 22 years.

As conventional oil and natural gas resources are consumed, we approach the point where impending exhaustion impacts on prices. Figure 4 shows one solution to the problem of pricing remaining oil resources.[13] Prices would stay near present levels (in real dollars) for many years, and begin rising sharply in the next century. Global use would stay near present levels of 20-25 billion barrels annually, and then fall sharply; see Figures 5 and 6.

The assumptions used in Figures 4-6 are simple: stable world population, and no effect of a rising third world income level on demand. If we assume both population and income growth, the solution is more complex but may show a short run rise in consumption followed by a more rapid decline to exhaustion.

An important generalization follows: energy intensive high technology agriculture can continue to expand for several decades. At some point in the next century, accelerating energy prices will require a new direction in production technology.

Hopefully, agricultural researchers will be aware of this problem a priori rather than post hoc. Future research will need to focus on high yields with less petroleum and natural gas inputs.

Several objections may be raised to this conclusion. First -- can today's alternative energy technologies provide substitutes for conventional oil and gas? The answer is negative. Synthetic gas from coal will cost \$16 to \$20 per 1,000 cubic feet. Synthetic gasoline from coal is more costly, in the range of \$2 plus per gallon production cost.[14]

A second objection: can biomass energy substitute for oil and gas in agriculture? The general answer is of course affirmative. Animal and plant waste are common forms of nitrogen fertilizer and heat energy. For vehicle fuel, Brazil

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13. Figure 4 assumes world population is stabilized at its current 5 billion level. It is adapted from Duane Chapman, "Computational Techniques for the Intertemporal Allocation of Natural Resources," American Journal of Agricultural Economics, 1987, February, vol. 69(1), pp. 134-142.

14. Duane Chapman, Energy Resources and Energy Corporations, Ithaca: Cornell University Press, 1983, Ch. 14.

has shown that sugar can be the fuel basis for automotive transportation. The problem here is cost: it appears that making biomass liquid fuel is so costly that it cannot be sustained. Rephrased, the point is that we cannot visualize technically an economy wherein tractors and trucks are manufactured with biomass energy, and these vehicles are used on biomass farms with biomass fuel to produce liquid fuels for general non-agricultural use. The most widely used processes today require 1 gallon of conventional petroleum to produce 1 gallon of conventional ethanol.[15] Brazil's debt problem is in part caused by the massive subsidies necessary to support its sugar-based ethanol program.

A final objection: can coal or nuclear power replace oil and natural gas as energy sources for agricultural inputs? The answer here is not clear. Increased global coal use may create global environmental problems with respect to climate change, upper atmosphere ozone depletion, lower atmosphere ozone pollution, and acid deposition. Nuclear power in the 1980s is much more costly than conventional electricity sources. From a technological perspective, there are no easy methods for creating fertilizer, pesticides, and on-farm transport by nuclear energy.

The immediate conclusion, then, is that energy intensive agriculture can continue to expand for some decades. Ultimately, agricultural research will need to focus on high yields with less conventional oil and natural gas requirements. If developing countries move towards U.S. levels of oil and gas use, this point will arrive much sooner.

15. Chapman, 1983, p. 286.

4. Fertilizer and Food

Ruttan notes that:

> We are, in the closing years of the twentieth century, completing one of the most remarkable transitions in the history of agriculture. Prior to this century, almost all increases in food production were obtained by bringing new land into production. . .By the end of this century almost all of the increase in world food production must come from higher yields - from increased output per hectare.16/

To this we can add that around half of the growth in yield per hectare will come from increased applications of chemical fertilizers, principally nitrogeneous fertilizers. Depending on a limited resource as a major source of food production is not a new phenomenon, and has been a matter of public concern since the late 18th century - the Malthusian era. As in the past, we will search for technologies based on less limiting resources that can be substituted in this instance for fossil fuel-based fertilizers as their supply becomes depleted.

There are, however, two factors which distinguish the current situation from previous experience. First, there is the likelihood that the path of depletion will lead to a sudden sharp drop in oil supplies (as depicted in Figure 5) with the result that the substitution must occur more rapidly. Second, the nature of the substitution differs from the so-called substitution of chemical fertilizer for land. In the latter case, chemical fertilizers added to the land have become the major source of added growth in output. However, when fossil fuels become depleted, or possibly before that time, we will in fact be substituting a different form of fertilizer technology for existing chemical fertilizer inputs. It will require a massive input substitution simply to maintain the gains achieved through the application of chemical fertilizers. Clearly, we cannot wait for the secular rise in oil prices to begin before we start planning for this eventuality. Before considering the implications for research and technology development, let us review

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16. Vernon W. Ruttan, "Implications of Technical Change for International Relations in Agriculture," paper presented at the conference on Technology and Agricultural Policy, National Academy of Sciences, Dec. 13, 1986.

both the achievements and problems created by the growing dependency on agricultural chemicals as a source of growth in agricultural production.

The long term down trend in the real price of wheat (Figure 7) and other major cereal grains speaks to the success of research and technology development. There have been some major deviations from trend such as occurred during the mid 1970s at the time of the oil crisis. The sharp rise in oil prices was accompanied by a sharp rise in fertilizer prices. Adverse weather factors were also instrumental in the rise in grain prices. However, Timmer[17/] indicates that a food supply reduction that reduces fertilizer demand in the short run will have as its long-term effect an increase in food grain prices sufficient to restore the profitability of the original level of fertilizer use. In short, with a growing dependency on chemical fertilizer, the price of food is becoming inexorably linked to the price of fertilizer. However, while a change in fertilizer prices will lead to a change in food prices, the reverse is not necessarily true. This is because, as noted earlier, agriculture accounts for only a small fraction of energy consumption.

