Maximum Production Capacity of Food Crops

S. H. Wittwer

Worldwide population increases of 2% per year coupled with rising incomes and affluence of many nations are a stress on existing food producing systems. For the first time in history there are hungry nations with money. They are bargaining for available food and feed grains. Developing nations with rising populations are living ever closer to the food margin. The more developed nations are striving to raise their standards of living by converting more grain through animal production to meat, milk, and eggs. Social, political, and environmental constraints on food producing systems have multiplied. Recent soaring of food prices is paralleled by price escalations in the essential resource inputs of energy, land, water, and fertilizer. Stabilization of food supplies and prices implies existence of food reserves (grain stocks) or idle production capacity which can readily be brought into production. Both are uncomfortably low. North America remains as the only major export source of feed and food grains. Food importing nations are taking a new interest in building reserves to insure their people's food supply. A new interest is emerging in the production of wool, cotton, and silk as renewable resources as prices of oil essential for synthetic fiber production continue to escalate.


How wide is the gap between what is being done and that which is possible? Can we reduce the spread between average yield of crops, top yields, and record high yields (Table 1)? What are the biological limits in crop productivity? If all the available technology were assembled, crop by crop, what could be accomplished? Can we meet calamities of the present and future, such as those we have experienced in the past—drought and dust storms, plant disease epidemics, insect infestations, and global adversities in weather? Are there still new frontiers and unexplored dimensions for crop productivity that could result in substantial breakthroughs in the now prevailing yield barriers? Answers to these questions will be addressed in this report.

TABLE 1. Average, top, and record crop yields in the USA. (Bushels per acre).

<table>
<thead>
<tr>
<th>Crop</th>
<th>1973 Average</th>
<th>Top</th>
<th>Record</th>
</tr>
</thead>
<tbody>
<tr>
<td>Corn</td>
<td>94</td>
<td>230</td>
<td>306</td>
</tr>
<tr>
<td>Wheat</td>
<td>32</td>
<td>135</td>
<td>216</td>
</tr>
<tr>
<td>Soybeans</td>
<td>28</td>
<td>80</td>
<td>110</td>
</tr>
<tr>
<td>Sorghum</td>
<td>63</td>
<td>200</td>
<td>320</td>
</tr>
<tr>
<td>Rice</td>
<td>28</td>
<td>130</td>
<td>350*</td>
</tr>
<tr>
<td>Potatoes</td>
<td>385</td>
<td>1000</td>
<td>1400</td>
</tr>
<tr>
<td>Sweet Potatoes</td>
<td>180</td>
<td>600</td>
<td>900</td>
</tr>
<tr>
<td>Barley</td>
<td>41</td>
<td>150</td>
<td>212</td>
</tr>
<tr>
<td>Oats</td>
<td>49</td>
<td>150</td>
<td>296</td>
</tr>
<tr>
<td>Sugar Beets</td>
<td>20†</td>
<td>40†</td>
<td>54†</td>
</tr>
</tbody>
</table>

* Obtained at the International Rice Research Institute, Los Banos, Philippines, in 1970 from a total of crops grown in one year.
† Tons per acre.

SCIENTIFIC FRONTIERS: Photosynthetic Efficiency and Inhibition of Photorespiration.

There is no research area where the opportunities are more attractive and the potentials greater for achieving results, reflected in increased crop productivity, than in maximizing the photosynthetic process. Some work has been initiated with agronomic crops.

Plants can be roughly separated into two categories—those with little or no photorespiration, the 4-carbon plants; and those with high rates of photorespiration, the 3-carbon plants (Jackson and Volk 1970, Tolbert 1974, Zelitch 1971). Species without photorespiration are mostly tropical grasses, maize, sorghum, sugarcane, sunflowers, and some prominent weeds. Such plants have low compensation points; light saturation is not achieved even at full sunlight; there is only a modest response to atmospheric CO2 enrichment; oxygen does not affect the rate of CO2 fixation, glycolate biosynthesis is less; and peroxisome respiration is absent (Tolbert and Yamazaki 1969). There is increased efficiency of photosynthesis at higher temperatures. Translocation rates from the leaf are high. Anatomical features prevent escape of CO2 from the leaf. Such plants more effectively utilize water during growth and are less subject to competition by weeds.

Species where photorespiration is significant include soybeans, other legumes, most cereal grains, tobacco, potatoes, cotton, and most fruits and vegetables. These plants have high compensation points; oxygen inhibits photosynthesis and growth; light saturation occurs at levels well below full sunlight. Translocation rates from the leaf are low. There is a striking response to atmospheric CO2 enrichment; glycolate biosynthesis is prominent; and peroxisome respiration is prevalent. Weed control is critical because seldom does the cultivated crop outgrow its more photosynthetically efficient competitors (Björkman and Berry 1973, Black 1973).

