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CONTROLLED ENVIRONMENT AGRICULTURE:

A GLOBAL REVIEW OF GREENHOUSE FOOD PRODUCTION

Economic Research Service
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ABSTRACT

Controlled environment crop production is most nearly approached, on a commercial scale, in greenhouses. Greenhouses have been used for food production for over a century, mainly in developed regions. The introduction of plastic film during the 1950's lowered construction costs and made it possible for less affluent nations to use greenhouses. Among the newer techniques of environmental control used commercially are artificial cooling, carbon dioxide enrichment, use of artificial soil, and automated irrigation with liquid fertilizers. Desalted water is even used for irrigation in some oil-rich desert nations. Complete environmental control is possible but is seldom economically justified.

Greenhouse labor and capital requirements per unit of land exceed those for outdoor food crop production. Much of the work must be done by hand; there are usually few economies of scale beyond family-sized operations. Capital investments for glasshouses in developed nations commonly exceed $100,000 per acre.

The most important crops produced worldwide are tomatoes, cucumbers, and lettuce.

Fuel shortages or higher fuel prices could hinder expansion in northern regions, and transportation improvements could increase competition from open-field crops from southern regions. But on a global basis, environmental control via greenhouses will be increasingly important in agriculture.

Keywords: Intensive agriculture, Controlled environment, Greenhouses, Protected agriculture, Cropping systems, Multiple cropping, Developed regions, Developing regions.

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CONTROLLED ENVIRONMENT AGRICULTURE:

A GLOBAL REVIEW OF GREENHOUSE FOOD PRODUCTION

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Washington, D.C. 20250

Economic Research Service
October 1973

CONVERSION FACTORS

Weight: 1 short ton = 2,000 pounds
1 metric ton = 2,204.6 pounds

Area: 1 acre = 0.4047 hectare = 4,047 square meters = 43,560 square feet
1 hectare = 2.471 acres = 10,000 square meters = 107,630 square feet

Currency: Conversions made on basis of 1972 exchange rates.

PHOTO CREDITS

Plate

1. Research and Experiment Station for Glasshouse Crops, Naaldwijk, Holland.
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15. The author.
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PREFACE

This study is an outgrowth of a survey I did a few years ago on multiple cropping in less developed nations. Multiple cropping aroused my interest in intensive cropping systems and in turn in the prospects for environmental control. Both led me to greenhouse food production. I found that, while much specialized technical literature was available, very little had been done in the way of general synthesis.

The purpose of this report, therefore, is to provide an introduction to the development, technology, and economics of controlled environment agriculture in the form of greenhouse food production. It should be useful in analysis of the prospects for, and implications of, this unique form of agriculture. Although written for a broad audience of trained agriculturists who have little, if any, specific knowledge of greenhouse production, it may also be of interest to greenhouse specialists.

Information for the study was gained from library-type research, supplemented by extensive correspondence and some overseas travel. A broad brush is utilized and most technical matters are necessarily not explored in depth; some (such as breeding, fertilization, and pest control) are given only brief mention. While relatively more complete coverage is provided on economic issues, the information base for these was smaller.

Given this focus and methodology, the report has undoubted limitations for some readers. Growers will clearly not find it an applied guide for the construction or day-to-day operation of a greenhouse. Some specialists will find too little detail in their area of specific interest and too much in others. Obviously no one report by one person will meet all needs--but it can provide a start.

Controlled environment agriculture is a massive and complex subject. It does not lend itself to easy generalization or prognosis. There is much to be learned on a wide variety of fronts. I hope this report will stimulate further inquiry.

ACKNOWLEDGMENTS

I am indebted to many people for their help in the preparation of this report. Included are the staff of the National Agricultural Library, USDA agricultural attaches, AID food and agriculture officers, and a host of greenhouse specialists from around the world.

The following individuals not only responded to many requests for information but were also good enough to review large parts or all of earlier drafts of the report:

- M. Eugene Cravens, Professor of Agricultural Economics, Ohio State University, Columbus, Ohio.
- A. J. de Visser, Agricultural Economist, Research and Experiment Station for Glasshouse Crops, Naaldwijk, Netherlands.
- R. R. W. Folley, School of Rural Economics and Related Studies, Wye College (University of London), Ashford, Kent, England.
- Carl N. Hodges, Merle H. Jensen, and associates, Environmental Research Laboratory, University of Arizona, Tucson, and Arid Lands Research Center, Abu Dhabi.
- D. W. Kretchman, Professor of Horticulture, Ohio Agricultural Research and Development Center, Wooster, Ohio.
- E. van den Muijzenberg, Wageningen, Netherlands. (Formerly director of the Institute of Horticultural Engineering, Wageningen.)
- G. F. Sheard, Deputy Director, Glasshouse Crops Research Institute, Rustington, Littlehampton, Sussex, England.
- S. W. Wittwer, Director, Agricultural Experiment Station, Michigan State University, East Lansing, Mich.

Others were of similar assistance in preparing portions of the manuscript. Helpful suggestions were provided by: (1) William A. Bailey and Donald T. Krizek of the Agricultural Research Service, Jules Powell and associates of the Economic Research Service (all are with the U.S. Department of Agriculture); and (2) Samuel Litzenberger and Guy Baird of the Technical Assistance Bureau, Agency for International Development. I am, of course, solely responsible for any errors which may remain.

Research was initiated while I was stationed in the Foreign Development Division of the Economic Research Service, U.S. Department of Agriculture. Further research and writing was done on my own time and fitted in between other assignments while on detail to the Bureau for Program and Policy Coordination, Agency for International Development. Some of the cost of publication was met by funds provided by AID.

CONTENTS

SUMMARY

Environment provides a severe restraint on conventional agricultural production in many areas of the world. Man has long responded by modifying some environmental factors such as fertility and water supply. But nature has generally remained the master, particularly with respect to climate.

Greenhouse food production offers a means for moving toward a greater degree of environmental control. The extent can vary from mere protection from rain to complete environmental control. Major factors influenced are light, temperature, atmospheric composition, and the root environment.

While greenhouses are often associated with flowers in the United States, their use for food production is much older and much wider on a global basis. Transparent coverings were used as far back as Roman times for cucumber production. Heated greenhouses have been used for commercial food production for over a century. And many of the current environmental control techniques have their early roots in the late 1800's and early 1900's.

Still, most of the refinements in structures and environmental control techniques which have made expanded food production possible have emerged in the post-World War II period. Structurally, the introduction of plastic films has vastly lowered building costs and led to a much wider geographic spread in the use of greenhouses. It has also made possible new forms of houses such as the air-inflated bubble. Among environmental control techniques, artificial cooling, carbon dioxide enrichment, use of artificial soil, and automated irrigation with fertilizers in solution form have been the most widely adopted.

The result of these and other innovations is, in its most advanced form, virtually complete and automated environmental control. Some systems may even do away with the greenhouse and rely entirely on artificial light. But the usual combination in most greenhouses currently is a far less sophisticated one. Yet even these systems offer the prospect of matching the environment of the more favored conditions found in nature. The most advanced facilities can significantly improve on nature.

As a consequence, greenhouse food production provides the present ultimate in intensive agriculture when the three major factors of production—land, labor, and capital—are taken into consideration. Yields are or can be higher than in all but the most favored field conditions—in part because multiple cropping can be practiced. Labor and capital requirements per unit of land are higher than in any other form of food crop production. Despite the control of environment, much of the production work must—because of the structure—be carried out by hand. There are usually few economies of scale in greenhouse operation beyond a family-sized operation. Capital investments vary widely by type of structure but commonly exceed $100,000 per acre for glasshouses in the developed nations.

Largely as a result of these high capital and labor requirements, greenhouse food production normally costs more per unit of product than field production. This generally limits greenhouse use to situations where field production is not feasible or economical and to products demanded by higher income groups. A further constraint is that field produce may be, and usually is, imported from more southerly areas where more favorable climates make out-of-season production possible. In some cases, production from simple unheated plastic structures in southern locations may compete with produce from more expensive heated greenhouses in northern zones.

As a result of the interplay of economic forces, food production in greenhouses has largely been limited to a few perishable and high-value salad crops such as tomatoes, cucumbers, and lettuce. Although these products usually are of high quality and bring premium prices, greenhouse production has not in general been exceptionally profitable except possibly in newly expanding areas. Climatic uncertainties are replaced by economic risk associated with the heavy capital investment and high operating costs; this risk is further accentuated by the volatile nature of the produce market.

Thus the technological possibilities of greenhouse food production are severely limited by more sobering economic matters. Even so, greenhouse food production is found in a surprisingly large number of nations and is going through a period of rapid growth in many. Greenhouses have long been heavily used for food in Western Europe (where the total area is in the tens of thousands of acres) and to a considerably more limited extent in the United States and Canada. These traditional regions have been supplemented by sharp expansion in the USSR and Eastern Europe, the Mediterranean region, South Korea, and Japan. A wide array of climatic regions is represented—from the Arctic regions of the Soviet Union to tropical areas such as the Philippines (where greenhouses provide protection from heavy summer rains).

While greenhouses have largely been concentrated in the developed nations, the use of plastic film has made it possible to extend some of their benefits into some of the less affluent nations or regions. Plastic houses were at first widely used in southern European nations along the Mediterranean, but subsequently moved into other areas such as South Korea and the Philippines. And oil-rich nations such as Kuwait and Abu Dhabi have been able to provide themselves with highly sophisticated units utilizing desalted water.

It is difficult to foretell what will happen in the future. Shortages of or higher prices for fuel could well hinder expansion in the more northerly regions unless new techniques of heating or heat retention are developed. And such cost rises coupled with improvements in transportation could raise the prospect of increased competition from southern areas. Some greenhouse areas will undoubtedly decline as others expand. Marked instability is likely to be a general characteristic of the industry—which in turn raises the economic question of whether heavy investments in elaborate and long-lasting structures are prudent.

Whatever its form, environmental control appears likely to be increasingly more important in the agriculture of the future.

I. INTRODUCTION

Fundamentally, the culture of crops consists of man's efforts to utilize a complex, dynamic environment to his economic benefit and well being.[1]*

Man has striven to adapt crop production to environmental conditions for centuries. Where this has not been possible, he has attempted to modify the environment through the use of devices such as windbreaks, shading, irrigation, drainage, fertilizers, and other cultural practices.[2] Some of these techniques are ancient; others (such as the use of sprinklers to prevent frost damage) are the product of an improved and more scientific agriculture. But in each case nature has remained the master: environment has only been *modified*, not *controlled*. Hence there has been a limit on how much production can be increased, even in the most favored areas of the world.

The steady increase in world population has accelerated the search for more intensive and more productive forms of crop production. Varieties have been bred which are much more responsive to modern inputs: a well-known Green Revolution has occurred in portions of some developing nations with a particularly severe food/population problem. Shorter season varieties have been developed which make multiple cropping increasingly possible in certain tropical and semitropical regions.[3] For much of the world, however, year-round farming is out of the question because of climatic conditions. Environment limits crop production to one season, and in most cases provides an upper limit as to the total amount of production economically possible.

In the future, it is likely that increased attention will be given to the question of environmental control. This may not come immediately because the prospects for adapting production to environment or of modifying environment in traditional ways are far from exhausted in many regions. In many cases, it is more economical to import food from other growing areas. But eventually it will prove desirable, perhaps even necessary, to start advancing the degree of environmental modification.[4] Though it is difficult to draw fine lines, this modification may ultimately reach the point of environmental control.

ENVIRONMENTAL CONTROL AND GREENHOUSES

All of this may seem overly visionary—except for the fact that it has been done in one small and little known sector of agriculture: greenhouses. Food

*Footnotes are grouped at the end of each chapter.

crops have been intensively produced in greenhouses for hundreds of years, and commercially for the past 100 years in some countries. The degree of environmental adjustment in greenhouses at first was quite limited; it can hardly be said to have been more than modification. With the introduction and improvement of effective heating systems, however, a greater degree of environmental control became possible. At present, the technology is available for virtually complete environmental control, although it is seldom fully utilized.

Despite the fact that greenhouses themselves are well known, their potentials and limitations for food production have received little general attention. In the United States, they are usually viewed as a research tool or as a source of out-of-season ornamentals. Probably only a small portion of the American population even knows that they are used for commercial food production. (The situation may be somewhat different in Europe, where a greater portion of the food supply is produced in greenhouses.) It is not surprising, then, that greenhouses have been almost entirely neglected in evaluations of food production systems or of potential ways of meeting future world food needs. To the extent that this neglect is due to the lack of any general introductory review, I hope that this report will provide at least a partial corrective.

Although the basic purpose of the report is to provide perspective on the broad question of environmental control, the discussion is largely cast in terms of greenhouses. This is because they are the basic ingredient in nearly every commercial environmental control system. Other variants, however, are possible. On the one hand, growth chambers or growing rooms which provide complete environmental control (the units do not even use sunlight, relying instead on artificial light) are finding increased use in the early growing period. On the other hand, it is possible—and indeed to be hoped—that ways may be found to apply a greater degree of environmental control to field culture. Both variants will be briefly noted.

The technical potential for environmental control is considerable. The basic present limitation is economic—and has received very little attention indeed. But before going further into these matters it might be well to more precisely define some terms and introduce (or review, depending on the reader's background) some of the basic technical and economic relationships which will be discussed in subsequent chapters.

DEFINITION OF TERMS

It may seem a little pedantic to define terms, but since the subject of this bulletin will probably be new to many readers, such an effort may reduce confusion later on.