To illustrate some of the problems that occur with a growing dependency on agricultural chemicals in developing countries, consider the case of Indonesia. Indonesia is regarded as one of the recent success stories in agriculture. In the late 1970s Indonesia imported 1.5 million metric tons of rice per year, but in 1985 exported one-half million metric tons. Rice production grew at 5 percent per year between 1968 and 1984, but roughly half of that growth is attributable to improved financial incentives generated by a massive fertilizer subsidy.[18/] Farm gate prices were less than half of world prices, and fertilizer consumption grew at

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17. C. Peter Timmer, "Fertiliser and Food Policy in LDCs," Food Policy, Feb. 1986, pp. 143-154.

18. C. Peter Timmer, "Indonesia: Transition from Food Importer to Exporter," in Terry Sicular, ed. Food Price Policy in Asia: A Contemporary Study of Origins and Outcomes, Ithaca, New York: Cornell University Press (forthcoming).

about 25 percent per year. The decline in Indonesian imports enhanced the decline in world market prices, and Indonesia was forced to subsidize exports of low quality rice.

The future is even more problematic. With oil revenues declining, the government can no longer afford the heavy subsidies on fertilizer. Furthermore, while one kilogram of fertilizer nutrients probably led to a yield increase of 10 kilograms of unmilled rice in 1972, this ratio has fallen to about one to five at present. The genetic yield potential of rice has not increased significantly since the release of the first of the high-yielding varieties in 1966.

The situation of Indonesia, an oil exporter, is not unique. A number of other Asian countries have experienced success in moving toward self-sufficiency with the result that rice prices have fallen, and even at today's bargain fertilizer prices farmers are feeling a cost-price squeeze. Today, policy makers are concerned about the global surplus of grain. But the case of Indonesia should suggest that there is a very fine balance between surplus and deficit in domestic and world grain markets. Even with an infinite supply of chemical fertilizers, we will have to continue to increase crop yield potentials to meet future food demands.[19] The eventual depletion of oil reserves raises an even stronger warning flag for the distant future. The danger is that today's surpluses will lead to complacency on the part of policy makers and a reduction in investment in agricultural research.

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19. This point is illustrated clearly for the case of rice in Randolph Barker and Robert W. Herdt, 1985, Ch. 18, "Projecting the Asian Rice Situation." The authors conclude from their analysis that the demand for rice in the year 2000 cannot be met without further technical advances stemming from research since most of the gains from futher fertilizer application will have been realized by the end of the decade.

5. Plant Protection and the Use of Chemicals

Considerable success has been achieved in developing insect and disease resistant varieties using conventional plant breeding methods. However, private firms and government agencies have continued to promote the use of chemical control and recommend dosages that are often harmful. Again, the case of Indonesia clearly illustrates the problem.

Farmers in Indonesia paid only 10 to 20 percent of the full economic cost of the most widely used pesticides, and the extremely low price led to widespread and heavy applications.[20/] The high rates of application have caused serious ecological problems poisoning the breeding grounds for fish and shrimp in the coastal waters. Furthermore, the heavy application of chemicals has promoted the buildup of the brown planthopper by destroying the predators of the planthopper and by encouraging the development of new planthopper biotypes. Overuse of chemicals caused serious damage to the 1986 rice crop.

We in the developed world have become considerably more conscious of the environmental damage caused by misuse of chemicals. Why is such misuse being encouraged in developing countries even when more effective plant protection methods exist? What will be the impact of advances in biotechnology on plant protection?

20. C. Peter Timmer, 1987.

6. Implications for Agricultural Research and Technology Development

There are two issues to be considered. First, we must develop the technologies which will enable us not only to find a substitute for agricultural chemicals, but also to continue to enhance yield potential and growth in agricultural production. Second, we must insure that as many farmers as possible around the world have access to these technologies.

Recent advances in the biological sciences offer the greatest hope for developing the needed technologies. This kind of research, including basic and applied aspects, is typically termed "biotechnology". In the broad generic sense, biotechnology includes such areas as tissue and anther culture, wide crossing and biocontrol, as well as recombinant DNA.

Advances in biotechnology have been more rapid in the animal than in the plant sciences. This is because biotechnology research is conducted in developed country laboratories. In the developed countries, emphasis is on human health issues rather than food production, and the spillover into the animal sciences has been very large. For example, the research budget for biotechnology research in the National Institute of Health was $1.8 billion, approximately 20 times the public sector investment in agricultural related biotechnology.

Most researchers seem to agree that technologies offering improved plant protection will be among the first biotechnologies released for adoption. The most rapid progress is predicted for the development of herbicide-resistant crops.[21/] This is because resistance is controlled by a single gene; tissue culture can be used to identify the resistant strains; and there appears to be a large potential profit for private firms. Whether herbicide resistant crop varieties will prove to be less costly than other weed control methods has yet to be determined, but a

21. Wojciech J. Florkowski and Lowell W. Hill, "Expected Commercial Application of Biotechnology in Crop Production: Results of the Survey." Urbana, IL: University of Illinois, Dept. of Agricultural Economics, AE 4605, 1985.

large market is anticipated. The technology will probably be ready for adoption in some crops in five years or less.

Crop loss due to insects and diseases can be reduced through cultural, biological, chemical, or resistance breeding methods. Relatively little research is devoted to cultural or biological methods because the private sector cannot easily capture the profits. Chemical methods, the most widely used control, are favored by private industry, although an increased emphasis is being placed on the development of disease and insect resistant varieties. The hope is that such varieties, by reducing the demand for chemicals, will be more profitable and more protective of the environment. However, the cost of resistant varieties developed through biotechnology could be even higher than the costs incurred using chemical control. In some cases, biotechnology innovations could enhance the effectiveness of chemical methods. Thus, whether advances in biotechnology will reduce the demand for chemicals remains to be seen.

Biological nitrogen fixation appears to offer the greatest potential as a substitute for chemical fertilizers in the long run. Historically, this has been an important source of nitrogen in crop production. Not many decades ago crop rotations involving legumes such as clover and alfalfa were commonplace in temperate zone countries. However, as fertilizer became cheaper, higher yields and greater profit could be achieved by growing crops such as corn continuously. In the tropics, research continues on organic fertilizers and green manure crops such as azolla, sesbena, and lucena. However, these crops require considerable labor and management and do not fix enough nitrogen to provide a complete substitute for chemical fertilizer.