There is a great challenge ahead in developing varieties of crops having low photosynthesis, and in the formulation of chemicals that will modify plant architecture and inhibit photorespiration (Marx 1973). Some interesting results have already been reported for soybeans (Stutte and Rudolph 1973).

Other approaches in modifying photosynthetic efficiency are to change the architecture of the plant and improve the light receiving system (Chandler 1969, Hutchinson et al. 1972, Ishizuka 1971, International Rice Research Institute 1972, Loomis et al. 1967, Loomis and Williams 1969). All crops show marked varietal differences in photosynthetic efficiency (Table 2) and photosynthetic heterosis has been identified (Heichel and Musgrave 1969).

### TABLE 2. Differences in leaf photosynthesis among plants and percentage increase in growth or yield from elevated atmospheric levels of carbon dioxide (Wittwer 1973). (Milligrams CO$_2$ per sq. dm. per hr.)

<table>
<thead>
<tr>
<th>Plant</th>
<th>At Normal CO$_2$ Levels</th>
<th>At Elevated CO$_2$ Levels</th>
</tr>
</thead>
<tbody>
<tr>
<td>Corn, Grain Sorghum,</td>
<td>60-75</td>
<td>100</td>
</tr>
<tr>
<td>Sugarcane</td>
<td>40-75</td>
<td>135</td>
</tr>
<tr>
<td>Rice</td>
<td>50-65</td>
<td>100</td>
</tr>
<tr>
<td>Sunflower</td>
<td>40-50</td>
<td>100</td>
</tr>
<tr>
<td>Soybean, Sugarbeet</td>
<td>30-40</td>
<td>56</td>
</tr>
<tr>
<td>Oats, Wheat, Barley</td>
<td>30-35</td>
<td>66</td>
</tr>
<tr>
<td>Tobacco</td>
<td>20-25</td>
<td>67</td>
</tr>
<tr>
<td>Tomato, Cucumber,</td>
<td>20-25</td>
<td>50</td>
</tr>
<tr>
<td>Lettuce</td>
<td>10-20</td>
<td>40</td>
</tr>
</tbody>
</table>

Photosynthesis is the most important biochemical process on earth. By it the sun’s electromagnetic energy is converted to chemical energy and stored in plants. About 100 billion tons of carbon dioxide are fixed into plant material each year. It remains today as the world’s most important energy producing process. The greatest challenge man faces in food producing systems today is to manipulate plants under environments to maximize this energy conversion process (Heichel 1973, Pimentel et al. 1973, Waggoner 1969).

High efficiency photosynthesis has recently been emphasized (Bjorkman and Berry 1973). The importance of building a stock of plants for agricultural purposes with the 4-carbon pathway in photosynthesis is suggested. This approach has been notably unsuccessful thus far. Agricultural practices should be adjusted to exploit this great renewable resource potential both for food and energy production.

The least efficient photosynthetic mechanisms exist in fruits and vegetables with the exception of sweet corn (Wittwer 1973). Little has been done to identify genotypes having higher photosynthetic efficiencies or to minimize photorespiration. With all plants there are three possible complementary and parallel routes—select genetic variables with greater photosynthetic efficiencies, modify plant architecture for better light reception, and apply chemicals to suppress glycolate biosynthesis and inhibit photorespiration. The balance between photosynthesis and respiration can be chemically, physically, and genetically altered to maximize productivity.

It is noteworthy that of the large research investments allocated to a better understanding of the photosynthetic process, there has been little payoff with food crops under field conditions. Progress has come in other approaches. These are some specific examples of enhancement of photosynthesis. The new short, stiff strawed rice varieties have a higher proportion of grain to plant. The short erect leaves capture light more effectively and have better light receiving systems in densely planted, heavily fertilized rice paddies (International Rice Research Institute 1972). One of the great advantages of the new rice varieties is the “flag leaf.” It is the one protruding above the head, and is vastly more prominent than on earlier varieties. The grain heads to casual observers appear hidden, but productivity is greatly enhanced.