Intensive agriculture. This is based on cropping systems which (1) require large amounts of labor and capital per unit of land per year, and (2) produce a high crop value per unit of land per year. It usually involves the extension of the growing season over a longer period than is possible under field conditions. Multiple cropping—the raising of more than one crop per unit of land per

Plate 1—*A typical greenhouse used for food or floral crops in developed nations. It is constructed with metal framing and covered with glass, and is equipped with roof ventilation and artificial heat.*

year—is often involved. Measures of intensity, in terms of the usual factors of production, will be discussed in greater detail in chapter III.

Controlled environments. Since, as noted earlier, environments have long been partially modified, it is necessary to draw some kind of dividing line between modification and control. I consider that protection from the elements (wind, rain, snow, and so forth) is the minimum factor in environment control. In most regions, temperature control is also a basic requirement. Many other factors are involved in more complete control, including light, atmospheric composition, and root medium. All are discussed in detail in chapter III.

Greenhouses. Over time and around the world, a wide range of structures have sometimes been classified as greenhouses. This report focuses on frame or inflated structures covered with a transparent or translucent material in which crops may be grown under conditions of at least partially controlled environment, and which are large enough to allow a man to walk within them and carry out cultural operations.

This definition normally excludes cold frames, hot beds, and low tunnels—all very low structures which cover only a few rows. Although hot beds or hothouses have been important in the past, they now are not heavily used except for propagating purposes. Their modern counterpart is the low plastic tunnel which is unheated and which serves basically as a hot cap. Although excluded from the definition of greenhouse, these structures are noted in the text of the report.

Reference will often be made to "glass" or "plastic" houses. This terminology refers to the covering material. "Plastic" normally means flexible films as typified by polyethylene. More rigid "plastic" sheetings (principally made of polyvinyl chloride or fiberglass) are sometimes used and fall between glass and plastic film in many of their characteristics.[5]

Commercial rather than research uses of greenhouses are emphasized.[6]

BASIC TECHNICAL RELATIONSHIPS

There are two basic processes involved in plant growth: photosynthesis and metabolism. Photosynthesis involves the transformation of carbon dioxide (CO_2) and water (H_2O), in the presence of energy, into carbohydrates and oxygen. Metabolism involves the conversion of carbohydrates into the energy which maintains the life processes of the plant. Of the two, photosynthesis is clearly the first step and is the most subject to external environmental factors. It is the main point of focus in this report.

The basic reasons for environmental control are to make possible and to accelerate the process of photosynthesis. Conceptually, this may be done in several different ways: (1) increase the supply of CO_2 and/or H_2O, (2) increase the amount of light energy, or (3) reduce the concentration of end products. Man has influenced the water supply in some regions for centuries so that this practice is not novel—except that the greenhouse structure provides protection from heavy or ill-timed rains. The adjustment of light energy and CO_2 is a more unique process.

Energy for photosynthesis is provided by light; light also produces heat, which accelerates the photosynthetic process. While the greenhouse structure slightly reduces incident light, it compensates by helping retain the radiant heat. Light can be provided artificially, and indeed this is done to a certain extent. But the general practice is to provide heat by artificial sources. Generally, the greater the heat supply (up to a certain point), the more rapidly photosynthesis will be carried out. Where heat levels are too high, ventilation or artificial cooling may be practiced.

The level of carbon dioxide may also influence the rate of photosynthesis. Since the carbon dioxide supply would soon be exhausted in a closed greenhouse, provision is usually made for ventilation with outside air. But it is also possible to raise carbon dioxide levels to higher than normal concentrations, thereby accelerating the rate of photosynthesis and speeding early growth. This process is carried out commercially in greenhouses, especially in the winter, when it is desirable to reduce outside ventilation.

Since more than photosynthesis is involved in plant growth, other conditions must also be met. And the more completely they are met, the better plant growth and the higher the quality of product. Included here would be the provision of fertilizer, protection against storms and winds, and control of insects and diseases. All of these steps can be carried out relatively easily in greenhouses. For instance: fertilizers are often mixed with the irrigation water; the greenhouse structure protects against dry winds which might increase irrigation needs; and the use of irrigation rather than reliance on rains may reduce insect and disease incidence.

In other words, a greenhouse with appropriate environmental equipment can provide nearly optimum growing conditions for plants on nearly a year-round basis. It generally does this, however, at a substantial financial cost—especially if artificial lighting must be provided.

BASIC ECONOMIC RELATIONSHIPS

Greenhouse production is nearly always more expensive per unit of product than field cultivation in the same area during the same time period—provided efficient field culture is possible. This is a big if, and is at the heart of the economic rationale for climate control in greenhouses. The purpose of greenhouse production is to provide a product either (1) *where* local field production is of lower quality or even higher cost, or (2) *when* local production is not possible. An example of the former is summer tomato production in northern Europe; an example of the latter is winter production of vegetables in the northern United States or in northern Europe. The situation is of course more complicated than this because of the presence of imports from other producing areas.

While nearly any crop, including tree fruits, can be and probably has been grown in a greenhouse, the process has proved commercially economic for only a few. The bulk of current food production from greenhouses is accounted for by only three vegetable crops: tomatoes, cucumbers, and lettuce. Why has production been so confined? It is a combination of the production and market characteristics of these three vegetables, such as their ability to come into bearing soon, their ability to respond with heavy yields to intensive greenhouse culture systems, the perishable nature of the product, the high value per acre, and other factors.

While greenhouse production lessens the climatic risks involved in production, it does not reduce the quality of management needed, and has probably increased economic risks. The economic problems are largely due to the heavy fixed investment which is necessary, the relatively limited range of alternative food crops available, and the constant competition from imported field products. Challenges facing the greenhouse grower today are not much different from those noted by Liberty Hyde Bailey in 1897:

> The growing of vegetables under glass for the winter market is one of the most special and difficult of all horticultural operations, . . .there are comparatively few varieties of vegetables particularly adapted to winter forcing, and the markets are less extensive and more unstable.
>
> To succeed with forced vegetables requires great skill in the management of glass houses, close attention to every detail, and the complete control of all the conditions of plant growth. To these requirements must be added a thorough knowledge of the markets, and the ability to have the crop ready at any given time.[7]

To reduce their economic vulnerability, some vegetable growers in the more settled greenhouse areas are diversifying into cut flowers and bedding plants, sometimes as part of a vegetable rotation.

GEOGRAPHIC RELEVANCE

Food crops are produced in greenhouses over a surprisingly wide geographical range. The commercial industry, however, has been concentrated in the developed nations, principally in Europe. Within these areas, production has typically been located in the colder temperate regions. Some greenhouses are found in developing nations, generally those with a temperate, Mediterranean, or arid climate. Only a few commercial operations are located in tropical or semitropical regions.

While this report, therefore, might at first seem to be of principal concern to the developed nations, there are reasons why it might be of interest to a wider range of countries:

– Greenhouses are, or are becoming, important commercial realities in several developing nations: Greece, Turkey, Lebanon, Kuwait, Abu Dhabi, Mainland China, and South Korea.

– Developing nations exporting winter produce, or planning to do so, to North America or Europe will be competing with greenhouse crops. Regions presently in this category include North Africa, Central America (including Mexico), the West Indies, and the northern part of South America. Some North African countries, moreover, make use of simple forms of environmental control to reach an early market.

– In some tropical regions with very heavy rainfall, simple greenhouses or plastic covers may provide a way of producing tender and high value crops during the wet season. This practice has been utilized to a limited extent in the Philippines.

– If desalinized water is ever to be used for irrigation, it may be necessary to use greenhouses to reduce moisture loss. This is already the case in Kuwait and Abu Dhabi on the Persian Gulf.

– Some of the environmental control concepts or techniques utilized in greenhouses may ultimately have some applicability to field culture.

– At the very least, interested developing countries should be aware of the forms and merits of environmental control before investing scarce capital.

Socially, intensive food production under controlled environmental conditions will probably never be a direct way of providing inexpensive food to low income groups in developed or developing nations. But it could have desirable economic benefits by serving as a source of import substitution, export expansion, increased farm income, and expanded employment. It is hoped that this report will help suggest where these goals are possible and will contribute to their more efficient realization.

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2. A comprehensive review of traditional practices is provided by Gene C. Wilken in "Microclimate Management by Traditional Farmers," *Geographic Review*, October 1972,

pp. 545-560. More general techniques are reviewed by L. P. Smith in *Weather and Food*, World Meteorological Organization, Geneva, 1962, pp. 37-60 (Freedom from Hunger Campaign Basic Study No. 1). Practices used to prevent frost are outlined by Jen-Hu Chang in *Climate and Agriculture: An Ecological Survey*, Aldine, Chicago, 1968, pp. 100-108.

3. I have discussed this subject in considerable detail in *Survey of Multiple Cropping in Less Developed Nations*, U.S. Department of Agriculture, Foreign Economic Development Service, FEDR-12, October 1971, 108 pp.

4. This may be particularly true if the earth continues a cooling process which has been underway since the 1940's. (See James D. Hays, "The Ice Age Cometh," *Saturday Review of Science*, April 1973, pp. 29-32; Bryan Silcock, "Ice Age to Come?" *The Sunday Times* (London), April 15, 1973, p. 17.)

5. For a more detailed discussion of the characteristics of the major plastic coverings, *see, inter alia*, J. A. Sondern, *Plastic Films Used in Horticulture*, Instituut voor Tuinbouwtechnick, Wageningen, Holland, September 1972, pp. 1-12.

6. The most advanced research units, involving both climate-controlled greenhouses and growth chambers, are known as phytotrons (see ch. III, fn. 120). Greenhouses are increasingly being used for experimental work in the developing nations. A phytotron is being erected at the International Rice Research Institute (Los Banos, Philippines) with the support of the Australian government.

7. Liberty Hyde Bailey, *The Forcing Book; A Manual of the Cultivation of Vegetables in Glass Houses*, Macmillan, New York, 1897, p. 1.

II. HISTORICAL DEVELOPMENT

The greenhouse as we know it dates back to the early 1800's. But several of its key features—the use of transparent covering and the provision of heat—are much older. They were first mentioned in Roman times and emerged again in more advanced form during the Renaissance in Europe. European developments in turn were transferred to the United States, where further improvements were introduced. By the late 1800's, greenhouse vegetable production had become a commercially important enterprise in America, England, and France.

These developments are discussed below. More recent advances in greenhouse construction and the development of other methods of environmental control are reviewed in chapter III. Developments in individual nations during the 20th century are noted in chapter IV.

ROMAN PRACTICES

The Roman Emperor Tiberius Caesar (who ruled between 14 and 37 A.D.), reportedly told by his doctor that he needed a cucumber a day, had arrangements made to produce them nearly the year round.[1] Moveable beds were placed outside on favorable days and inside during inclement weather. According to Pliny, on wintry days the beds were covered by frames glazed with transparent stone.[2] This was done "so that. . .when days were clear, they may be safely brought out into the sun."[3] Among the transparent stones (specularia) used were those formed in slate-like plates such as mica, alabaster, and talc.[4] While Columella recommended the use of well-manured soil, it is not clear whether he had its heat-producing qualities in mind.[5] In any case, the use of such cultural methods was undoubtedly very limited and seems to have ceased, at least as far as recorded history goes, with the decline of the Roman Empire.

THE 15th TO 19th CENTURIES IN EUROPE

Nothing more is known of the precursors of the greenhouse until the beginning of the Renaissance in Europe. From the late 1500's until the 1800's, many of the present characteristics of the greenhouse began to emerge. Nearly all of the efforts recorded here were in England and France.[6]

The first known reference to vegetable forcing appeared in Gerarde's *Herball*, published in London in 1597. The role of manure in forcing early cucumbers in beds is clearly reported. Moreover, the beds were insulated: they were crossed with hoops and poles and then covered with "mats, old painted cloth, straw or such like." Once the seedlings emerged, the beds were "opened when the day is warmed with the sun beams" and covered at night until the danger of cold nights passed.[7]

The growth of protected gardening, however, proceeded slowly while a means was found to conserve heat and shelter the plants without blocking the necessary light. Claude Mollet, gardener to Louis XIII (who reigned from 1610 to 1643), was presumably the first to mention the use of frames which were heated by manure and evidently covered with glass panes.[8] Forcing frames were also noted by Andre Mollet in 1650, Winchester in 1660, and van der Groen in 1670.[9] In 1690, de la Quintinye commented on the use of (1) "glassed frames" and glass bells to cover hot beds for a wide variety of vegetables and small fruits, and of (2) square glass frames with dimensions of 6 to 7 feet to warm or force fig trees.[10] Just when glass was first utilized is not certain, but bell jar coverings were probably used before panes in frames (lanterns without bottoms were also used to cover plants).[11]

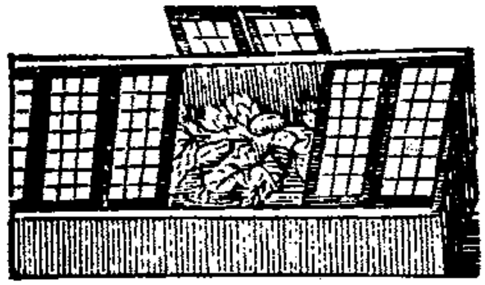

Plate 2--*At top, glass lanterns used to cover plants in the 1600's. At bottom, earliest known published drawing of vegetables growing in a frame covered with glass (Holland, 1670).*

Forcing subsequently moved into wider use in England and France. Amherst notes that "enterprising gardeners. . .began to make attempts at forcing greens and salads, asparagus, and cucumbers" in England in the 1700's. Samuel Collins in 1717 wrote a treatise on the culture of melons and cucumbers, suggesting various glasses and frames for their protection.[12] Similar discussions were presented by Bradley and by Miller in 1731.[13] Kalm, a Swedish horticulturist who passed through England in 1748, described some gardens where the beds were "covered with glass frames which could be taken off at will." Vegetables most numerous around London in May of that year were beans, peas, cabbage, leeks, chives, radishes, lettuce, asparagus, and spinach.[14] Market gardeners in France began to sell early vegetables from forcing frames around 1780.[15]

Glass was not the only covering material at this point. In the 1700's, oiled paper was used to cover portable wooden frames in England. The frames were generally 5 to 6 feet wide and the distance between the supporting hoops not more than a foot. A paper called Dutch wrapper was used and generally only lasted one season. One of the two basic frame models was designed with a hinged side. It is not clear whether manure was used as a heating agent.[16]

Other forms of heat began to come into use for more exotic crops and plants in the late 1600's. Stoves were probably first used for conservatories (orangeries).[17] In 1684, it was noted that a Mr. Watts, gardener at Apothecaries Garden in Chelsea, heated a greenhouse from below with a flue system; this was known as a dry stove.[18] Bark stoves, which provided a moderate moist heat, were probably first developed in Holland after 1600; in the early 1700's, they were used for the cultivation of pineapple.[19]

At first, the greenhouse of the 1700's used glass on one side only in the form of a sloping roof. Later in the century, glass was used for the front and on both sides of lean-to houses. The two-sided greenhouse emerged through the 1800's,[20] but was seldom used for vegetable production. The vast bulk of vegetables continued to be raised in the more prosaic manure-heated frame.