In the examples of symbiotic nitrogen fixation described above, bacteria in the rhizosphere of the plant convert atmospheric nitrogen to nitrate. Managing rhizobium through improved inoculum could significantly increase the yield of leguminous plants.[22/]

The hope, however, is that biotechnology research can extend nitrogen fixation to non-leguminous plants. Ralph Hardy, Director of the Boyce Thompson Institute for Plant Research, states that all crops - cereals, legumes, grasses, and even trees - might become nitrogen self-sufficient.[23/] There is much debate among scientists as to how long this process will take, and whether it can be achieved without significant reduction in plant yield potential. Hardy is optimistic. He states that it is reasonable to suggest that a nitrogen self-fertilizing plant will be invented by the early 1990s with possible commercial use by the late 1990s. Other scientists feel that it will take a matter of decades to achieve these goals. It will still have to be determined whether technical feasibility translates into economic viability, and this will depend on the cost of alternatives.

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22. Wojciech J. Florkowski and Lowell W. Hill, 1985.

23. Ralph W.F. Hardy, "Emerging Technologies Significant for Change in Agriculture: Plant Production," Paper presented at Conference on Technology and Agricultural Policy, National Academy of Sciences, Dec. 13, 1986.

7. Conclusion

In summary, we can see that the shift from a natural resource based to a science based agriculture creates a new set of uncertainties. We must invest enough in agricultural research to insure that we have the capacity to meet future demands for food and other agricultural products, whether or not we use all of the capacity. The uncertainty increases when we consider the need to provide developing country farmers with access to the new technologies.

Advances in agricultural production in the future will depend increasingly on scientific advances in laboratories in the developed world. Because biotechnology innovations are patentable, the private sector in the developed countries is making a major investment in biotechnology research. A new alliance is developing between the public sector engaged in basic scientific research and private sector engaged in technology development. How will the developing world share in these advances? Is there a danger that they could increase their dependency on chemical fertilizer, and then be left without an option when oil resources become depleted?

The lesson that we have learned from the Green Revolution is that technology tends to be very location specific. Problems are solved when scientists work in the location where these problems exist. Furthermore, we know that a lack of basic scientific knowledge represents a serious constraint on the development of viable and sustainable technologies in many areas of the tropics.

Table 4 shows that there has been a very rapid growth in agricultural research investment and scientific manpower in nearly all parts of the world. However, when one examines the country level data, it is clear that most of this growth has occurred in a relatively few countries such as Brazil, Philippines, India, China, and Nigeria.

Furthermore, the public sector pipelines through which advanced scientific knowledge or biotechnology can flow are very poorly developed. For export crops, access to advanced scientific knowledge can be provided by multinationals. For the main food crops, access can come through the International Agricultural Research

Centers and through national programs in the larger countries such as India or Brazil. However, at present the linkage between these institutions and the advanced laboratories in the developed world is very weak, and the funding to strengthen these linkages must come largely from the developed country donor agencies.

Ruttan suggests the need for a truly global research system which would tie together the national and international research establishments in both the developed and the developing world.[24] There will be a continuing need to upgrade the scientific and research capacity in the developing countries to insure that these countries have the capability to utilize a new scientific knowledge and adapt technology to local conditions.

Sustainability in an economic context implies a stable and satisfactory relationship between agricultural production and consumption. It implies a world population level or growth rate which is supportable on a long term basis. It implies that negative byproducts such as hazards from pesticides and fertilizers are controlled. Sustainability probably requires sufficient equity in access to production capacity and distribution to ensure political stability.

The current period is fortunately characterized by the disappearance of world monopoly pricing in petroleum, and the rapid growth of energy-intensive productivity in agriculture. Our research agenda should be planned now in anticipation of the need for different agricultural technologies in the future.

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24. Vernon W. Ruttan, "Toward a Global Agricultural Research System: A Personal View," Research Policy 15 (1986), pp. 307-327.

Table 1. Annual Rates of Increase in World Agricultural Production and Inputs 1975 to 1983

Agricultural production index	2.2%
Cropland, sq. km	0.3%
Cereal yields per ha.	2.5%
Roots and tubers yields per ha.	0.6%
Irrigation, ha.	3.3%
Pesticides, 1983$	4.2%
Tractors, per ha.	2.3%

World Resources Institute (WRI), World Resources 1986, New York: Basic Books, 1986.

Table 2. Energy Use in Corn Production in the United States per Hectare

INPUT FACTOR AND MAJOR ENERGY TYPE	QUANTITY PER HECTARE	ENERGY Mcal/ha
Petroleum Intensive		
Gasoline	26 liters	264
Diesel	77 liters	882
L.P. Gas	80 liters	616
Seeds	18 kg	446
Insecticides	1.4 kg	120
Herbicides	7 kg	778
Transportation	200 kg	51
Total Petroleum Intensive Inputs per Hectare		3,157
Natural Gas Intensive: nitrogen fertilizer	151 kg	2,220
Coal Intensive Industrial Inputs		
Machinery	55 kg of machinery	990
Electricity	33.4 kWh	96
Phosphorus	72 kg	216
Potassium	84 kg	134
Lime	426 kg	134
Total Coal Intensive Industrial Inputs per Hectare		1,570
TOTAL ENERGY INPUT per HECTARE		6,947

Note: Yield is 7,000 kg corn grain per hectare, equivalent to 24,500 Mcal. The calorie output per calorie input in energy is 3.5. Drying does not use conventional energy, but may use 7,000 kg stover. Labor input is 12 hours/ha. Sources are Pimental and Hall (p. 8), and Pimentel, 1980 (pp. 9-14, 23-26, 46-47, 55, 72). See footnote 8. Since crude oil average 5.8 MBtu per barrel, the 3,157 Mcal/ha are equivalent to 2.2 barrels of oil per hectare, or .9 barrel per acre. Pimental (1980, pp. 15, 16) argues that these last figures should be increased 23.5% to reflect energy needed to produce crude, refine it, and deliver the products to farm use.