Corn (maize) will produce more digestible nutrients per unit area of land surface than any other food crop that can be grown. Sorghum is a close second. Both have high levels of net photosynthesis with a minimum of energy loss through photorespiration. Corn is the major crop in the United States. Among nine modern food producing systems, it is the most efficient in the use of cultural energy. It is also the only crop where the ratio of energy output over input has increased with the adoption of more technology (Heichel 1973). There has been, during the past 10 years, a precipitous rise in maize production in Northwestern, Western, Eastern, and Southwestern Europe. Millions of acres formerly devoted to pasture, potatoes, small grains, and sugar beets now grow maize.

A major limitation to the attainment of optimal yields in corn, sugar beets, sorghum, soybeans, and many other crops in temperate zones is the length of time required from planting until the leaf canopy covers the ground. There is an ineffective utilization of solar energy when it is at a maximum. Early plantings, equidistant plantings, high plant populations, narrow rows, and the selection of varieties having plant and leaf (lanceolate-soybeans, vertical corn) types for maximum light reception will greatly enhance photosynthetic capabilities.

### Biological Nitrogen Fixation

Enhancement of biological nitrogen fixation in the soil, and particularly in the plant’s rhizosphere, constitutes one of the greatest opportunities to improve production efficiency of all crops, especially the legumes. Symbiotically associated with the roots of legumes and potentially associated with many other plants are the rhizobia—the nitrogen-fixing bacteria. These along with the blue-green algae and the azotobacters appropriate 7 times more nitrogen from the atmosphere than is now accomplished from chemical fixation in the production of fertilizer for crop improvement (Hardy et al. 1971). This is an anaerobic process that can now be measured with great precision and sensitivity under field conditions (Hardy et al. 1968, 1973). Nitrogenase activity is reflected by the reduction of acetylene to ethylene. This natural plant biological system may be the best avenue for incorporating nitrogen into our soils and protein into our food supplies. Maximization of this process would greatly reduce the current energy input into food producing systems (Pimentel et al. 1973).

There is also great potential for extending the fixation of nitrogen to nonlegumes. The development of bacterial strains capable of fixing nitrogen in the root environment of corn, wheat, and rice is a definite possibility (Phillips et al. 1971). Contributions in the rhizospheres of nonlegumes can be significant. Biological nitrogen fixation in rice paddies ranges from 22 to 63 kg per hectare per year (International Rice Research Institute 1972). Up to 90 kg of nitrogen per hectare have been fixed by semisymbiotic association of Azotobacter.
tinuous manufacture and use of the world’s crops is not being produced. A biological nitrogen fixation and chemical fixation in industrial factories. Best estimates indicate 200 million metric tons of nitrogen per year are made byproduct of refining petroleum now in esti-

techniques (Hardy et al. 1968, 1973) for detection of biological nitrogen fixation have demonstrated the re-

action in the root environment of corn (Raju et al. 1972) and with termites (Breznak et al. 1973). Identification of such nitrogen fixing bacteria in the rhizospheres of nonleguminous plants offers the possibility of making nitrogen from the air available to some of the major food crops. Alternatively, growth patterns of legumes and the environment may be altered to maximize nitrogen fixation (Hardy et al. 1971, Hardy and Havelka 1973). Peas, beans, including soybeans, pulses, and lentils are the logical crops for initiating research in such efficiency studies.

Whereas photorespiration is inhibited by lowering the oxygen level of the atmosphere (Tolbert 1974), the rate of nitrogen fixation is increased immensely. The gas mixture (21% O_2 and 0.03% CO_2) in the air we breathe favors photorespiration and depresses nitrogen fixation. Raising the atmospheric level of carbon dioxide greatly enhances photosynthesis and growth in crops (Wittwer 1973a) and also magnifies severalfold biological nitrogen fixation (Hardy and Havelka 1973).

There are two main sources of nitrogen for protein synthesis in crops, biological nitrogen fixation and chemical fixation in industrial factories. Best estimates indicate 200 million metric tons of nitrogen per year are made available to plants on earth through biological nitrogen fixation. This is an annual resource of $40 billion. Chemical fixation by contrast accounts annually for about 30 million tons per year. The chemical process requires hydrogen, a byproduct of refining petroleum now in critical supply, and additional energy in the form of pressure and heat.

Sufficient nitrogen fertilizer for the world’s crops is not being produced. A wide gap still exists in unmet protein needs of an expanding population. Continuous manufacture and use of chemical forms of nitrogen fertilizer for crop production will be necessary. The desirability of the biological approach, however, in closing the gap for nitrogen rather than an expansion of nitrogen fertilizer production is dictated by cost of distribution, inefficient utilization by crops, the potential of nitrogen pollution, and the high nonrenewable energy requirement.