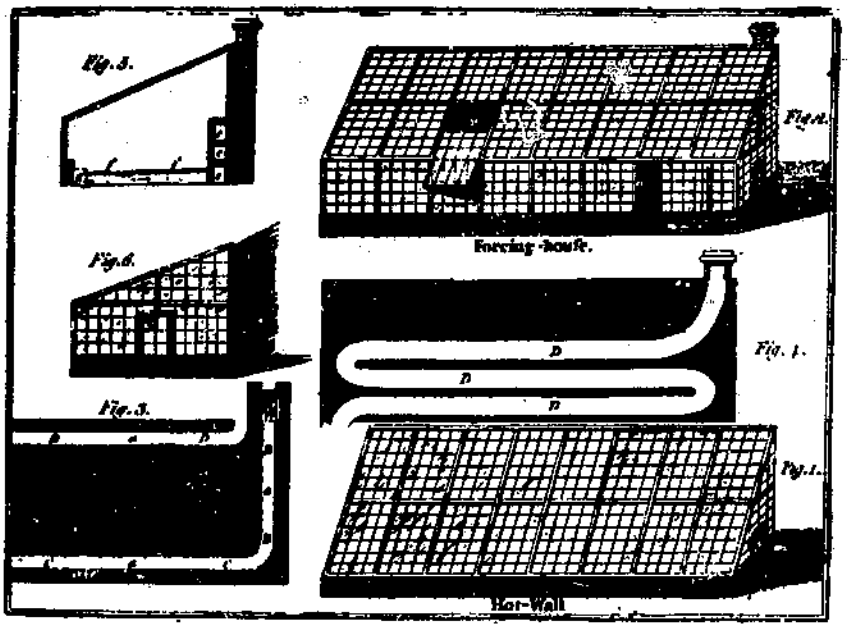

Plate 3—*Typical heated greenhouses of the late 1700's, showing arrangement of heating flues. At the time, these structures were known as forcing houses or hot walls. (England, 1789.)*

By the late 1700's and early 1800's, the forcing of food crops was a subject of a number of books in England.[21] The technique, however, was initially limited to private estates, and consumption of the produce was confined to the wealthy. Around the middle of the 1800's, greenhouse products such as grapes, melons, peaches, and strawberries began to arrive on English markets. Greenhouse tomatoes did not appear until the 1870's and did not begin to become popular until the 1880's. Important early greenhouse areas included, roughly in chronological order, Guernsey, Worthing, North London and Lea Valley, Swanley, and Blackpool. Four tons of Guernsey grapes were sold in Covent Garden in 1856. Worthing had about an acre of greenhouses by 1870 and

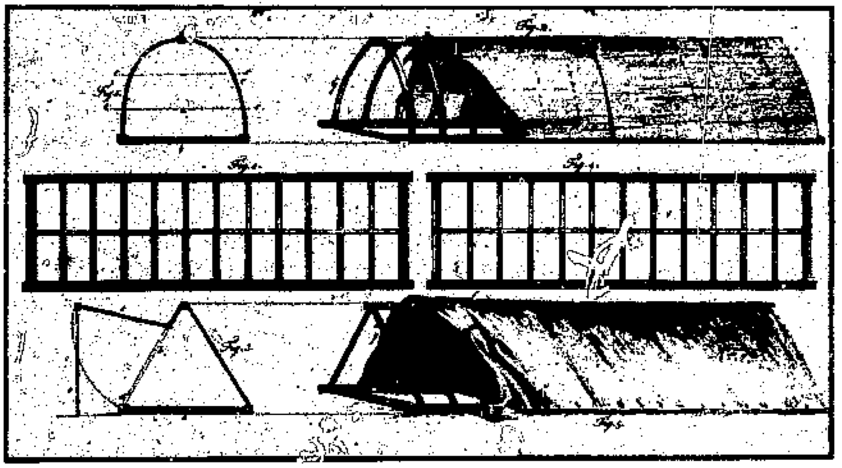

Plate 4—*Portable wooden frames covered with an oiled translucent paper, which served much the same warming purpose as low plastic row covers today. The bottom design had a hinged side. (England, 1764.)*

about 45 acres by 1898.[22] Thus by the end of the 19th century, commercial greenhouse food production was well established in the United Kingdom.

THE 18th AND 19th CENTURIES IN AMERICA

With the development of forcing frames and greenhouses in Europe in the 1700's and 1800's, it was not surprising that these practices made their way to the United States. Here we will review developments in vegetable production in the United States through 1900. A few post-1900 statistics will also be included.

EARLY DEVELOPMENTS

Several structures were built between 1700 and 1800 which provided varying degrees of protection for plants:

– Andrew Faneuil is said to have erected a hothouse on his estate in Boston between 1709 and 1737. Unfortunately, no description exists, but presumably it was a manure-heated frame.[23]

– A small conservatory with glass windows on at least one side was built on the estate of James Beckman in New York in 1764. It reportedly contained exotic shrubbery and plants. (The building obtained a certain historical distinction by serving as the place of confinement for Nathan Hale the night before his execution.)[24]

– A larger conservatory (or orangery), partly modeled after one near Baltimore, was built by George Washington at Mount Vernon in the middle to late 1780's. It was heated by flues under the floor and contained citrus trees and potted plants. Although destroyed by fire in 1835, it was carefully reconstructed in 1950 and 1951 and is now open for viewing.[25]

– The earliest known structure resembling a modern greenhouse was constructed on the Lyman estate in Waltham, Mass., around 1800. Remarkably, it is still standing and was recently restored. It was in effect half forcing frame and half greenhouse, consisting of a low sloping roof covered by sash windows which could be raised for ventilation. Heat was provided by a brick fireplace with a horizontal flue. The structure was probably used for growing flowering plants and exotic fruits. A grape house was built a few years later.[26]

Except for a small quantity of grapes,[27] essentially all of the food crops raised under cover in the early 1800's were grown in hot beds, covered by glass sashes and heated by manure. M'Mahon, in 1806, referred to the cultivation of cucumbers, kidney beans, and strawberries in hothouses.[28] Directions for the construction and operation of a hothouse were included in a book published in 1819.[29] The forcing of vegetables was reported in the Boston area in 1830, and a prominent garden magazine in 1836 carried a series of articles "On the Construction of Brick Pits for Early Forcing."[30] During this period, considerable attention was also given to the midwinter forcing of lettuce. Along with lettuce, the principal hot bed crops were radishes and cucumbers.[31]

By 1860, the forcing of vegetables in hot beds had assumed "important proportions." A committee of the Massachusetts Horticultural Society noted the growth of early vegetables under glass in 1867 and recommended that prizes be given to encourage it.[32]

IMPROVEMENTS IN STRUCTURES

During the mid-1800's, significant changes began to be made in both the design and the heating of facilities used for vegetable forcing.

Boston had long been the center of this industry, and in the 1860's a few of the more progressive growers in the vicinity took the glass sashes used for hot beds and made houses of them. The first houses were low, had flat roofs, and were barely high enough for a man to walk erect within them.

Between 1875 and 1880, increasing competition from southern-grown vegetables made further improvements necessary. The newer houses were at first of the lean-to type:

> They were from 20 to 25 feet wide and 10 to 12 feet high at the back, with the slope to the south side, where there was a 5-foot wall, the upper half of which was ventilating sash.[33]

Houses of this design were also put up around Providence and some near New York. By 1894, a greenhouse covering nearly a third of an acre had been erected near Arlington, outside of Boston.[34]

The move from frames to greenhouses for vegetable production entailed a change in the mode of heating. In 1869, a committee of the Massachusetts Horticultural Society:

> . . .noticed the erection by way of experiment, of forcing houses heated with hot water, in the hope of saving the heavy cost of manure used for hot beds, as well as of the transportation and labor in handling.[35]

Through the 1870's, there was a continued substitution of houses heated by hot water for hot beds. The lean-to type of houses noted above were steam-heated. Both hot water and steam heating systems had been used for ornamental crops for some time.

CROPS GROWN

The main greenhouse crop in the late 1800's was lettuce, followed initially by cucumbers and then later by tomatoes.

Lettuce was the first to appear in greenhouses. The houses built of sashes in the 1860's were designed for lettuce (and were built low because it was believed that lettuce should be grown near the glass). A committee of the Massachusetts Horticultural Society visited a house heated by hot water on December 22, 1869, and found it "filled with a fine crop of lettuce and radishes nearly ready for market."[36] Despite these two accounts, other sources place the origin of lettuce cultivation in greenhouses in the early 1880's,[37] and this may indeed have been the period of most rapid development. Growth in the Boston area was soon followed by expansion around Grand Rapids, Mich.[38] Often, two crops of lettuce were grown followed by a crop of cucumbers or tomatoes, but near the turn of the century there were numerous references to the culture of three crops in a row between September and April.[39]

Tomatoes did not begin to become important until the late 1800's. In 1883, one grower began to transplant them in beds of carnations in February. He subsequently wrote in 1887:

> Don't put up houses on purpose to grow tomatoes, expecting to get much fruit before April, for it won't pay; you can't make sunshine, and without it in abundance you can't have much fruit. Besides the demand in mid-winter is limited and price no higher than in the early spring months.[40]

The grower noted a sharp increase in demand for greenhouse tomatoes, which he felt was based on their superior quality.

Liberty Hyde Bailey began experimental work with greenhouse tomatoes at Cornell University during the winter of 1889/90. In 1891, he stated:

> The winter forcing of tomatoes is little understood by gardeners, and the literature of the subject is fragmentary and unsatisfactory. Yet it is a promising industry for all the older parts of the country, particularly in the vicinity of the larger cities. We have made careful experiments upon it during two winters and our efforts have met with uniform success.[41]

In the same work, Bailey reported that winter tomatoes found a ready sale.

Thus tomatoes were raised both as a midwinter crop and as a spring and early summer crop. Bailey and another writer noted that the forced tomatoes sold well in the presence of a cheaper product shipped in from the south.[42]

What of other crops? Aside from lettuce, tomatoes, and cucumbers, other vegetables were grown in only limited quantities. While it was possible to raise a wide range of vegetables under glass, only a few were profitable—those which could be raised in a short season, had a heavy yield for the space occupied, and which were quite perishable. The minor greenhouse crops included carrots, celery, cress, beets, eggplants, peas, and string beans. Some crops, such as radishes, could be more economically raised in hot beds. Others, such as spinach and peppers, could be grown in the south and shipped to northern markets in good condition.[43]

Most of the greenhouse vegetable producers—perhaps 90 percent in the early 1900's[44]—were also market gardeners. Consumers, to judge from prices received, must have been in the wealthier classes.

VEGETABLE STATISTICS

By the turn of the century, an estimated 1,000 establishments were "engaged exclusively, or nearly so, in the forcing of winter vegetables." The total area under glass, including houses and frames, was placed at about 100 acres for winter vegetables, 40 percent of which was in the Boston area. The wholesale value of the product was set at about $2.25 million and the retail value at $4.5 million. Since the total area under glass in 1899 was 2,200 acres for all crops, vegetables—if estimated correctly—were relatively unimportant.[45]

The situation changed rather sharply in subsequent years. By 1912, the greenhouse vegetable area in Boston, Rochester, Grand Rapids, and Ohio totaled about 260 acres.[46] By 1929, 1,285 acres of vegetables were raised under glass in the United States, accounting for nearly one third of the total glasshouse area of 3,980 acres. The value of the vegetable crop at the farm level was placed at $9.66 million. Tomatoes represented 43 percent of the total value, followed by cucumbers with 33 percent, lettuce with 18 percent, and all others with 6 percent.[47]

Unfortunately, further statistics are not available until the post WW-II era; these are given in chapter V.

* * *

Thus by 1900, greenhouse vegetable production in the United States had assumed many of the general technical and economic features which were to characterize it for many years. Since American production was generally aimed at the winter and early spring markets, environmental control practices were relatively advanced for the period. But concurrent research, both in the United States and Europe, was to lay the basis for further technological developments. These are reviewed in the next chapter.

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4. Georges Gibault, "Les Origines de la Culture Forcee," *Journal de la Societe Nationale d'Horticulture de France*, Paris, 1898 (3 ser., tome 20), p. 1111. Glass was known but it was probably too difficult to produce the right size.

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6. Many of the references in this section were kindly suggested by E. W. B. van den Muijzenberg. (Most are to be found in the rare book rooms of the Library of Congress or of the National Agricultural Library.) Van den Muijzenberg is currently writing the definitive history of greenhouses (in Dutch); some of his findings are summarized in "Historie van het Energie Verbruik in Kassen," *Groenten en Fruit* (Holland), December 20, 1972, pp. K55-K57. Considerable detail on general greenhouse developments in England through 1900 is provided by Lemmon, *op. cit.*, 284 pp.