Table 3. Remaining Global Oil and Gas Resources

	Oil	Gas
Quantity Remaining	1,150 billion barrels	7575 trillion ft^3
Energy content, remaining resources	6,700 Q	7,600 Q
Current annual use	20-25 billion barrels	60-65 trillion ft^3
World use at U.S. rate	122 billion barrels	350 trillion ft^3
Ratio, remaining resources		
to current use	51 years	121 years
to world use at U.S. rate	9 years	22 years

Note: Quantity remaining is the sum of proven reserves and geologically estimated undiscovered resources. Actual studies use probability distributions; this table is derived from modal values. We have used about one-third of our original endowment of oil. Masters (footnote 12), modified by recent consumption data in Monthly Energy Review and Oil and Gas Journal.

Table 4. Growth in Agricultural Research Expenditures and Workers 1959-1980.

Region	Expenditures (million 1980$ U.S.)			Scientific Workers (thousand labor years)		
	1959	1970	1980	1959	1970	1980
Western Europe	275	919	1,490	6.3	12.6	19.5
Eastern Europe/USSR	568	1,282	1,493	17.7	43.7	51.6
North America/Oceania	760	1,485	1,722	8.4	11.7	13.6
Latin America	80	216	463	1.4	4.9	8.5
Africa	119	252	425	1.9	3.8	8.1
Asia	261	1,205	1,798	11.4	31.8	46.7
WORLD TOTAL	2,063	5,359	7,391	47.1	108.5	148.0

Sources: Adapted from James K. Boyce and Robert E. Evenson, National and International Research and Extension Programs. New York: The Agricultural Development Council, 1974 and M. Ann Judd, James K. Boyce, and Robert E. Evenson, " Investing in Agricultural Supply," New Haven: Yale University, Economic Growth Center, Discussion Paper No. 442, 1983.