Novel approaches under investigation for enhancement of biological nitrogen fixation include the following. Multifold increases in nitrogen fixation by legumes have been demonstrated by adjustments in the atmospheric levels of O_2 and CO_2. The potential is a doubling of soybean yields with most of the nitrogen obtained from the air rather than from the soil or fertilizer. The domestication of natural or synthetic symbiosis could extend the ability of nitrogen fixation to weeds (rice, wheat, maize, sorghum). Currently nitrate fertilization inhibits normal symbiotic fixation beyond about 100 kg of nitrogen per hectare. Perhaps forms of nitrate fertilizer may be found less inhibitory to symbiotic fixation, or strains of nitrogen-fixing bacteria that tolerate high rates of nitrogen fertilization may be identified. Finally, new catalysts are being sought that are effective in chemical fixation of nitrogen. Some have been found which function at room temperatures and one atmosphere of pressure.

**Water and Fertilizer Management**

Trickle irrigation offers a new and exciting innovation in water use for crop production. It is the first major breakthrough in irrigation in the last 40 years. Drip or trickle irrigation may reduce water requirements for crop production by one third. Installation costs approximate one third of the costs of conventional systems. Interest is worldwide. The technique is widely used in Israel where it had its first major application under field conditions with strawberries and row crops, deciduous fruit trees, and citrus (Goldberg and Shmueli 1970, Gustafson 1973, Shmueli and Goldberg 1971). It is estimated that over 20,000 hectares of high value crops in California alone are now fitted with drip or trickle irrigation systems. Trickle irrigation is particularly adapted for high value row and fruit crops (Kenworthy 1972) in areas where water is limited, costs are high, and where the greatest efficiency in water utilization and conservation is desired. Several worldwide conferences have been held. The adoption of this new technology has been so widespread and rapid, an accurate inventory is not possible.

The nonvariable root environment is a key for optimal production for many row crops (Geraldson 1970). It consists of a water gradient having as a point source either a constant water table from below, or trickle or drip irrigation on the surface. The system also provides a point source of water-soluble nutrients with a concentration gradient originating either from a band application of fertilizer along the row or at the point of drip in the trickle irrigation system. The gradients in moisture and fertility are maintained by use of synthetic plastic mulches or row covers. Subsurface asphalt barriers for droughty sand soils (Hansen and Erickson 1969) have the capability of increasing the water holding capacity and reclaiming millions of acres for crop production in arid and semiarid lands.

New strategies appear in fertilizer management. Application through irrigation systems is widely used in some of the most productive food crop systems. Foliar application and absorption of nutrients are taking on new dimensions. Increases in efficiency from foliar application and timely placement could become prominent in view of rising prices for fertilizer constituents. There is the opportunity to add water and fertilizer simultaneously and to parallel crop needs for both. Thus, the absorptive capacities of both leaves and roots are utilized. It has now been established that atmospheric ammonia may be absorbed directly through leaves and subsequently metabolized (Hutchinson et al. 1972, Porter et al. 1972). Recent reports also indicate a fourfold greater efficiency in utilization over soil applications of a postharvest 5% urea spray applied to senescing apple leaves (Shim et al. 1972). Many crops can benefit from foliar applications of the micro-, secondary, and the major nutrients under certain climatic and soil conditions and with appropriate carriers (Rathore and Wort 1971, Wittwer and Bukovac 1969).

One of the most remarkable soil-water-fertilizer management systems ever conceived has been developed for potatoes in the Columbia basin of Washington. Here the highest yields in the nation are achieved. The area is favored during the growing season with high light intensities, long warm days, and cool nights, and inherently productive soils. A package of technology has been assembled consisting of soil fumi-
New Strategies for Pest Control

Total pest management is evolving in food producing systems (Kirby 1973). The intent is to reduce the use of pesticides which could be environmental threats, decrease costs of production, and enhance productivity. Great progress has been made in the integrated control of fruit pests in orchards of the Northwest (Hoyt and Caltagirone 1971) and more recently in the eastern Great Lakes states.

Environmental monitoring and the development of models for improved strategies in pest management is still in its infancy. Considerable progress, however, has been made in the control of the cereal leaf beetle, the alfalfa weevil, the cotton boll weevil, and the two-spotted and European red mites on apples. The intent is to reduce energy inputs, the environmental hazards, and costs of pest control by fewer and more effective chemical treatments.

Integrated control encompasses the use of resistant varieties (Michigan Agricultural Experiment Station 1973, Painter 1968). More than a hundred varieties of insect-resistant crop plants have thus far been released carrying insect-resistant factors to more than 25 insects (Sprague and Dahms 1972). These include the major food crops of the earth. Host resistance to insects or diseases means control without cost to the grower or toxic residues, no damage to pollinating insects, and nature's balance between insects and their natural enemies is not upset.