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8. Georges Gibault, *Historie des Legumes,* Librarie Horticole, Paris 1912, pp. 367-368.

9. Andre Mollet, *Le Jardin de Plaisir,* 1650, ch. VII (cited by Gibault, *op. cit.*, 1898, p. 1113); Robert Sharrock, *History of the Propagation and Improvement of Vegetables,* Oxford, 1660 (cited by Lemmon, *op. cit.*, p. 31); J. van der Groen, *Den Nederlandtsen Hovenier,* Amsterdam, 1670, p. 40. The first mention of bell glasses may have been in *Le Jardinier Francais,* 2nd ed., 1653.

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14. Amherst, *loc. cit.*

15. Gibault, *op. cit.* (1898), p. 1117.

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22. W. F. Bewley, *Commercial Glasshouse Crops,* Country Life Ltd., London, 1950, pp. 472-474; "The Evolution of Glasshouses," in *The Construction and Heating of Commercial Glasshouses,* Ministry of Agriculture and Fisheries, London, 1953, Appendix IV, pp. 68-75. The latter reference suggests that the construction of the 19-acre Glass Palace in London in the 1850's may have convinced many people of the possibilities of glasshouses for commercial plant production.

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25. Details of the reconstruction are provided in the *Annual Reports* of the Mount Vernon Ladies' Association for 1951, pp. 34-40, and 1952, pp. 18-26. The heating system was based on one utilized in the greenhouse of Mrs. Charles Carroll at Mt. Clare. A similar structure was built at Wye House in Maryland during the late 1700's (see H. Chandler Forman, *Old Buildings, Gardens and Furniture in Tidewater Maryland,* Tidewater Publishers, Cambridge, 1967, pp. 69-75).

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III. METHODS OF ENVIRONMENTAL CONTROL

Greenhouse production exceeds all other forms of agriculture in the degree of control possible over plant environment. If environment is defined as being composed of the four major factors of (1) temperature, (2) light, (3) composition of air, and (4) the nature of the root medium, then a high degree of control is possible. In commercial practice, of course, the degree of control exercised is considerably less than the potential. But at the very minimum, the presence of a greenhouse provides the basis for greater control than is found in traditional agriculture. Hence with proper management, the biological uncertainties of greenhouse production are typically less than for field culture.

This chapter outlines and traces the development of the major ways of modifying plant environment in greenhouses. Emphasis is first placed on the above four factors in the context of their physiological effect on plant growth. Brief mention is made of their interactions. Then new forms of environmental structures are noted. Finally, some extraordinary new complexes which offer virtually complete climate control for desert regions are discussed.

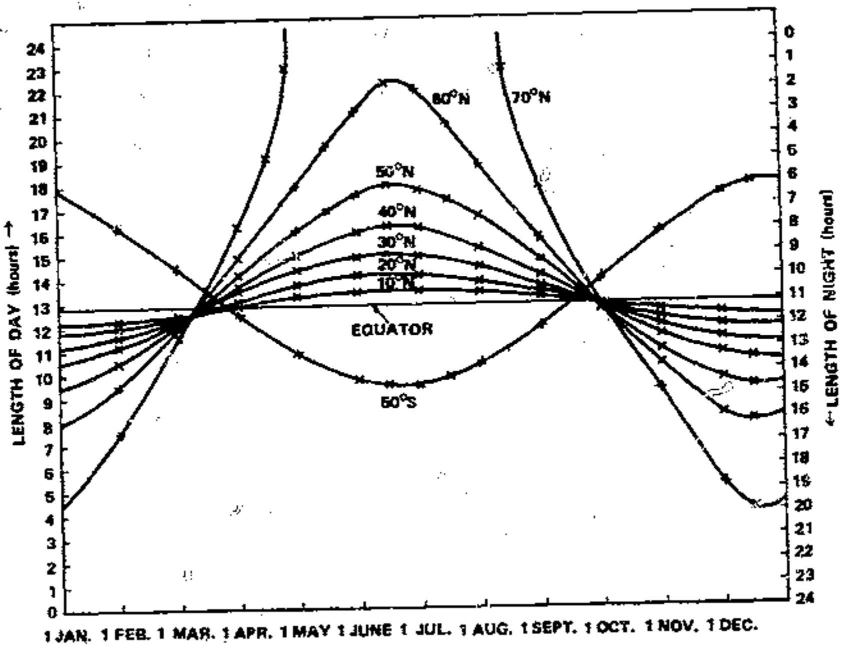
There is a vast body of scientific literature available on the various aspects of environmental control. This chapter only skims the surface. Portions will be quite familiar to plant scientists. Persons whose botanical background is limited may find more that is new or long forgotten. Hopefully, both groups will gain a clearer idea of the potentials and limitations of environmental control for food production.

LIGHT CONTROL[1]

Light is essential for photosynthesis. The amount of natural light available is influenced by both the length of the day and the intensity of the light. Day length, in turn, is a function of season and latitude. Days in the northern hemisphere, of course, are longer in the summer than in the winter; the variation in day length, moreover, increases as one moves from the Equator to the North Pole. These general variations are pictured in figure 1. Intensity of light is in part a function of cloud cover. Where overcast skies are combined with the short days of the northern latitudes, the amount of light available may be inadequate for satisfactory growth of a crop.

Regardless of the latitude where greenhouses are used for food production, they are more apt to face a problem of too little than too much light. The structure and covering inevitably reduce light transmission. The houses,

VARIATION IN DAY LENGTH BY MONTH AND LATITUDE



Note: Some leading cities are located roughly as follows: 30°N, New Orleans/Kuwait; 40°N, New York City/Ankara/Peking; 50°N, Winnipeg/Prague; 60°N, Oslo/Stockholm/Leningrad.

Source: Reproduced from A. E. Canham, *Artificial Light in Horticulture,* Centrex Publishing Company, Eindhoven, Holland, 1966, p. 36.

Figure 1

therefore, are situated and constructed to admit a maximum of light. Expanded use is being made of white plastic and aluminum foil spread between the rows to increase light reflectance. In extreme cases, artificial lighting is used. Greenhouses seldom suffer from too much light unless it is connected with a high-temperature difficulty—in which case shading may be utilized.

The use of artificial light to influence plant growth has been studied in England and France since the late 1870's.[2] The first scientific work on the influence of light on greenhouse food crops in the United States was initiated by Liberty Hyde Bailey at Cornell University during the winter of 1889/90, utilizing arc lamps.[3] The results on lettuce were significant; in some cases, the light led to a gain in maturity of as much as 2 weeks. Bailey concluded, however, that "It will be found profitable to use the electric light for plant growing, if at all, only in the three or four months of mid-winter."[4] Similar results were obtained from tests initiated at the West Virginia Agricultural Experiment Station in 1892 with incandescent lamps.[5] A commercial grower, W. W. Rawson of Arlington, Mass., used lights to hasten his lettuce crop during the 1890's; they shortened the maturing of each crop by 5 days, or by 15 days for three crops.[6] Although he used the lights for a number of years, they were finally abandoned. In 1917, it was reported that "commercial growers have not regarded electro-culture as a practical business proposition."[7]

It is not known how much commercial use has been made of artificial lighting since then, but it is certainly not common in food production because of the cost. Lights are currently mainly used during the winter months in northern Europe to raise seedlings to the transplanting stage. In Sweden in 1972, lighting was applied to 75 to 80 percent of the cucumber plants in December and January and to 30 to 40 percent of the tomatoes in the November-February period.[8] In 1969 in Norway, 4.7 million watts of electricity were used in 645 establishments for plant production.[9] As of 1955 in the Soviet Union, about 4.4 acres of cucumber plants were raised under lights; in 1969, a Soviet publication referred to a new greenhouse complex near Moscow where "each section will have hundreds of artificial suns switched on and off automatically."[10] In Holland as of 1972, about 125 acres of early strawberries were lighted to promote flowering, and early cucumbers raised to the transplant stage under lights were planted onto about 1,000 acres.[11]

Experience in North America is more limited. In 1966, a 1-acre greenhouse was constructed in Soldatna, Alaska, which was to use 4,000 lamps to provide artificial light in the winter. Use of the lamps on a 16-hour day basis was said to cut growth time by 20 percent and enable production of three crops a year (only lettuce and cucumbers were raised initially).[12] Research work in Ohio has suggested that it might be worthwhile to use artificial light during the winter to raise tomato plants from seed emergence to the transplant stage, but not after transplanting under normal light conditions.[13]

Growth chambers with completely artificial lighting, used for many years for research, are now finding increasing commercial use. They are discussed in further detail later in this chapter.

Just how far the commercial use of artificial light may be expected to expand will, if past experience is any guide, depend on technological developments, which influence cost. Unless some striking breakthroughs are made, lighting will probably be limited for some time to raising seedlings to the transplant stage and in extreme northerly locations.

TEMPERATURE CONTROL

Temperature exerts a significant influence on the rate of photosynthesis. Generally, the higher the temperature, assuming carbon dioxide and light are abundant, the faster photosynthesis takes place.

However, there are upper limits to the process, and individual plants differ somewhat in their optimum range. University of Arizona researchers have, for example, divided vegetables into three main temperature categories for their work in northern Mexico:[14]

Category	Temperature (F) Day	Night	Crop
Warm	80-100°	75-80°	cantaloupe, cucumber, squash, watermelon
Moderate	75-80°	60-65°	eggplant, okra, onion, pepper, tomato
Cool	70-80°	50-60°	beans, beets, broccoli, cabbage, carrots, cauliflower, lettuce, radish, spinach

The high temperature requirements of cucumbers explain why they were among the first to be grown in greenhouses. Similarly, the cool temperatures tolerated by lettuce suggest why they are most often raised in midwinter.

HEATING

The basic original purpose of the greenhouse was, of course, to raise the temperature of the plant-growing environment. Solar heat energy is of a wavelength that passes readily through glass to warm up the interior of the house. The soil and other objects inside the house absorb this heat and reradiate it in the form of heat energy of a different and longer wave length. The glass covering of the greenhouse resists the passage of this radiation, thus retaining some of its heat energy. (Plastic covers permit more of the heat to be reradiated, resulting in slightly lower temperatures.)[15]

Early methods of temperature control, as noted in chapter II, centered about the use of rotting manure, moveable glass frames, and matting or other coverings. The process of heating by manure began to be augmented by use of hot air directed through flues in the 1700's and by circulating steam and hot water in the late 1700's and early 1800's. Hot water heat was suggested as a heating device to the French Academy of Sciences by Bonnemain in 1777; its application to horticulture was largely due to Gautier in France and to Atkinson and Bacon in England.[16] Steam heating of glasshouses was reportedly introduced by Wakefield of Liverpool in 1788 and subsequently was effectively applied by Butler in 1792.[17] Both hot water and steam systems continued to be used in most greenhouses well into the 1900's. They have many advantages, not the least of which is an even, moist heat.

In recent years, the trend in most of the temperate countries has been towards an increased proportion of heated greenhouse area. This is true even in nations which typically produce a large proportion of their output in the summer period; to obtain higher prices, growers have been forcing earlier production. Along with these shifts, there has been a change in the type of heating system used. Fan-coil space heaters, together with plastic tubing used for air distribution, have almost entirely replaced radiant heating systems in new installations. Space heaters do not have certain technical advantages of the older systems, but they do not require such a massive fixed investment. They fit in well with the lower capital costs of plastic structures.

One unique source of heat has been provided by hot springs and waste heat from power stations. Iceland's greenhouses are all heated by steam from hot springs. The same practice was used in Bulgaria through 1956. In 1957, Bulgaria began using hot water from industrial enterprises and thermoelectric stations.[18] Similar systems are used in the USSR.[19] Although the heat sources are free, the systems have their disadvantages: (1) extensive piping may be involved, (2) mineral water may be corrosive or leave deposits, (3) industrial locations may have an air pollution problem, and (4) the temperature of the waste water is too low. For these reasons, Bulgaria switched to other sources of heat in 1964. The use of hot water springs also proved to be impractical in Utah.[20] However, there may be locations where such energy sources are appropriate.

COOLING

Plants themselves have a built-in cooling system in the form of transpiration of water vapor; about 50 percent of the radiant energy received by the plant is lost in this way.[21] The cooling process may be augmented by the use of forced ventilation,[22] through shading by whitewashing the glass with various forms of lime or mechanical devices, or by sprinkling the outside of the glass with water. Still, the temperatures may rise too high, and provision has long been made for ventilation to release the warm air and admit cooler outside air. The process has often been made automatic through the use of thermostatically controlled fans and other devices.