FIGURE I. THE ECONOMIC MEASURE OF CONSUMER VALUE

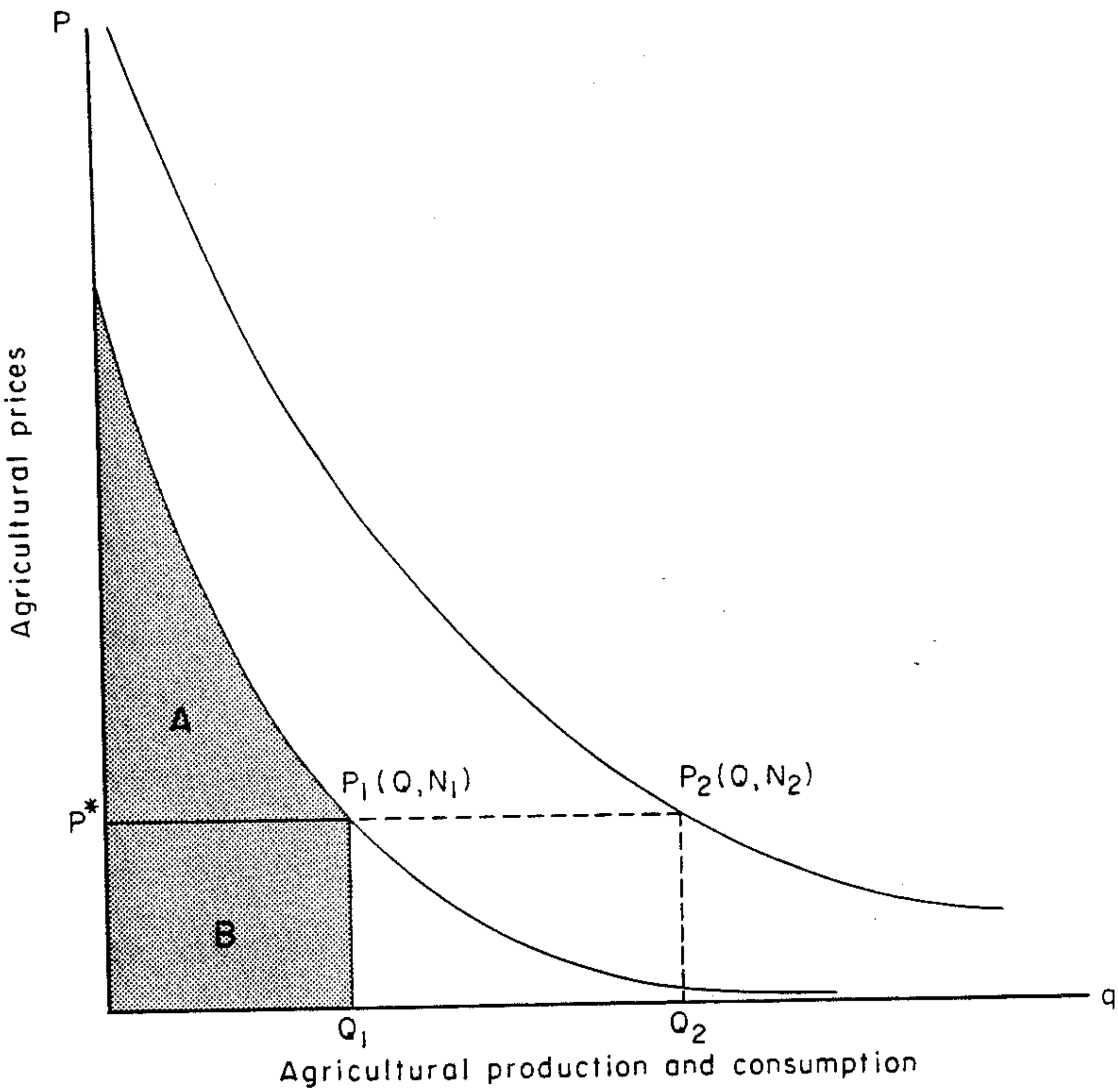


FIGURE 2. POPULATION CARRYING CAPACITY

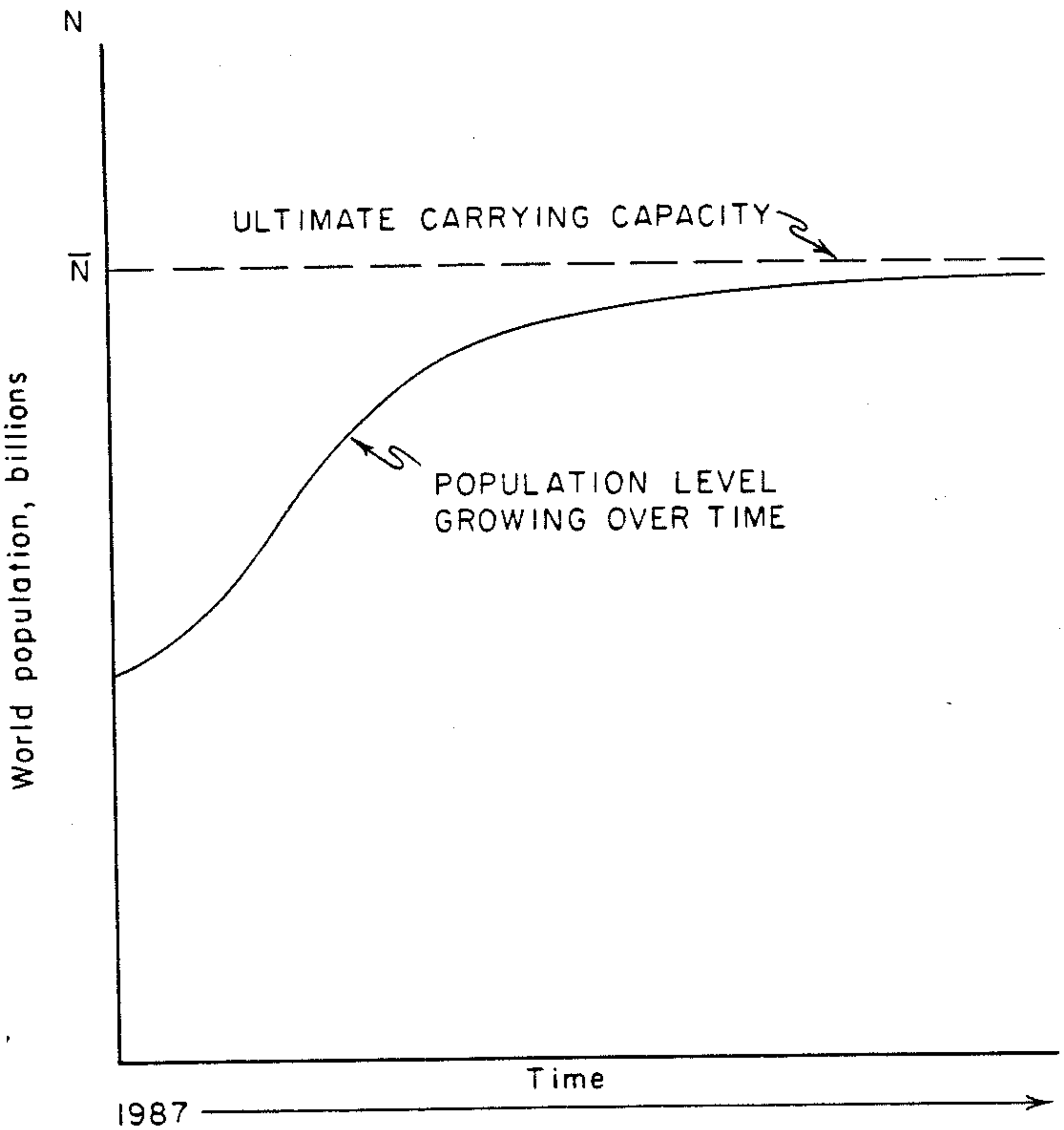
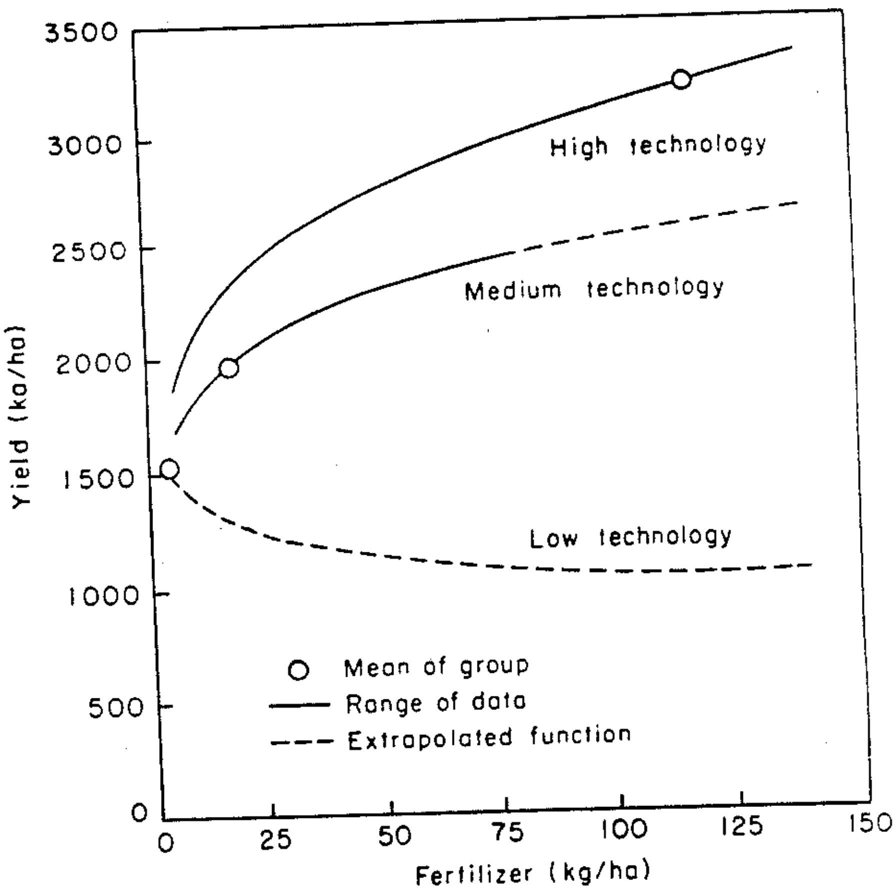


Figure 3. Yield, Technology, and Fertilizer for Asian Rice Production



Estimated response of rice yield to fertilizer based on log-log production function fit to data for thirteen Asian countries, 1951–55, 1961–65, and 1971–75

Reproduced from Barker <u>et al</u>., <u>The Rice Economy of Asia</u>.