Pheromones or female sex attractants are the newest weapons against insects (Marx 1973a). Phenomenal success has recently occurred in synthesizing fruit insect pheromones. They are now available for many species of Lepidoptera insects including codling moth, red-banded leaf roller, oblique-banded leaf roller, oriental fruit moth, bud moth, grape berry moth, and the gypsy moth.

Research in juvenile hormone analogs has undergone rapid progress during the past few years because of the possibility of using them as a third generation pesticide (Marx 1973b, Schneiderman et al. 1969, Slamo 1971). There are over 500 compounds. They do not kill immediately but cause developmental disturbances which are lethal and prevent reproduction. Contrary to insecticides, they are not toxic to insects or, hopefully, to higher animals. Most have selective action against determined insect pests. Some have a wide spectrum of activity and act on many unrelated species. Others specifically act on representatives of one family. Some are enormously active in micrograms per metric ton of insects or a hectare area of surface. Others are highly systemic in plants. They can be of long or short persistence with completely harmless degradation products. A disadvantage is that their use has to be anticipated in advance. Treatment is not followed by an immediate destruction of the harmful stages of the insect.

Protected Cultivation

Remarkable increases in worldwide acreage under protected cultivation have recently occurred. By this system it is possible to grow around the calendar (Kuiken and Germing 1972), prolong the growing season, and extend the areas of productivity in the Temperate Zones. Just as agriculture has become more intensive over the years so also has greenhouse vegetable production. The currently expanding and future use of protection or covers over crops is one of economics rather than technology (Dalrymple 1973). Plastics have had a tremendous impact, especially in the last 5 years, and particularly row crop covers (Hall and Besemer 1972). Protected cultivation can lead to increased yields and much greater efficiency for individual crops and can enable the growth of additional crops. One environmental factor only—the solar radiation—remains beyond control. This agricultural specialty has not been seriously considered with respect to world food needs but it does offer a technology for magnifying by severalfold the productivity of crops per unit land area (Rudd-Jones 1972). Rising costs of fuel for heating and questionable availability of needed resources calls for novel approaches in energy use and conservation for future expansion of this industry or even its survival. Only in America, however, are the structures and growing practices designed for large energy consumption. Twenty-five to 40% of gross sales goes for cost of heating in greenhouse tomato production in the Cleveland, Ohio, area. There is, for example, the opportunity for energy and water conservation through use of geothermal resources and diversion of thermal discharges from power generating plants.

Protected cultivation using covers over plants, with or without the addition of heat and carbon dioxide, has progressed worldwide from approximately 10,000 hectares in 1960 to 20,000 hectares in 1965 to over 50,000 hectares in 1970 (Dalrymple 1973). The most remarkable increases have been in Japan, South Korea, Israel, Holland, Italy, and many of the Eastern European countries. There are many unique environmental, ecological, economic, social, geographical, and technological features of food producing systems in greenhouses (Wittwer 1973a). Arid lands and desert coastlines offer unique advantages for these food producing systems (Clawson et al. 1969, Hodges 1969, 1970, Wolfe 1969). They could, with the abundant sunlight, mild temperatures, and fertile soils, become the most productive on earth.

Carbon Dioxide Enrichment

Associated with protective coverings of glass or plastic over plants has been a surge of interest in the enhancement of plant growth by enriched atmospheric levels of carbon dioxide in these contained or enclosed structures. There is, however, a paucity of field experiments with carbon dioxide to determine if increased photosynthesis and overall production can be achieved (Wittwer1). This is one of the most surprising deficiencies of modern plant science research. It has been concluded that it is economically feasible to add carbon dioxide under intensive field cultivation systems (Harper et al. 1973). Furthermore, carbon dioxide enrichment of a crop canopy can be achieved if economical supplies of CO2 become available at the crop site. Both the availability of geological resources and favorable responses of crops in the field have been demonstrated. Enrichment under field conditions with proper crop selection and management may have considerable potential for increasing crop yields (Hardy and Havelka 1973, Harper et al. 1973, Wittwer1).