As greenhouses have moved into some of the hot arid regions of the world, such as the American southwest or West Asia, traditional cooling systems have

Plate 5—*Evaporatively cooled greenhouses in Hawaii. The square units at the front of each house are composed of batting of excelsior-type materials over which water is dripped. Air is sucked through the batting by large fans at the inside rear of the houses. The ensuing evaporation results in cooling. The houses have fiberglass covering.*

been found to be inadequate. Two adaptations of an ancient technique—evaporative cooling—have been most widely used by commercial greenhouses: mist spray, and fan and pad. The latter is by far the most common. It is very similar to the old *tatty* system for cooling houses, which involved hanging a mat of fresh straw or fiber in door and window openings and sprinkling it with water.[23] The technique was perhaps first adapted to greenhouses in Texas in 1954 and utilized power-driven fans to blow air through a water-soaked pad. The evaporation process can cool the temperature 15°F or more depending on the relative humidity. In many of the hotter regions, the relative humidity is fairly low and most growers do not have much difficulty keeping temperatures down.[24] It has been suggested that evaporative cooling might even make it possible to raise vegetables in areas like the Sudan, where summer temperatures are too high for the growth of such crops.[25]

One major problem in the provision of heating or cooling in the future may be the growing shortage of power. Although greenhouse farming makes substantial use of solar energy, it still requires supplementation by other sources of power. A small contribution can be made through devising ways to reduce heat loss.[26] Some long-run hope lies in the greater use of solar energy; solar powered heating and cooling systems, however, are only in the experimental stages.[27]

ATMOSPHERE CONTROL

The gaseous composition of the atmosphere has a significant influence on plant growth. It has long been recognized that greenhouses need to be ventilated to provide adequate carbon dioxide. What of the payoff from increasing carbon dioxide levels? What influence does relative humidity have? What are the possibilities of aerial fertilization? Over 100 years ago, Leuchars asked:

> When shall we have an instrument, equally simple and efficient as [the thermometer and hydrometer]. . .with which we may ascertain the proportion of [the air's]. . .gaseous elements, so that we can regulate the constituents of atmospheric volume as easily as we can do its heat and moisture?[28]

Atmospheric regulation has provided the key for a revolutionary new method of fruit preservation—controlled atmosphere storage.[39] Does it offer comparable opportunities for greenhouse crops?

CARBON DIOXIDE

Carbon dioxide (CO_2), along with water, is one of the two major ingredients in the process of photosynthesis. Below-normal levels of CO_2, often found in unventilated greenhouses, can reduce the rate of photosynthesis, while above-normal levels can hasten photosynthetic activity.

Early Studies of Effect on Growth

The importance of CO_2 for plant growth was perhaps first discussed by a French scientist, de Saussure, in 1804. He analyzed the effect of various carbon dioxide levels on plant growth and showed that growth was enhanced at a higher than normal concentration. He also suggested that the main value of humus to plants was through its release of CO_2.[30]

Further developments in Europe awaited the late 1800's. In 1884, a patent was awarded in Germany which covered two possible ways of adding CO_2 to field crops; it is not known whether either was actually used.[31] The following year, Kreusler reported a series of experiments on the effect of different proportions of CO_2 on the assimilation rate of plants.[32] Subsequent studies in England, reported in 1902, were not promising.[33] Demoussy, in France, attributed the poor results to impurities in the CO_2 and went on to report that a fivefold enrichment of CO_2 led to an average increase in plant weight of 160 percent.[34]

Investigations were begun in the United States by Cummings and Jones in 1909 and continued for 7 years. They revealed beneficial effects in terms of crop weight on a number of vegetables and strawberries. The authors concluded that added CO_2 appeared to function much as a commercial fertilizer and that plants "can use advantageously more than normally occurs in the air."[35]

A number of further studies were subsequently conducted in northern Europe, especially in Germany.[36] Wittwer and Robb report that:

> In some instances, yields of cucumbers and tomatoes were doubled and even tripled. Carbon dioxide enrichment of atmospheres, however, did not become a generally accepted practice. Toxic impurities were all too frequent in the products of combustion exhausted into the plant growing structures.[37]

There are, however, several sources of carbon dioxide, with differing levels of impurities, so perhaps it would be best to examine the effect of each separately.

Role of Natural CO_2

A sizable portion of the CO_2 utilized by plants in many habitats is provided by the respiration of local soil micro-organisms. The generation of CO_2, as first suggested by de Saussure, can be markedly increased by the addition of fermenting manure and other forms of organic material. On a well-fertilized field, the formation of CO_2 during a 24-hour period may equal or exceed the consumption in photosynthesis during the daylight hours.[38]

This point is important for greenhouse culture because in the past large quantities of manure have been used for some crops, particularly cucumbers. It has, for instance, been a common practice in America as well as in northern Europe, to use 200 tons of manure per acre.[39] While the manure was applied for other purposes (fertilization and/or heat), it could well have had an important secondary effect in providing CO_2.

Heavy applications of manure can also be of significance for field grown crops. For example, it is thought that some record corn yields may have partially been the result of heavy application of manure "from which large quantities of CO_2 enriching the atmosphere were evolved." Other field treatments have included liming to control soil pH, spraying with carbonated water,[40] and the application of waste furnace gases rich in carbon dioxide.[41]

In the case of either greenhouse or field culture, the beneficial CO_2 effect of manure is lost with the substitution of chemical fertilizer. This might be a particular problem in the case where hydroponics or artificial soil is utilized.

Use of Manufactured CO_2

During the 1960's, there was an upsurge of interest in utilizing CO_2 in greenhouse operations. This was due in part to the development of (1) safe and economical combustion unit sources of CO_2, (2) CO_2 monitoring devices, and (3) plastic tubing for the distribution and circulation of CO_2.[42]

The expansion first took place in Holland. It started in February 1961 when a grower used a small paraffin (kerosene) oil warming stove during the daytime hours on lettuce and obtained exceptional quality and weight: the effect was traced to CO_2. Followup work at the Glasshouse Experimental Station in Naaldwijk showed outstanding results on lettuce and strawberries and good results on tomatoes, endive, spinach, and radishes. The weight of the lettuce was increased and growth accelerated by 20 to 30 percent. During the 1962/63 season, the area of treated lettuce expanded into thousands of acres and 25 percent of the early greenhouse tomato growers used CO_2. By 1972, the total area treated in Holland was about 7,000 acres, of which 3,800 were lettuce, 2,800 tomatoes, and nearly 400 cucumbers.[43]

The most recent wave of experimental work with CO_2 in the United States began during the winter of 1961/62 at Michigan State University. Increases of 30 percent in lettuce yields were obtained; the following winter the figure rose to 70 percent—in part because extremely cold weather made it necessary to close the ventilators more than usual. Increases in tomato yields ranged from 25 to 70 percent, depending on variety, and averaged 43 percent. CO_2 proved to be especially effective in midwinter because crops in nonventilated houses quickly utilize most of the available CO_2 during the early morning hours and thereafter receive little benefit from sunlight.[44]

Further research, at the Ohio Agricultural Research and Development Center, indicated that CO_2 supply is the prime factor limiting plant growth and development under all levels of light intensity except perhaps the very lowest. In experimental work conducted since 1965, the addition of CO_2 has consistently increased tomato yields by 15 to 24 percent for the spring crop and 0 to 15 percent for the fall crop (it is usually necessary to keep the ventilators open to reduce temperatures for much of the growing period of the fall crop). It is not certain how much of an increase has been obtained in commercial practice, but one estimate for tomatoes places the range at 10 to 15 percent. Data for lettuce are more limited, but they do show that one leading grower has obtained an extra crop by using CO_2. A rough guess suggests that 50 to 60 percent of the tomatoes and 70 to 80 percent of the lettuce raised in Ohio in 1971/72 received added CO_2. Cost data are not available, but one grower calculates that he needs to get an increase of 5 percent in yield to offset the expense of CO_2 addition.[45]

Use of CO_2 in the United Kingdom seems to be heavily oriented toward the early heated tomato crop; most of the 400 acres or so in England and Wales are enriched with CO_2.[46] About 28 percent of the cropped area in Guernsey in 1970, or over 300 acres, was equipped for CO_2 enrichment.[47] Research work on tomatoes has shown yield increases of up to 90 percent on the early harvest of November-sown tomatoes and 30 percent in the total crop with proper heating.[48] Enrichment is not profitable, however, for all tomato varieties.[49]

Recent work on intensive food production at Texas A&M University has suggested a possible new dimension for the use of CO_2. Preliminary theoretical and experimental studies indicate that CO_2 enrichment is also effective in reducing water losses per unit of plant growth. Above-normal levels of CO_2, in addition to enhancing plant growth, reduce the size of stomatal openings and therefore lessen the loss of water vapor. The effect is intensified by the presence of high humidity. At first it was hoped that field applications would be possible, but subsequent analysis suggested that an enclosure would be necessary to keep the amount of CO_2 needed within an economically acceptable range.[50] (An attempt was made in California in 1965 to use one of the greenhouse CO_2 generators to force field planted cucumbers and tomatoes under plastic row covers. While the process increased plant growth, it did not notably increase fruit production or set. The effect on water use, however, was not studied.)[51]

We are far from knowing all the possible physiological interrelationships of the use of CO_2.

HUMIDITY

The relative humidity in a greenhouse is usually higher than in the open air. While all plants produce water vapor in the course of transpiration, the relative humidity in greenhouses builds up to higher levels than in the field because of the heavier plant populations and reduced air movement. Also, the level of water application may be higher, increasing evaporation from the soil. Humidity is generally controlled by ventilation, but it can be increased by misting devices and reduced by use of heating (night firing).

Just what effect different levels of relative humidity have on plant growth—as long as they are above the point of desiccation—is evidently not well understood. As early as 1857, Leuchars recognized the potential importance of humidity, and wrote of the hydrometer:

> . . .we hope the time is not distant when it will find a place side by side with the thermometer in our hot houses, to which it does not yield one iota of importance, of interest or of utility.[52]

Yet as late as 1971, University of Arizona researchers referred to "the scarcity of experimental results on the effects of atmospheric humidity on plant growth," and the conflicting results from the few studies that had been conducted.[53]

The subject has become of increasing importance in recent years because of the expanded use of plastic greenhouses. Many of these structures are more air-tight than glasshouses—and often may not be as well ventilated by artificial means. Hence humidity may build to higher levels.

Some recent studies have not shown high humidity to have a deleterious effect on plant growth. University of Arizona scientists working with air-inflated plastic structures under carefully controlled conditions found that variations in the relative humidity from 35 to 100 percent had no significant effect on growth and yield of red kidney beans; tests on taller plants were under way at the time these results were reported.[54]

A review of some earlier investigations suggests that high humidity might have at least two beneficial effects on plant growth. First, many plants can absorb moisture directly from unsaturated air of high humidity, thus supplementing soil sources. Second, the rate of photosynthesis may increase with humidity, only slowly at low light intensities but substantially at high intensities.[55]

The effect of humidity on pollination, fertilization, and fruit set is uncertain. An Ohio study has suggested that the optimum humidity level for tomatoes is about 70 percent.[56] Yet University of Arizona work has suggested that even higher levels present no problem in the presence of ample light.[57]

The effect of high humidity on the spread of disease is also an important question which has not been fully answered. Tests by the Arizona group at a facility at Puerto Penasco, Mexico, revealed that the high-humidity greenhouses remained virtually free of disease. This may have been due to the air movement or because a given volume of air in the greenhouse was put through a spray of seawater every 2 minutes.[58] Just what the disease situation would be in other high-humidity conditions is not clear.

There is, however, a difference in response among varieties to high humidity and heat. The Arizona group found that in the Mexican greenhouses, tomatoes developed in Florida and Hawaii performed well, while those commonly grown in greenhouses did not. Similarly, leaf and bibb types of lettuce did well but other types did not form marketable heads. The researchers said that generally there are one or two cultivars of each kind of vegetable that do well.[59]

The whole matter of humidity and plant growth needs further study.

AMMONIA

In the early 1800's in England, some greenhouse operators placed bird droppings in evaporating pans on top of steam pipes because:

> the ammoniacal fumes given out. . .bring the atmospheres of a Hot House to about the same state as did the old dung beds, known. . .to be so pre-eminently valuable for the restoration of sickly plants, and the vigorous growth of healthy ones.[60]

"Is this smelly practice," one writer recently asked, "something of which we have lost track. . .and have our modern glasshouse scientists and research stations proved or disproved the efficacious effect or otherwise of dungy smells on plants?"[61]

Interestingly, some recent research does shed light on two ways in which ammonia (NH_3) may be of value in greenhouse operations. Neither is as yet very fully defined.

The first ties in with CO_2 enrichment. As noted earlier, above-normal levels of CO_2 reduce the size of the stomatal openings and hence reduce gaseous exchange. Ammonia, at low doses, has been shown to keep stomatal apertures open in the presence of abnormally high levels of carbon dioxide.[62]

Second, recent studies have suggested that plant leaves absorb significant quantities of ammonia from the air. A field crop growing in air containing NH_3 at normal concentrations might satisfy as much as 10 percent of its total nitrogen requirements by direct absorption from the air. This finding may not be of immediate practical use in greenhouses, but may modify growers' attitudes towards the presence of ammonia.[63]

In either case, it appears that manure may have further beneficial effects which have not been heretofore widely realized.

* * *

Atmosphere regulation, at least with respect to carbon dioxide, has been significant in the production of greenhouse crops. Assessment of the role of humidity, ammonia, and possibly other atmospheric components must await further technological and economic study.

ROOT ZONE CONTROL

Plants absorb through their roots virtually all of the water, most of the nutrients, and some of the oxygen they utilize. Hence plants require root mediums with adequate moisture, fertility, and aeration. Greenhouses by their very nature must offer a greater degree of control over water supply than is true of field culture. The same is true, to some degree, of fertility and aeration.

The high plant population density in greenhouses means that close attention must be given to moisture control and fertilization. In the more advanced facilities, the two are linked: fertilizer is applied in solution form in the irrigation water. The amount of fertilizer applied in this way can, depending on the root medium, go as far as to provide for the complete nutrient requirements for the plants.

In the past, the application of all nutrients in solution form has been known as hydroponics. This term, however, usually applies to systems in which the nutrient solutions are recirculated. More recent commercial installations use drop or trickle irrigation, which minimizes water use and eliminates solution recirculation. The method is very similar to field irrigation except for the inclusion of nutrients. We shall refer to it, for lack of a better term, as "trickleculture."

Trickleculture is of increasing importance because of the increasing use of sand, gravel, and artificial soils. It also makes possible a significant reduction in water needs and pumping equipment requirements.