FIGURE 4. PRICE PATH FOR COMPETITIVE WORLD OIL MARKET

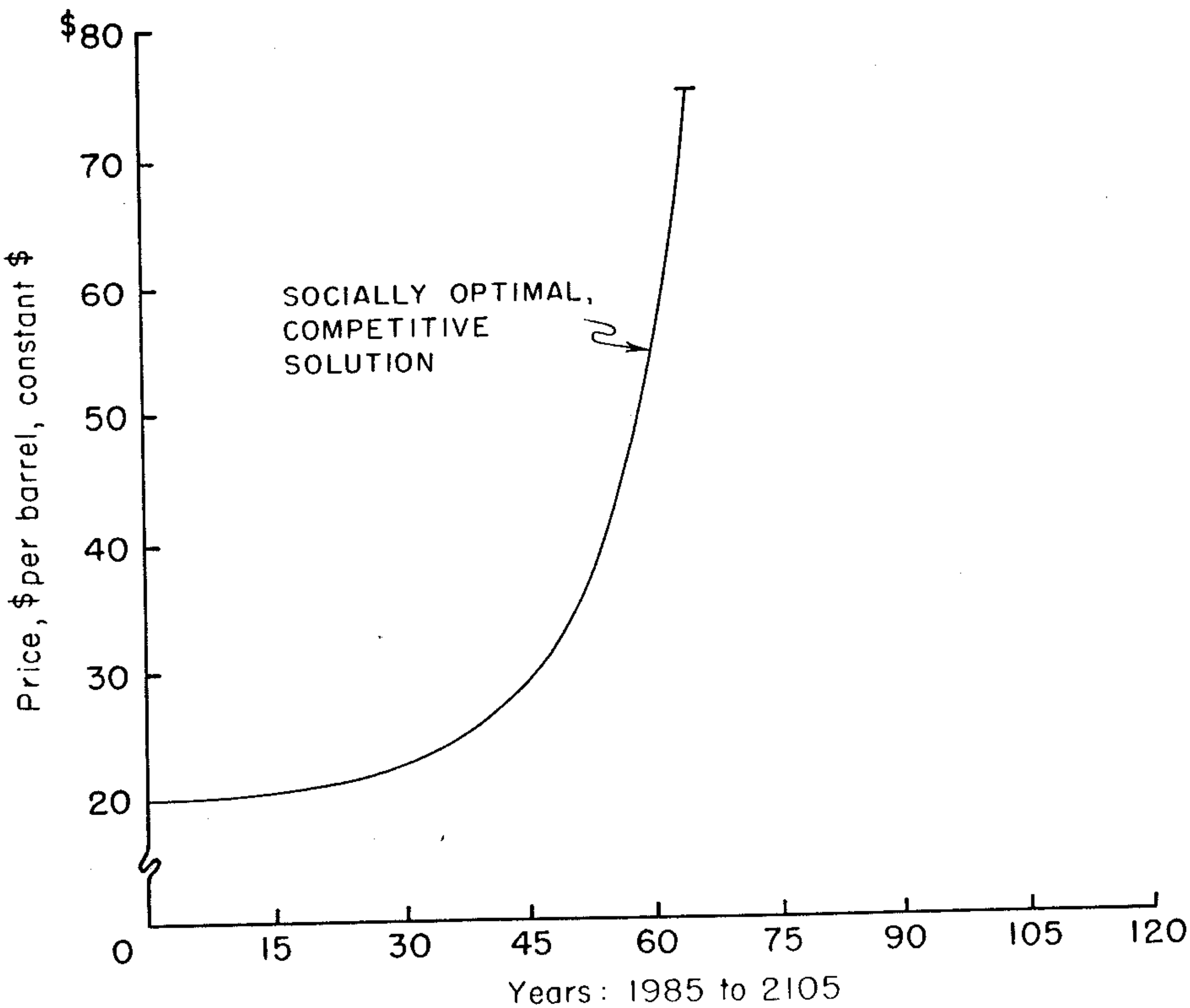


FIGURE 5. PRODUCTION PATH

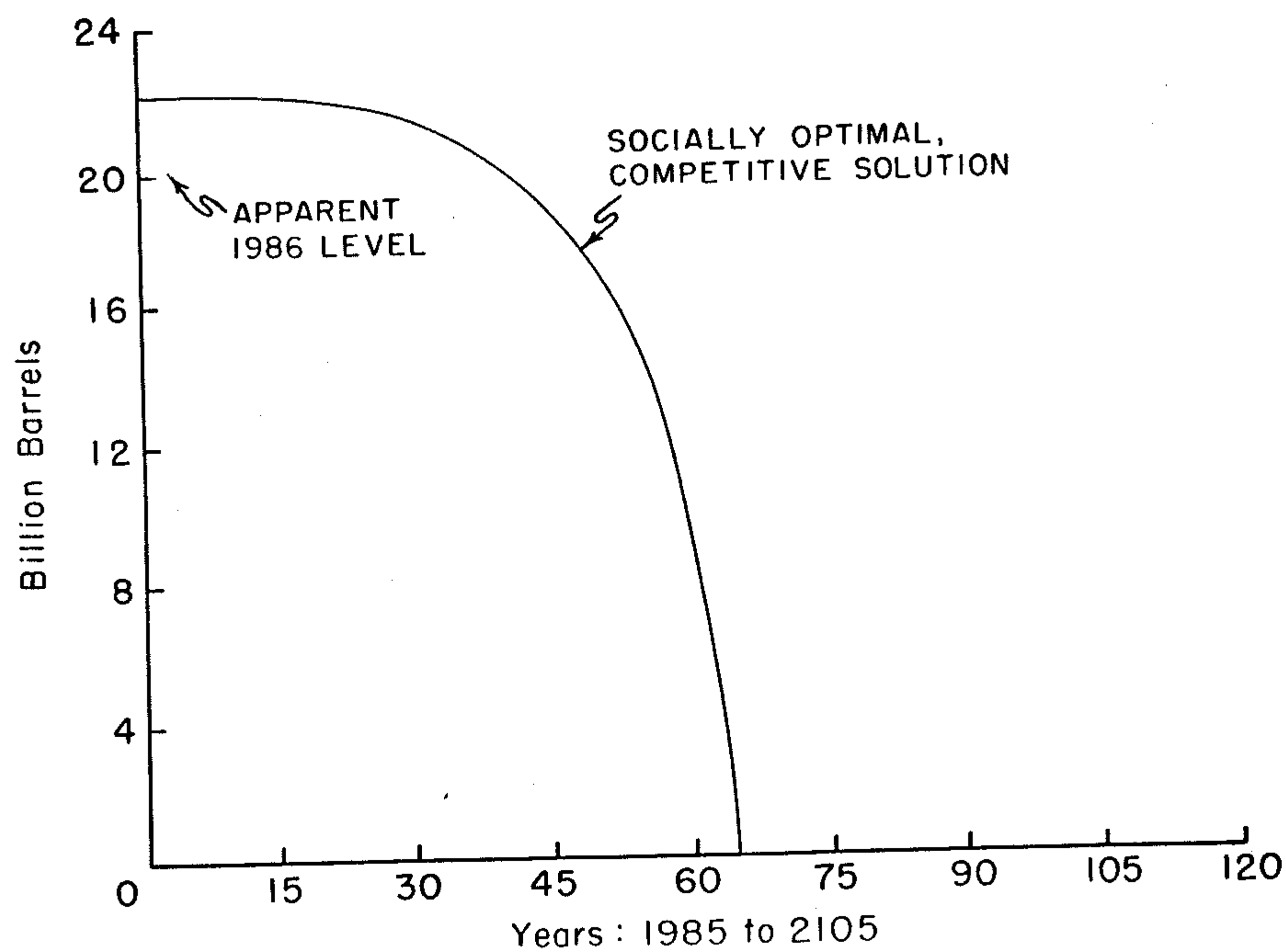