The concentration of atmospheric carbon dioxide is a dominant factor as a rate-determinant in photosynthesis. All economic plants, thus far evaluated, respond to elevated levels by increased growth and productivity (Table 2). Rice is one of the most responsive (Yoshida 1972, Yoshida et al. 1971, Cock and Yoshida 1973). Carbon dioxide enrichment of greenhouse atmospheres and of

other controlled environment facilities enhances growth rates and the economic commercial productivity of many vegetable and flower crops (Wittwer 1970a). The major food crops also respond, whether in the controlled atmospheres of greenhouses or in open fields. Root-top ratios, relative growth rates, and net assimilation rates are increased (Tognoni et al. 1967, Wittwer1). Leaf area ratios are less. Full benefits are conditioned by adjustments in other variables—light, temperature, plant variety, soil moisture, and nutrient levels. Some of the more dramatic increases in productivity from atmospheric carbon dioxide enrichment of crops in the field have been with cotton, soybeans, grain sorghum, potatoes, and rice (Wittwer2).

A multifold increase (570%) in symbiotic N2 fixation with soybeans, under field conditions, has been induced by atmospheric enrichment (1,000 ppm) with carbon dioxide (Hardy and Havelka 1973). The CO2 effect is more pronounced than from any other environmental variable. Recent tests indicate carbon dioxide enrichment of field crops in Mississippi may be economically feasible. The geologic world resources for release of carbon dioxide for enhancement of plant growth are enormous. Estimated volume for a single well 15 miles north of Jackson, Mississippi, is one half trillion cubic feet. The analysis is 98% pure carbon dioxide under 12,000 lbs/inch2 pressure (Harper 1971). Exploration and harnessing of this natural resource for the enhancement of plant growth are enormous. Estimated volume for a single well 15 miles north of Jackson, Mississippi, is one half trillion cubic feet. The analysis is 98% pure carbon dioxide under 12,000 lbs/inch2 pressure (Harper 1971). Exploration and harnessing of this natural resource for the enhancement of productivity of the major food crops remains as a challenge for the combined efforts of scientists from many disciplines (Wittwer2).

Multiple and Intensive Relay Cropping
This has its greatest potential in the Tropics and for developing countries (Bradfield 1970, Dairymple 1971). Water management through irrigation is usually essential. Two, three, and even four crops can be produced in many areas of the earth, and double cropping in many parts of the United States is feasible. Even in the northern states soybeans and forage crops, such as sorghum and sorghum-sudan grass hybrids, may follow barley or early wheat harvest. The double puddy system of barley and rice is common in South Korea. The world record for rice production, 24 metric tons per hectare (approximately 350 bushels per acre) (Table 1), has been achieved by growing 4 crops of rice on the same land area in a single year utilizing transplants (International Rice Research Institute 1972). Productivity in the Tropics is indexed by the yielding capacity per unit land area per year. There are two additional facets of intensive cropping that tend to optimize crop productivity. The first is early planting in temperate zones to produce leaf coverage of the soil as quickly as possible. This maximizes incident radiation interception. Transplants can greatly aid in achieving this goal. Secondly, plant populations may be increased by higher rates of seeding, narrower rows, or equidistant planting (Thorne 1971).

Reduced Tillage
Favorable effects of zero or minimum tillage on the productivity of corn and sugar beets (White and Robertson 1972) and for water, soil, and energy conservation have long been known. It is currently known as conservation tillage (Owens 1973). The practice has now been extended to asparagus (Putnam 1972) and the small grain crops (Evans 1973). With asparagus there is not only a substantial increase in productivity of crown plantings, but weed control problems and plant injuries are lessened. Direct drilling of wheat, rye, oats, barley, and main crop fodder brassicas, as well as oil seed rape, is expanding rapidly in the United Kingdom (Evans 1973). The estimated hectare for 1973 is 120,000. Minimum tillage for rice is being widely adopted in Sri Lanka (Ceylon), Malaysia, and Japan (Elias 1973) to help alleviate shortages of water, power, and time. Productivity is also enhanced. Worldwide progress and summaries of recent developments in reduced tillage are covered by a series of articles in a recent issue of an international trade journal (Brown and Quantrell 1973, Cannel and Finney 1973, Damour et al. 1973, Evans 1973, Gad and McKibben 1973, Koronka 1973, Leonard 1973, Stonebridge and Fletcher 1973, Toohey 1973, Young 1973).

Direct drilling or zero tillage of main crops such as sugar beets, corn, and cereal grains reduces the energy input into these food production systems. It is also a soil and water conservation practice usually accompanied by an enhancement of productivity. The single advantage which comes through most clearly to the producer is the saving of time, reflected in a reduction of costs, greater land utilization, and taking advantage of short spells of good planting weather. One of the most rapid transitions occurring in American agricultural soil management is the impact of no-till or minimum tillage. Approximately 2 million hectares of crop land was subject to no-till, and over 13 million hectares to minimum tillage in 1973. This was a 15-20% increase over the previous year. Ten years ago 75% of the corn and soybeans in Virginia were produced with conventional tillage. Eighty percent was with minimum tillage in 1973. There was a sixfold increase in minimum tillage for soybeans and corn in Iowa from 1968 to 1973 (Owens 1973).