MOISTURE

Water is, along with carbon dioxide, the main chemical ingredient in photosynthesis. Since the greenhouse structure bars rainfall, water has to be provided by other means. Generally these involve the use of overhead sprinklers, perforated pipes on or beneath the surface of the soil, or hand-held hoses. In some cases furrow irrigation is used.

Water Needs

It is not clear whether greenhouses require any more water *per unit of product* than field culture. Different factors affect water loss in greenhouses than in the open. Greenhouse water loss is largely a function of solar radiation;[64] water loss in the field is the sum of many environmental factors. On balance, though, some greenhouse specialists feel that crop water loss in the open and under cover under similar weather conditions is not materially different. Yet one wonders if the water loss in actual greenhouse operation might not be less because: (1) water is applied only as needed, (2) runoff or leaching should be minimal, (3) evaporation loss may be reduced where the greenhouse structure provides a barrier to drying winds, and (4) the humidity may build to higher levels, reducing transpiration.

In any case, greenhouses, because of their high plant concentrations and generally improved growing conditions, require large amounts of water *per unit of area.* One acre of land would require about 27,000 gallons of water to equal the amount applied by 1 inch of rainfall. During the bright, hot days of the summer, it may be necessary to irrigate with this much water or more each week (on Malta, up to 39,000 gallons are required). Needs during the winter are much lower. Altogether, it is estimated in Ohio that the production of a fall and spring crop of tomatoes requires about 1 million gallons of water per acre.[65]

In most areas with greenhouses, water is no great problem. It is usually available from municipal water supplies, wells, or canals (as in the case of Holland). The cost seldom represents a major expense. But in other areas, it can be more of a difficulty because of short supplies and/or high cost. One partial solution is to collect the rainfall runoff from the greenhouse roof in a cistern.[66] Alternatively, it is possible to reduce water loss by using (1) sprinkler irrigation in place of furrow irrigation,[67] or (2) drip or trickle irrigation instead of sprinkler irrigation. (The effects of atmospheric conditions on water use have been noted in previous sections.)

Desalinized Water

Still, other sources of water may be needed. Desalinization is a possibility for some regions. Because of the expense, it might seem inconceivable that desalinized water would be used for irrigation, but it has been in some rather special cases.

Initially, these operations involved hydroponics (to be discussed in a following section). Perhaps the first units were open beds on the barren islands of Ascension in the South Atlantic[68] and on Aruba, just off the northwest coast of Venezuela.[69] A U.S. air base was located on Ascension, and Aruba was the site of an oil refinery. Work on both units was started in 1944. The hydroponic bed on Ascension was about 0.7 acre, and that on Aruba was initially one-fourth of an acre. The Aruba installation continued in operation up to a few years ago (new or additional desalinization units were installed in the late 1950's). Water on Aruba was clearly expensive—about $6,000 per acre per year. Of the water used, about 75 percent was lost to evapotranspiration. A greenhouse structure might have helped cut this loss.

Although the Island of Guernsey would hardly be expected to fall in the same category as Ascension and Aruba, it too has a water problem. The island experiences dry spells every 6 to 8 years and there is insufficient storage on the island to provide for the needs of the relatively large greenhouse area. Since greenhouse production is the economic mainstay of the island, a drought could be very expensive. A desalinization plant was opened in October 1960 to provide supplemental irrigation water during the fall. The cost of the water for horticultural use is subsidized. According to a United Nations study, "The case of Guernsey proves that, under exceptional conditions, limited areas devoid of fresh water can afford partial use of desalinated water for irrigation of high value crops even before the costs of conversion are substantially reduced."[70]

These conditions are also found in Bermuda and certain areas along the Persian Gulf. A Bermuda grower has purchased a desalting unit to provide a standby source of irrigation water (when not used for this purpose, desalted water from the unit is sold for drinking purposes). Desalinized water is used for all of Kuwait's 6.2 acres of hydroponic greenhouse installations and for the 5 acres recently placed under operation in Abu Dhabi (to be discussed later).

Two recent studies of the use of desalted water for agriculture point out that prospects are most favorable in areas capable of producing crops that produce high net farm incomes under yearlong, or nearly yearlong, growing conditions. They also recommend that techniques be developed for reducing irrigation water losses in order to lessen water needs.[71] These requirements are more easily met in greenhouses than in the open.

In some cases, it is possible that greater use might be made of solar distillation. The basic method is to admit solar radiation through a transparent cover over a shallow brine basin; water evaporates from the brine and the vapor condenses on the covers which are so arranged that the condensate flows into collection troughs. Although the idea was first applied in 1872, it is not known to have been used for growing crops.[72] Still, it might prove useful in certain situations.

In any case, it is essential to minimize desalinized water use. Toward this end, the entire greenhouse complex in Abu Dhabi makes use of trickle irrigation. Perhaps the future will also see the unveiling of other ways to reduce water use or water loss.

SOIL

Soil is the basic element of field agriculture but not necessarily of greenhouse culture. The intense method of culture in a greenhouse places a heavy load on the soil base in terms of structure, fertility, and content of disease organisms. In some greenhouse areas, it has been standard practice to renew the soil periodically. In permanent greenhouses in Japan, for example, the soil is replaced once a year or in every five to six cropping periods.[73] In others, it is sterilized to kill off disease organisms. Heavy fertilization with manure will help restore fertility and structure, and will provide a source of CO_2; chemical fertilizers do only the first.[74]

The difficulties in obtaining good soil for greenhouse soils and in disease control have led to an interest in artificial root mediums. This interest is not new—many potential mediums such as peat moss, sawdust, coconut shell, and cotton waste were studied as early as the 1930's in Holland and the 1940's in California.[75] There are currently two main forms: artificial soil and straw bales.

Artificial Soil

A large number of partially or completely artificial soils are available for greenhouse use. Peat is often used as a base in Europe—either in pure form or in combination with sand or vermiculite.[76] Two recent mixtures developed at Cornell University, for instance, are basically composed of sphagnum peat moss and horticultural vermiculite or perlite. They usually do not require sterilization, compare to good topsoil in cost, are light and easy to handle, and produce uniform plant growth.[77] On the other hand, heavy fertilization is required because most mixtures have little fertility; and low-cost combinations of ingredients are not available everywhere.

Several different tomato cultural systems are also in use with the artificial soils. Two better known ones are trough culture and ring culture (the latter is patterned after a method used for many years on the Island of Guernsey). Both involve the use of long narrow beds which are lined with plastic to make them impermeable. In the trough system, the beds are simply filled with the artificial soil. In the ring system, the beds are filled with lightweight aggregate; round rings of plastic or paper which are filled with artificial soil are then placed on the bed. Results are very similar with each system, but the ring method does seem to have an advantage in that the "soil" will warm up faster and the greater height provides for better root aeration.[78]

Many variations of these systems may be in use throughout the world. Sawdust, for instance, is being used in British Columbia.[79] And, as we will see, gravel and sand bases are used in hydroponics and trickleculture. They could well become more common in greenhouse food production.

Straw Bales

If the artificial soils seem strange, an even more peculiar innovation is provided by the use of straw bales. This method involves two steps: first, ordinary straw bales are first soaked with water for 2 or 3 days and fertilizers are then applied; second, a bed of peat or peat over manure is then placed on the bale. The bale can be placed on plastic or directly on the soil. The system was first used for cucumbers in the Lea Valley in England in 1949 and is now widely practiced.

The advantages of this system over regular soil culture are stated to be as follows: a well aerated disease-free medium, no soil cultivation required, a reduction in steam sterilization requirements, provision of heat through fermentation of the bales, a natural release of carbon dioxide, a reduction of labor, and low initial cost. The main disadvantage is that careful attention must be given to the irrigation and nutrition of the crops.[80]

Several variants of the bale system have been utilized. Straw wads may be used in place of bales. In the United States, a peat-lite mix has been used experimentally in place of a manure-peat bed.[81] In Japan, straw is simply placed between the surface soil and the subsoil. It is claimed that this method provides "easy control over the distribution of air, water, and fertilizer within the limited soil layer by cutting off capillary communication with subsoils."[82]

The knowledge that traditional soil is not necessary, nor even necessarily the best choice, for greenhouse food production means greenhouses may be less dependent on a limited resource than many may think. But with a few exceptions, these systems may be more a novelty at this point than a widely adopted practice.

HYDROPONICS

It has long been known that it is possible to dispense with soil entirely, even artificial soil, and grow plants in aerated nutrient solutions. The commercial form of this practice is known as hydroponics. It usually involves the use of some sort of material such as sand or gravel for the substrate, but all the nutrients are applied in solution form and recirculated. While there is an immense amount of published material available on hydroponics, relatively little relates to greenhouse operations.

Some of the early experimental work with hydroponics in the United States was carried out in greenhouses. In turn, the greenhouse industry reportedly showed the first interest in hydroponics; this interest stemmed from the previously mentioned problems with replacement of soils as well as problems in fertilization. As a result, research workers in a number of State agricultural experiment stations started studying different systems. During 1925-35, sand culture was studied in New Jersey and water and sand culture in California. Starting in 1934, another system known as subirrigation was investigated in New Jersey and Indiana.[83]

During World War II, the U.S. military developed a strong interest in using hydroponics to produce fresh vegetables in remote installations. Following the subirrigation system developed at Purdue, hydroponic farms were reportedly established on Ascension Island (as noted), British Guiana, Coconut Island (Hawaii), Iwo Jima, Nanking (not verified), and near Tokyo. All were located in the open except for a 5-acre greenhouse which was part of a 55-acre hydroponic installation at Chofu in Japan designed to provide for U.S. occupation forces. Construction of the greenhouse was started in 1946 and it was placed in operation early in 1947. The greenhouse was designed both to provide transplant seedlings for the outdoor installations at Chofu and Otsu and to extend the growing season from 4 months to 8 months in order to provide vegetables for patient diets in hospitals.[84] It remained in operation until the early 1960's.[85]

Considerable interest in hydroponics continued after World War II, but it is not known to what extent these systems were initially used for food crops in greenhouses. By 1969, Wittwer and Honma were able to write that commercial hydroponic culture of tomatoes in the United States "consists of a greenhouse to control the critical environmental factors." They noted however, that the costs of such installations were well above those for conventional greenhouses.[86] As of 1972, known commercial installations were as follows: Florida, perhaps 5 to 6 acres of hydroponic vegetable beds covered by plastic greenhouses;[87] Utah, about 3½ acres under fiberglass;[88] Arizona, some 14 acres in Glendale under fiberglass;[89] and Hawaii, about 2½ acres.[90] Other concentrations are found in Louisiana, Texas, Nevada, California, and Washington.[91] Scattered units are found in other States as well.

Many of these hydroponic greenhouses have been commercially manufactured. The first such units were produced in Texas; others are currently being produced in Utah and Arizona.[92] The Arizona units, for example, contain 3,300 square feet (or .075 acre). They are provided with virtually complete environmental control equipment and cost $18,200 each (erected in Glendale in early 1972). Eight may be placed on an acre of land. The units in Glendale are principally used for tomato production. Other installations—not all necessarily for commercial vegetable production—were reported in 20 States, Canada, Guam, and Lebanon.[93]

Outside the United States, greenhouse hydroponic installations for vegetables are found in Italy,[94] West Asia, Japan, and the Soviet Union. In addition to the unit in Lebanon,[95] hydroponic greenhouses are located in Kuwait on the Persian Gulf. About 74 acres were hydroponically farmed in Japan in 1968.[96] In the Russian Republic in the Soviet Union, some 25 acres of hydroponic greenhouses had been built by 1967. Out of 25 acres of glass greenhouses at the "Kiev Vegetable Factory" in the Ukraine in 1969, 15 were hydroponic.[97]

It is difficult to evaluate the prospects for hydroponics. Effective operation of a hydroponics unit involves a great deal of skill; small errors in mixing solutions or in carrying out sanitation can be costly. A Russian article cautions, for instance, that the technique should be carried out only on farms "where there exists advanced agro-technology and where there are qualified workers. . ."[98] Little factual information is available on the economics of the process, but it is known that costs are high and that many such units have fallen by the wayside in the past.

TRICKLECULTURE[99]

Trickleculture, as defined previously, is basically trickle or drip irrigation with a complete nutrient solution. It occupies a place somewhere between regular irrigation and hydroponics and combines some of the advantages of both.

Recent commercial installations have taken the following form. Sand, or in some cases gravel, is spread over the ground area to a depth of about 1 foot. This is either completely underlaid with plastic sheeting or plastic sheeting is placed under the rows as in trough culture. Small plastic tubing with minute holes in it is laid on the surface near the base of the plants. The holes are sized and placed so that only a small amount of water drips in the root area. From this point on, culture is much the same as in a regular greenhouse except for the periodic mixings of solution.

The main advantages of this system are its relatively low installation and operating cost compared with traditional hydroponic units and its adaptability to a wide variety of substrates. The total area so cultivated is not known exactly, but includes 15 acres in Arizona, a few acres in California, about 10 acres in Hawaii, nearly 5 acres in Abu Dhabi and a few acres in Canada. It will undoubtedly increase in use.