FIGURE 6. CUMULATIVE PRODUCTION TO EXHAUSTION

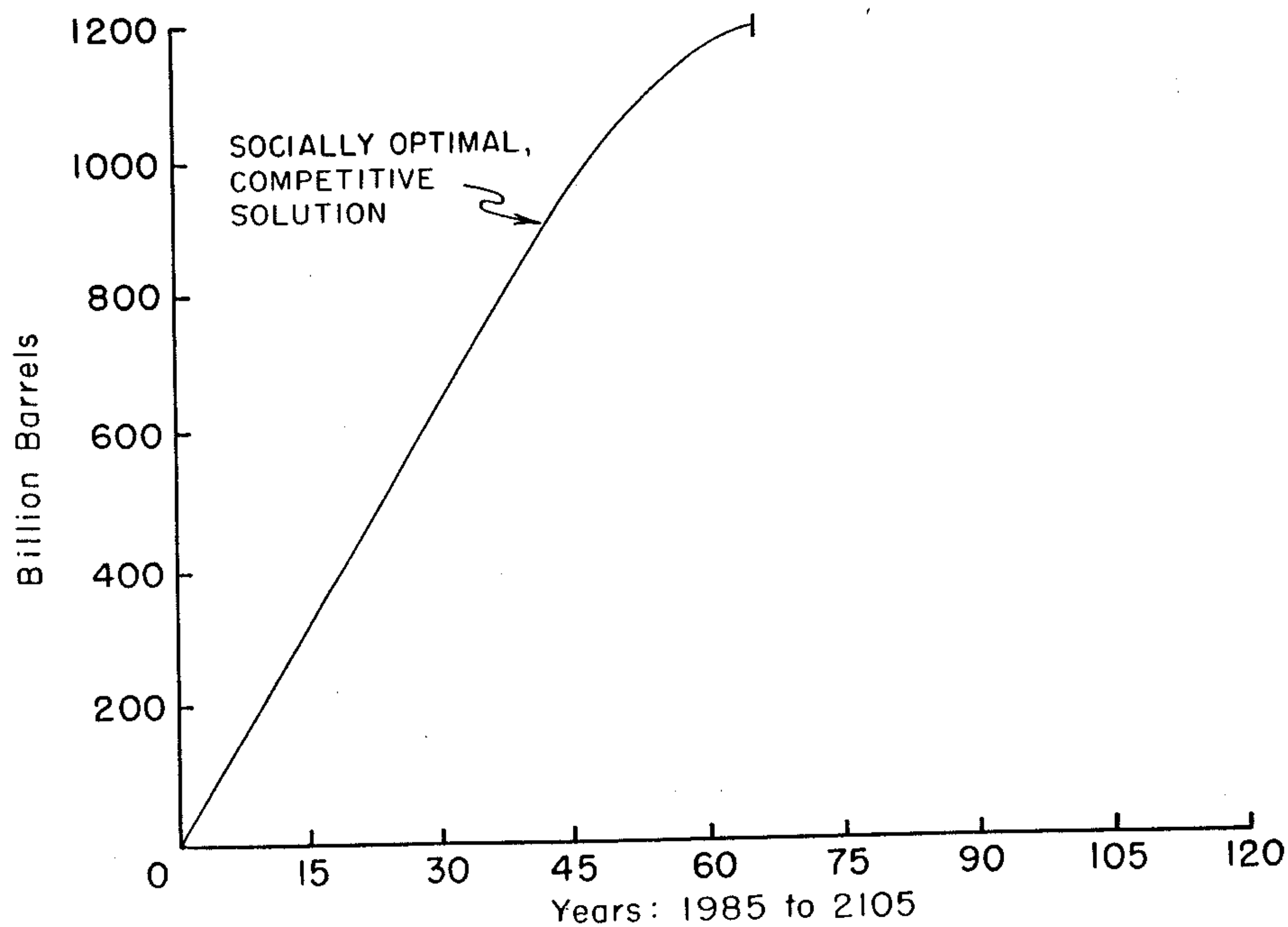
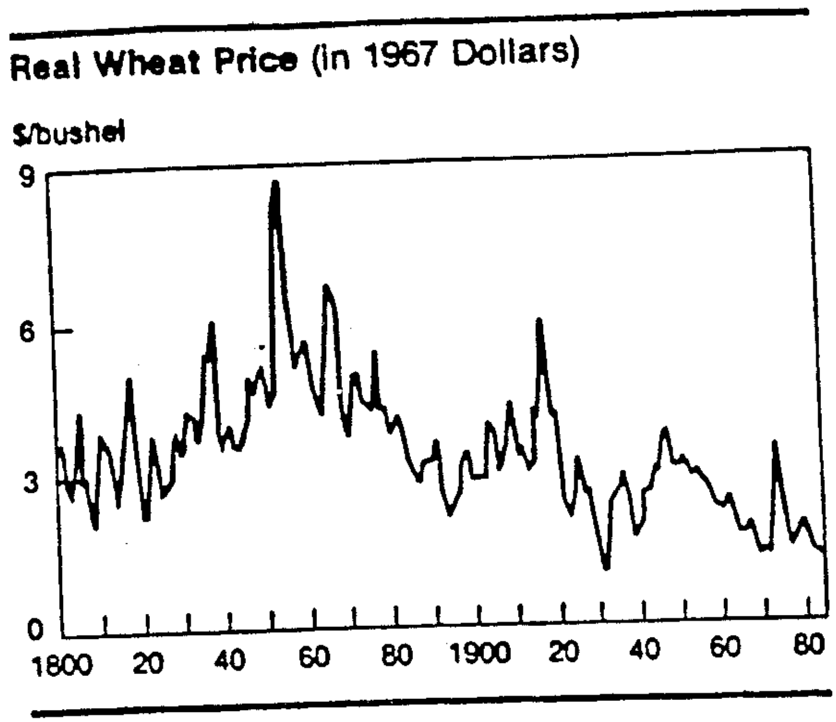