Plant Growth Regulants
Growth regulants were first identified in the early 1930's as significant in crop production, and much has happened since those early days of exciting discovery (Wittwer 1971c). Today many natural and synthetic substances are available for crop production (Weaver 1972). They bring new possibilities in circumventing environmental limitations, relaxing genetic restraints, improving quality, enhancing production, and aiding mechanical harvesting. While relatively few chemicals have emerged as important plant regulants and are commercially available, the potential is great. 2,3,5-Triodobenzoic acid (TIBA) has been used successfully for improving the yield of soybeans through foliar application. Pod set is increased, lodging is reduced, earlier maturity is stimulated, and harvesting is facilitated with an overall yield increase. Other chemicals promise on soybeans (Stutte and Rudolph 1973). More recently alfalfa seed yields have been upped by 60% above controls by the use of TIBA with as little as 150 to 300 grams per hectare (Hale 1971). Yields of still other legumes appear to be enhanced by TIBA (Sinha and Ghildiyal 1973). The enhancement of protein yields of cereal grains and some legumes by the application of low, but biologically active levels of herbicides, is a novel approach (Kies et al. 1967, 1968).

The gibberellins are widely used in the production of seedless grapes, and Alar is applied to regulate the flowering of fruit crops. CCC or Chlormequat is used extensively on wheat and rye in western Europe to prevent lodging and to enhance productivity. The 1970's may be heralded as the decade of wide scale field applications of growth regulants for crop improvement. A
national working group of agronomists, horticulturists, plant breeders, and plant physiologists with industry input has emerged.

One of the most significant and recent achievements has been the enhancement of sugar production on sugarcane with the chemical ripeners (Nickell 1972, 1973). Other uses include gibberellins for reducing the chilling requirements and increasing yields in forcing rhubarb, adjusting the production cycle in globe artichokes, increasing the yield of fuggle hops, and induction of staminate flowers on gynoeocious types of cucumbers and melons (Byers et al. 1972), thus facilitating hybrid seed production (Table 3). Other possibilities include the use of ethylene and ethylene-generating chemicals for the induction of male sterility in wheat for possible hybrid seed production, and as an aid in the mechanical harvest of cherries (Jonkers 1973).

New Crops
There is a continuing search for alternate food crops (Burton 1968, 1973, Holland 1973, Skrdla 1972). Some may not be new but merely left behind in our stampede toward specialization. Genetic vulnerability (National Academy of Sciences 1972) is great if food plant sources are limited. The increase in the production of grain sorghum as an alternate to corn and triticale for wheat and rye are major steps to increase variability. Oats are particularly adapted to cool lands, have the highest protein content and best amino acid balance of the cereal grains.

Wheat, corn, and rice alternatives are badly needed. Soybeans and field beans are extremely vulnerable (Brown 1973). The sunflower may be a good alternative to the soybean. Newly developed hybrids yield up to 30% more than the old inbred cultivars (Skrdla 1972). The world is far too dependent upon single crop harvests in many geographic areas. Tree crops have not been extensively utilized in many parts of the world. Research with long lived perennials is expensive. Perennials useful for human food consumption have not received adequate attention in tropical regions. The emphasis, until now, has been on export items such as tea, coffee, and rubber.

Science must dedicate itself to the building of new food species. The biological efficiency and desired new qualities cannot always be obtained from existing germ plasm combinations. Species building programs will greatly enhance productive newicity reserves in food production systems. The incorporation of genetic materials from wild species into useful plant varieties could extend even further the limits of crop productivity in the Northern Hemisphere. This could be a significant research venture in view of the recently recorded climatic changes (Starr and Oort 1973). Food crop production under less than optimal conditions (cooler regions, arid lands, and high temperatures) could be maximized (Bjorkman and Berry 1973).