Plate 6—A *modern commercial greenhouse facility in Arizona utilizing a trickleculture system. Irrigation and fertilization, with nutrients in solution form, are provided by plastic tubing from tanks at right. The roof is composed of plastic "pillows"—two layers of plastic separated by air.*

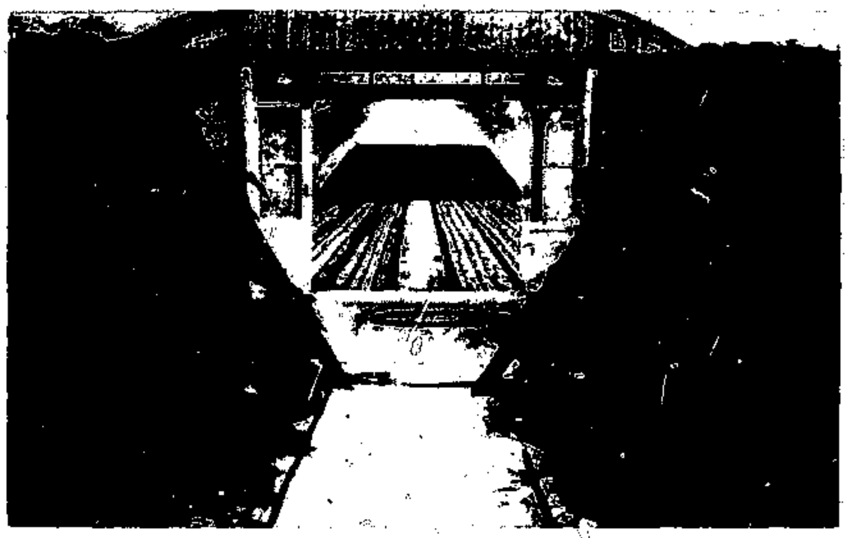


Plate 7—*A modern research facility in Abu Dhabi also utilizing a trickleculture system. Sand comprises the root medium. Individual units are air-inflated plastic "bubbles." Evaporatively cooled air is drawn in by fans at far end of structure.*

FACILITIES AND CONTROLS

Just as advances have been made in the individual components of environmental control, advances have been made on other fronts. Of special importance are structural innovations and automatic control mechanisms. All these factors, in turn, have been combined in some highly advanced growth facilities.

STRUCTURAL INNOVATIONS

The basic glass greenhouse structure has not changed greatly in a century. The major changes have been refinements to allow for control of specific environmental factors. Improved construction techniques and materials (including larger panes of glass) have, however, made possible wider spans with fewer obstructions to block light transmission. Here we will look at the use of plastic and at vertical mechanized structures.

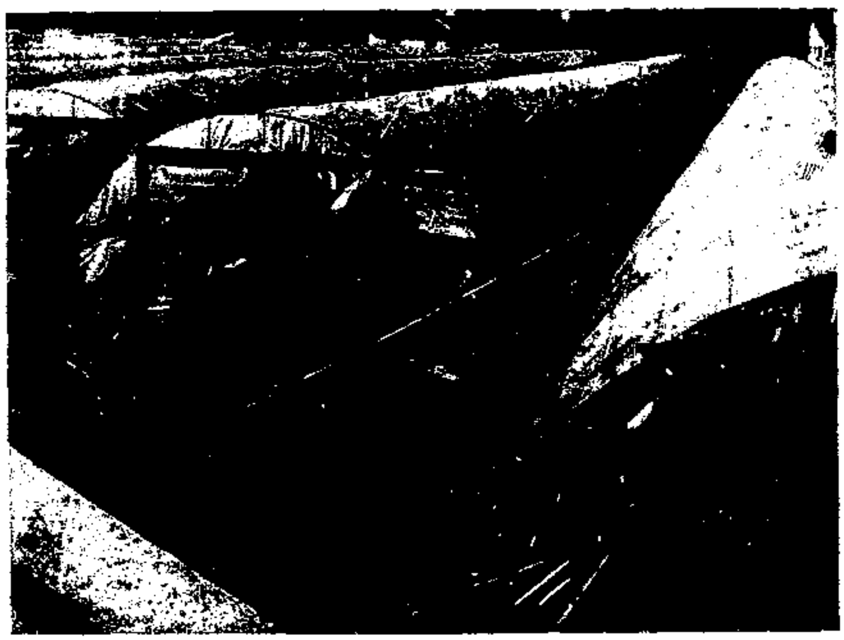
Plastic Greenhouses

The major shift in the post-World War II period has been the adoption and widespread use of plastics as a covering.[100] In the early years, plastic did not offer a qualitative improvement over glass in terms of environmental control. But plastic was considerably cheaper and lighter (less expensive framing was needed). The combination meant that greenhouse culture could be extended into areas—such as the Mediterranean and East Asia—where greenhouse culture was not previously economical. With technical improvements in plastic greenhouse construction, the qualitative difference between it and glass in terms of environmental control has narrowed. Plastic covered houses are now in wide use throughout the world and represent the largest share of new greenhouse construction.

Emory M. Emmert of the University of Kentucky had a key early role in the development of the plastic greenhouse in the United States. Because he could not afford a glass greenhouse in 1948, Emmert designed narrow wooden structures covered with wooden frames with cellophane film stretched over supporting form wire.[101] He grew commercial crops of lettuce, tomatoes, and bedding plants in these structures for several years. When polyethylene became available a few years later, he used it for a small privately-owned range. The first plastic greenhouse was constructed at the Kentucky Agricultural Experiment Station in the winter of 1953/54; it was still functional in 1967.[102]

In Europe, experiments involving plastic (dialux) were reported as early as 1945.[103] Polyethylene (also known as polythene) was perhaps first used in the early 1950's in Scandinavia to line the inside of glasshouses to reduce heat loss. The first polyethylene-covered house in the United Kingdom was erected in November 1955.[104] Growth in the use of plastic in Europe was fairly slow until the 1960's, when widespread use began in Russia and southern Europe.[105] In the case of southern Europe, and elsewhere in the Mediterranean region, houses are of simple design, and environmental control is minimal.

Plate 8—*Simple and inexpensive plastic-covered greenhouses in Turkey. Similar units are found elsewhere in the Mediterranean region and in East Asia.*



Commercial adoption of plastic greenhouses in the United States was also slow at first, mainly because of problems in ventilation and heating. For the plastic houses to retain their low-cost character, inexpensive methods had to be found. The space heater offered a solution, but methods had to be worked out for even distribution of the warm air; plastic tubing is now widely used. In warmer weather, ventilation by large fans proved feasible and has been widely used.

Another problem was that single layers of plastic covering are not as effective as glass in reducing heat loss.[106] Furthermore, single-layer coverings also collect a great deal of condensation underneath—reducing light transmission, and sometimes leading to disease problems. These difficulties were partly solved by the use of two layers of plastic with an air space between. Depending on temperatures, this method also resulted in a 30- to 40-percent saving in fuel bills.

Since the plastic used in the early houses had to be replaced every year because of deterioration induced by the ultraviolet rays of the sun (newer materials will last 2 to 3 years in northern latitudes), a considerable amount of labor was involved, especially for the double-wall houses. Growers and researchers began to investigate other methods of handling the second layer. In the late 1950's, a Minnesota grower started to use air pressure to separate the two layers. Subsequent research at Rutgers University led to further development of this method. Essentially, one piece of plastic is simply spread over a regular plastic-covered house; inflation is provided by small squirrel cage blowers. The smooth unbroken layer easily sheds snow.[107] Several new greenhouses in Arizona combine conventional framing, fiberglass walls, and a roof of inflated plastic "pillows" (see plate 6).[108]

Air has also been used as a method of supporting the greenhouse structure. In 1959, scientists at Washington State University built three air-supported plastic greenhouses. In 1960, a second layer of plastic was added to reduce heat loss and reduce condensation.[109] Further research on both air-supported and air-inflated (pneumatically rigid) houses was done at Rutgers.[110] Subsequently, a U.S. rubber company developed a much larger structure held in place by cables. A double-wall unit covering 1 acre was erected on an Ohio vegetable farm in 1969, and a 1.3-acre unit was installed in a hydroponic vegetable farm in Houston, Tex., in 1972.[111]

What are the advantages and disadvantages of the air-inflated structures over those supported by more conventional means? The most obvious advantage is their wide unobstructed span: the elimination of framing increases light transmission and makes possible the use of large equipment. The use of fans for inflation provides a built-in ventilation system, readily adapted for evaporative cooling. Double-wall plastic reduces condensation and heat loss. On the other hand, the covering must be replaced every 3 to 5 years. Operation of the inflation fans adds to operating costs. To the extent that outside air is introduced for inflation, the costs of CO_2 fortification may be increased. Framing must be installed so that plants can be tied up. The relative initial capital cost is a moot point: prices quoted by a leading firm in 1972 suggest that they cost

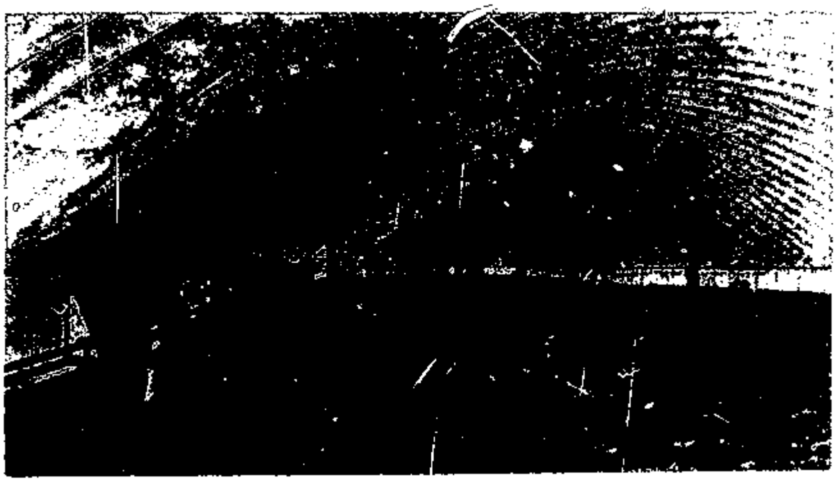


Plate 9—*Interior of a large air-inflated plastic greenhouse in the United States. Note the wide clear span. Although this particular unit is used for growing roses, similar structures have been erected for vegetables.*

less than some new metal and glass units but considerably more than wood and plastic film units.[112]

While initial adoption of the air-inflated structures has been slow in agriculture, their rate of adoption could increase as relative costs decrease and as growers develop cultural techniques to better utilize the clear span.

Vertical Mechanized Greenhouses

Greenhouses are virtually always low, one-story structures, with most production steps carried out by hand. But they do not have to be.

In 1964, a tower greenhouse 130 feet high was built for the International Flower Show in Vienna. The plants were placed on trays on a continuously moving vertical conveyor belt. Similar structures have also been built in several other European nations and Canada for floral crops. Crops reportedly mature more quickly than in conventional houses; the structure is easy to heat (as heat rises), is 10 to 15°F cooler in the summer, and has a short watering time.[113] On the other hand, European studies have indicated that they do not use solar radiation efficiently and give nonuniform growth.[114] The conveyor system is best adapted to short crops. None are known to be used commercially for food crops.

The tower houses, however, raise the idea of making more efficient use of the vertical space in existing greenhouses. Some crops such as tomatoes are tied up to stakes or wires and do utilize much of the space; others such as lettuce and strawberries do not. Vertical growing stands have been utilized for strawberries in Italy, but it is not known if they are widely used. A comparable solution will be more difficult for lettuce because of its shorter growing season and lower value.

The vertical houses also raise the question of designing structures for mechanized handling of greenhouse crops. The matter is being studied in Europe, particularly in Holland. Already lettuce production in greenhouses can be completely mechanized.[115]

The greater use of vertical space and mechanization will be an increasingly important matter in the future.

CONTROL MECHANISMS

Environmental control can be, as the previous pages may have suggested, a very complex process. Although I have treated environmental factors individually, each interacts with others so that a combination of effects must be considered. Except in the very simplest greenhouses, management of these factors can require a high degree of skill.

A number of mechanical and electronic devices have been introduced in recent years to assist in commercial greenhouse operation. At first, the devices were relatively simple—such as thermostatically controlled heat. But as technology has advanced, control units for more than one environmental factor have been introduced.

A very brief, nontechnical review of control mechanisms includes the following:

(1) Automatic light control. Too much light is seldom a problem in food production unless linked to high temperature; and ventilation is the cheapest way to reduce heat. Still, it may be desirable to reduce light transmission in some cases, and automatic shading devices have been built though are not widely used. Artificial illumination may, of course, be easily controlled by electronic or mechanical devices.

(2) Automatic ventilation. Since ventilation is usually used for heat control, the process can be simply controlled by a thermostat. This is particularly true if—as is usually the case in plastic houses—a fan is involved. If natural ventilation through vents is involved, as is often the case in glasshouses, the process is mechanically more complicated. Fans are, as we have noted, also used for wet pad cooling systems.

(3) Automatic humidity control. Humidity can be lowered by increasing ventilation. The need is generally greatest during the day and is less during the night when cooler temperatures prevail. Economical control devices are commercially available.

(4) Atuomatic carbon dioxide control. Generally, carbon dioxide is provided by a combustion unit. The units may be set by timers to operate in the daytime when photosynthesis takes place. Infrared gas analyzer controls activated by CO_2 levels are quite expensive at the present but a single unit can be used to control several greenhouses.[116]

(5) Automatic watering. Watering may be easily controlled automatically through the use of timers. Soil sensors which reflect the moisture level in the soil are available but are often thrown off by salts; a new device is said to avoid this problem.

The commercial hydroponics unit noted in the previous section has automatic controls for supplying nutrients and for temperature and humidity control. More complicated control devices are being developed which, while presently in the realm of the research greenhouse or growth chamber, may eventually find commercial use. One English mechanism will:

> . . link heating and ventilating, control the CO_2 concentration and relate temperature and CO_2 concentration to the prevailing light intensity. It is also possible to include an over-riding control of humidity to prevent the rise of R.H. above a set level.[117]

Experimental work with light-modulated temperature control has recently been reported in England and Holland.[118] And the linking of artificial light in combination with CO_2 enrichment is considered promising.[119] While the list is impressive, scientists and engineers still have a considerable way to go before optimum technical combinations are reached.