Figure 7



Source: Clark Edwards, U.S. Agriculture's Potential to Supply World Food Markets (Washington, D.C.: United States Department of Agriculture, Economic Research Service, AER 539, August 1985, p. 5)

APPENDIX: ECONOMIC MODEL

Maximize

(1) $$NSV = \int_0^n \frac{\int_1^Q P(Q,N)dQ - C(Y,R,S,L,K) * Q - D(X)}{e^{rt}} \, dt$$

with respect to Q, R, S.

(2a) $$Q(N,P) = f(N)Q_0P^{\alpha},$$

(2b) $$\int_1^Q P(Q)dQ = \frac{1}{f(N)} \; \frac{\alpha}{1+\alpha} Q^{(1+\alpha)/\alpha},$$

(2c) $$f(N) = \frac{\overline{N}}{1 + he^{-\rho t}}, \quad h = \frac{\overline{N} - N_0}{N_0} .$$

(3a) $$C = \frac{c_0 + c_1 \dfrac{S_0 - S_t}{S_0}}{f(Y)}, \text{ or,}$$

(3b) $C = c_2$, whichever is smaller;

(3c) $$f(Y) = \frac{\overline{Y}}{1 + ue^{-\theta t}}, \quad u = \frac{\overline{Y} - Y_0}{Y_0},$$

(3d) $$\theta = \varepsilon \int_0^t R \, dt.$$

(4a) $$\frac{dX}{dt} = \delta X + \beta Q(t), \text{ or } \beta Z(t),$$

(4b) $$X(t) = e^{-\delta t} \int_0^t e^{\delta t} Q(t) \, dt;$$

(4c) $$D(X) = \nu_0 X^{\nu_1}.$$

(5a) $$Z_t = \gamma Q_t,$$

(5b) $$L_t + Z_t = \frac{-dS_t}{dt},$$

(5c) $\int_0^n Z\,dt + \int_0^n L\,dt \leq S_0,$

(5d) $L_t = L_0$, or $L_1 e^{\lambda t}$.

NSV = net social value, present value, $

n = years in time period under consideration

Q = agricultural production and use, metric tons corn equivalent

C = average cost per unit output; may vary

D = damage from byproducts, in monetary units, $

X = accumulation of byproducts; pesticide residue, carbon dioxide, etc.

t = time

r = real interest rate

c_1 = variation in average production cost attributable to depletion of energy resources

c_2 = fixed average production cost with renewable energy

S = remaining energy resources

δ = decay rate of hazardous byproduct

β = generation rate of hazardous agricultural byproducts

ν_0, ν_1 = damage parameters, $ per unit accumulation

Z = energy requirements for agriculture, kcal

γ = energy requirement coefficient for agriculture

L = energy consumption in other uses, kcal

S_0 = original finite energy resources

L_0, L_1 = energy consumption parameters for other, non-agricultural uses

λ = rate of growth in non-agricultural energy consumption

ρ = population growth rate

P = price or price function

N = world population

R = annual research and education expenditures on agriculture

S = current remaining energy resources

α = demand elasticity

$f(N)$ = logistic population growth

$\overline{N}$ = ultimate global population

h = percentage movement from initial to ultimate population

$f(Y)$ = logistic yield growth

$\overline{Y}$ = ultimate yield possible

u = percentage movement from initial to maximum yield

θ = intrinsic yield growth

ε = impact of research expenditures on yield growth rate