Man’s search for new industrial, food, and feed crops includes crambie, faba beans, sunflowers, triticale, bird resistant sorghums, hybrid pearl millet, saffoin, rape, feed wheats, tassel-seeded corn, and wild rice (Burton 1968, 1973, Price 1973). Milestones in the creation of new improved types of minor crops include use of Lycopersicon pimpinellifolium for resistance to Fusarium wilt in tomatoes; resistance to pea wilt (Race 5) attained by selecting 10 of 1,300 new introductions, the Shogoin cucumber from Korea as a source of the gynoeocious character, and the Kerman pisastro (Skrdla 1972). The recent production of new plants without recourse to sexual reproduction affords one of the greatest potentials for the future. Fusion of protoplasts of vegetative cells from different species of tobacco has been demonstrated (Carlson et al. 1972). The hybrid is the same as that produced by sexual methods. Crossing of species that cannot now be hybridized sexually is a definite possibility. It may also be possible to produce somatic hybrids between genera and families of distantly related plants. Thus, there is now the potential of breeding widely divergent species and creating new crop varieties not heretofore possible for conventional variety development techniques (Nickell 1973a, Nitsch 1972).

Genetic, somatic, and chemical modification of the protein content and amino acid distribution of the major food grains of the world offers one of the greatest challenges and opportunities for improving their biological value and providing needed protein (Harpstead 1971, Nelson 1969, Protein Advisory Group of the United Nations 1972, Schweizer and Ries 1969). For the first time, man has the technological means of converting, by genetic and to some extent chemical manipulation, the proteins of cereal grains to protein comparable in food value to those in meat, milk, and eggs.

It began with the announcement of opaque-2 (high lysine) corn (Mertz et al. 1964). It ended, for the moment, with the high lysine sorghum (Singh and Axtell 1973). The recent impact of spiraling food and feed prices has established a new interest and economic feasibility for the production of hybrid wheat and high lysine corn. Hyproly barley has protein and lysine contents 20 to 30% higher than commonly grown varieties (Munck et al. 1970).

There have been significant breakthroughs, landmarks, and decades of achievement associated with the productivity of all major food crops through variety development. It was hybrid corn in the 1930’s. Hybrid monogerm sugar beets, grain sorghum, and pearl millet were introduced in the 1950’s (Table 3). Short-statured, high yielding, disease resistant wheat and rice varieties received

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TABLE 3. Commercial Hybrid Varieties in Food Crops.

<table>
<thead>
<tr>
<th>Early (before 1955)</th>
<th>Recent (since 1955)</th>
<th>Future</th>
</tr>
</thead>
<tbody>
<tr>
<td>Field Corn (1921)</td>
<td>Grain Sorghum (1955)</td>
<td>Asparagus (1975)</td>
</tr>
<tr>
<td>Sweet Corn (1933)</td>
<td>Sugar Beets (1957)</td>
<td>Celery (1975)</td>
</tr>
<tr>
<td>Summer Squash (1941)</td>
<td>Spinach (1961)</td>
<td>Rye (1975)</td>
</tr>
<tr>
<td>Watermelon (1949)</td>
<td>Pearl Millet (1965)</td>
<td>Field Beans (1985)</td>
</tr>
<tr>
<td>Muskemelon (1954)</td>
<td>Barley (1968)</td>
<td></td>
</tr>
<tr>
<td>Cabbage (1954)</td>
<td>Rice (1972)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Sunflower (1972)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Coconut (1965)</td>
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</tr>
</tbody>
</table>

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worldwide attention in the 1960's, and many nations became self-sufficient for the first time in these food grains. Hybrid wheat (Reitz and Lucken 1972) and rice (Murayama 1972) are being commercialized for the 1970's.

As one views a world of scarcities ahead—shortages of food and natural fibers, an accelerating global demand for foodstuffs generated by population growth and affluence, and soaring food, energy, land, and water prices—one looks to production capacity reserves. It would be a noble experiment, and likely the opportunity, with an economic incentive, has arrived, to take the lid off U.S. agricultural production. Only in this manner, with reserve technology at hand, and a driving economic incentive coupled with an urgency to perform, can we assess the food production capacity of this nation and the world.

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Bonner, J. 1962. The upper limit of crop growth and affluence, and soaring food, energy, land, and water prices—one looks to production capacity reserves. It would be a noble experiment, and likely the opportunity, with an economic incentive, has arrived, to take the lid off U.S. agricultural production. Only in this manner, with reserve technology at hand, and a driving economic incentive coupled with an urgency to perform, can we assess the food production capacity of this nation and the world.

Brown, L.R. 1967. The world outlook for growth and affluence, and soaring food, energy, land, and water prices—one looks to production capacity reserves. It would be a noble experiment, and likely the opportunity, with an economic incentive, has arrived, to take the lid off U.S. agricultural production. Only in this manner, with reserve technology at hand, and a driving economic incentive coupled with an urgency to perform, can we assess the food production capacity of this nation and the world.


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