Another question that cannot be answered without considerable further investigation is the economic one: how far is it economically worthwhile to carry the use of automatic control devices? The costs of simple thermostats or timing mechanisms are not great, but it may be more expensive to hook them up. Other devices may cost much more to install and repair. One needs to consider whether automatic controls can do the job better or more cheaply than humans. None of the environmental control tasks discussed in the preceding pages, except possibly watering, are very time-consuming in themselves. But continuous monitoring may be needed so that the needed tasks are carried out when environmental conditions change. The skilled labor required to do this is often scarce or high priced. Under such conditions, the benefits of automatic controls could outweigh the cost.

ADVANCED GROWTH FACILITIES

The advent of advanced techniques of environmental control together with innovations in structure and control mechanisms means that the greenhouse of tomorrow may be quite different in nature from the unit of the past. In some cases it may not even be a greenhouse, but rather a closed chamber with complete environmental control including artificial lighting.

It cannot be claimed that the packaging of environmental control elements into sophisticated units is entirely new from a research point of view. Complex research units now known as phytotrons were placed in operation as early as 1924 and 1939 in the United States.[120] But their combination at the commercial level is more recent.

As the degree of environmental control advances, it will be increasingly possible, technologically, to avoid local environmental restraints. Two examples are particularly worthy of mention. One is composed of greenhouse complexes in barren desert areas. The other is represented by the growth chamber, a research tool which is finding increased commercial use.

Desert Complexes

Webster defines a desert as an arid barren tract incapable of supporting any considerable population without an artificial water supply. Surely this is the

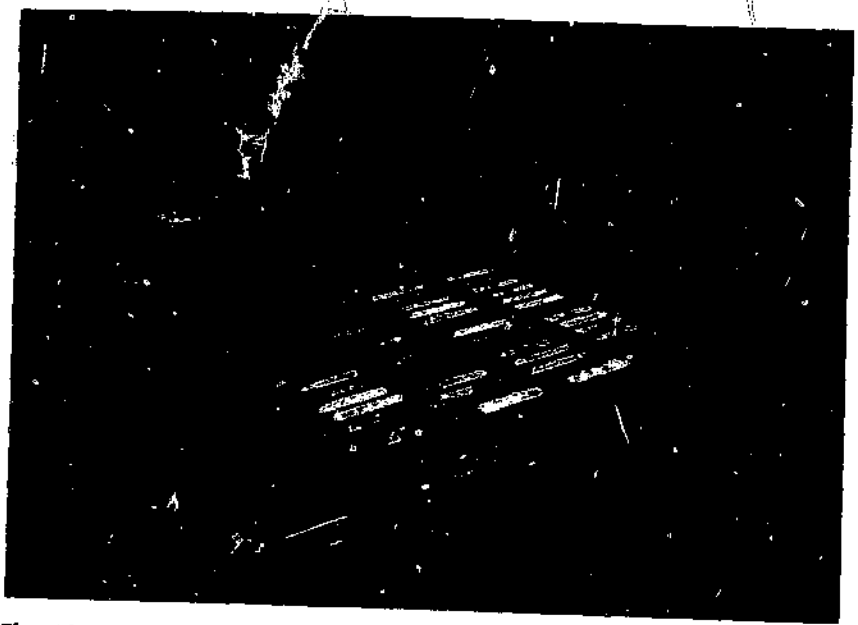


Plate 10—*Arid Lands Research Center in Abu Dhabi. The Persian Gulf is at top. The tanks at the left contain desalted water produced in the building to the immediate right. Two types of greenhouse structures are evident: large fiberglass-covered units at each end, and smaller air-inflated units in between. All are evaporatively cooled with salt water.*

last kind of place where one might expect to find a greenhouse. But if the desert is short on water, it is long on sunshine and sand. Greenhouse complexes have been developed in Puerto Penasco in northern Mexico and Abu Dhabi on the Persian Gulf by the Environmental Research Laboratory at the University of Arizona.[121]

The complexes represent an extremely high degree of environmental control in an otherwise inhospitable region. Soil is absent, so a trickleculture system (sand base) is utilized. Fresh water is also absent, so both units—which are located on the coast—make use of desalted water. The power for desalinization is provided by heat exchangers attached to the exhaust and water jackets of diesel engines which drive the electric generators. To reduce water loss from evaporation and transpiration, virtually air-tight plastic greenhouses are used. The result is, paradoxically, a very high humidity. Cooling is accomplished by blowing the air through a honeycomb of corrugated asbestos over which seawater is sprayed. By regulating the rate of flow, the seawater can also be used for heating. (In the process, some seawater evaporates, further enhancing the humidity level.) Experiments have been made to utilize engine exhaust as a source of CO_2 but as yet it has not been possible to sufficiently remove impurities. When varieties are selected which are tolerant of warm humid climates, the system seems to work technically.

All of this is a striking technological accomplishment. Virtually self-contained units are a definite possibility for desert regions. The big unsettled question at the moment is one of economics. A key factor is water consumption; desalted water is, as we have noted, expensive. Water consumption needs in plastic greenhouses with trickle irrigation and high humidity in Arizona, however, were found to be about 30 percent of those required in conventional greenhouses.[122] If similar or greater reductions can be realized elsewhere, it may bring the cost of desalted water down to economic levels.

Even so, it may not be economical to produce some vegetables during the 2 hottest months of the year. Water losses and high temperatures, despite the steps taken, may be just too great for some crops. It may be more appropriate in certain instances to use the period to carry out annual repairs and maintenance.

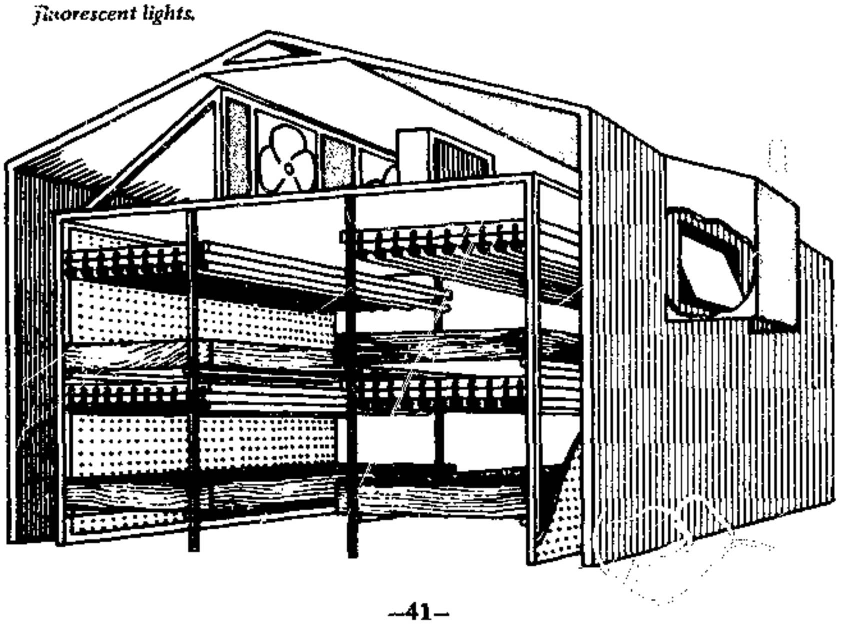
Further details on the Abu Dhabi complex are provided in chapter V.

Growth Chambers and Growing Rooms

Growth chambers and growing rooms are basically small insulated rooms or cabinets with full environmental control. Unlike greenhouses, they make no use of sunlight, but rely completely on artificial lighting. Hence they offer the present ultimate in liberation from natural environmental factors. While it is difficult to draw a precise definitional line, growth chambers are usually relatively small and sophisticated units used for research, and growing rooms are usually larger and less complex units used commercially.[123]

Growth chambers have been used at least since 1924. It was not until the late 1950's and early 1960's, however, that their commercial potential for markedly shortening the time required to raise plants from seedlings to the

Plate 11—*Drawing of typical growing room in England. Seed beds are covered by banks of fluorescent lights.*



transplant stage began to be realized. Prototype growing rooms were developed and commercial use began in England and Holland in the mid-1960's. By the early 1970's, they were reported, for example, to be "well-established" in early tomato production in Ireland.[124]

In the United States, growing rooms were first adopted by bedding plant growers and then taken up by some northern greenhouse vegetable growers. The impetus for much of this development was provided by research initiated in 1966 at the Phyto-Engineering Laboratory of the U.S. Department of Agriculture at Beltsville, Md.[125] The USDA studies revealed dramatic increases in the early growth of lettuce, tomato, and cucumber seedlings—so much so that the researchers believe that the greenhouse may some day be obsolete in the propagation of seedlings of high-value crops.[126]

While growing rooms seem destined to have an increasingly important role in the raising of transplants, it is an open question whether they are likely to be used to raise plants to the harvest stage. There is some thought that the accelerated rate of growth that is possible may offset the added cost of artificial lighting. Initially, such use would probably be limited to small high-value crops in areas or seasons where natural light is very limited and/or the natural temperature very low.[127] The rooms, however, could conceivably have a multitude of uses—for starting plants of various types (food or ornamental) at some times and for raising food crops to the harvest stage when prices are particularly high.

Growth chambers and growing rooms, therefore, offer considerable technical promise and are well worth keeping a close eye on. They could prove to be the next stage of environmental control beyond greenhouses in some locations and for some purposes. Time will tell.

* * *

Both types of advanced growth facilities—desert complexes and growth chambers or rooms—are exciting technological developments. But before one gets too enamored with them, he had better turn to the more sobering question of the economics of environmental control in general. We do this next in terms of commercial greenhouse operations.

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In the sun, hot westerly wind	118°F
In the shade, in the wind	110°F
In a tatty-cooled house	87°F

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67. This is the case in the Canary Islands, where the use of sprinklers has reduced water use by 40 to 50 percent (M. Robledo, "Plastics Applications in Spanish Agriculture," *Plasticulture*, Paris, March 1971, p. 13). The relative efficiency of sprinkler and furrow irrigation under field conditions is discussed by Jack Keller in "Effect of Irrigation Method on Water Conservation," *Journal of Irrigation and Drainage Division, Proceedings of ASCE*, June 1965, pp. 61-72.

68. "Army Grows Miracle Salad on Bare Mid-Atlantic Rock," *Newsweek*, May 21, 1945, p. 116; W. Robert Moore, "Greens Grow for GI's on Soilless Ascension," *National Geographic*, August 1945, pp. 219-230; D. R. Hoagland and D. I. Arnon, *The Water Culture Method for Growing Plants without Soil*, University of California (Berkeley), Agricultural Experiment Circular 347, rev. January 1950, p. 11.

69. Maxwell Bentley, *Commercial Hydroponics*, Bendon Books, Johannesburg, 1959, p. 79; *Water Desalinization in Developing Countries*, United Nations, ST/ECA/82, 1964, pp. 45, 65, 68.

70. *Water Desalinization. . . , op. cit.*, pp. 45, 144, 146, 147.

71. *The Value of Desalted Water for Irrigation*, U.S. Department of the Interior, Office of Saline Water, June 1969, p. 10; "Case Studies of Desalted Water for Irrigation," U.S. Department of the Interior, Office of Saline Water, December 1971 (draft copy), p. 20. Also see Marion Clawson, et al., "Desalted Seawater for Agriculture: Is It Economic?" *Science*, June 6, 1969, pp. 1141-1148.

72. *Solar Energy. . . , op. cit.*, pp. 17-18. Also see: *The Sun, the Sea, and Fresh Water; Solar Distillation Technology*, U.S. Agency for International Development, Office of Engineering, November 1966, 30 pp.; and *Solar Distillation as a Means of Meeting Small-Scale Water Demands*, United Nations, Department of Economic and Social Affairs, 1970, 86 pp.

73. Ichiro Kato, "Future Prospects of Equipped Horticulture," *Farming Japan*, November 1969, p. 11.

74. According to Cornell greenhouse specialists, sterilization of the soil for tomato plants must be done at least once a year. Steaming is the best method and chemicals provide a poor second. But steaming requires special equipment and it is practically impossible to completely decontaminate soils throughout the entire root zone (Raymond Sheldrake, Jr., and Stewart Dallyn, "Production of Greenhouse Tomatoes in Ring Culture or Trough Culture," Cornell University (Ithaca, N.Y.), Vegetable Crops Mimeo 149, March 1969, pp. 1-2.)

75. Letter from E. W. B. van den Muijzenberg, Wageningen, Holland, November 8, 1972; K. F. Baker, *The U.C. System for Producing Healthy Container-Grown Plants*, University of California, Division of Agricultural Sciences, Manual No. 23, September 1957, pp. 3, 12, 93.

76. References to European work in this area may be found in: F. Penningsfeld, *Hydrokultur und Torfkultur*, Eugen Ulmer, Stuttgart, 1966 (French translation titled *Cultures Sans Sol et Sur Tourbe*, La Maison Rustique, Paris, 1969); G. F. Sheard, "Loamless Composts in Modern Horticulture," *Span* (U.K.), January 1969, pp. 35-38; and "Loamless Composts," Query File No. 5933. (84 References, 1947-1971), Commonwealth Bureau of Horticulture.

77. James W. Boodley and Raymond Sheldrake, Jr., *Cornell Peat-lite Mixes for Commercial Plant Growing*, Cornell University (Ithaca, N.Y.), Extension Bulletin 1104, November 1967.

78. Raymond Sheldrake, Jr., and Stewart Dallyn, *Production of Greenhouse Tomatoes in Ring Culture or in Trough Culture*, Cornell University (Ithaca, N.Y.), Vegetable Crops Mimeo No. 149, March 1969.

79. E. F. Maas and R. M. Adamson, "Soilless Culture for Greenhouse Tomatoes in Coastal British Columbia, Canada," in *Proceedings, World Congress on Hydroponics, November 1969*, Wageningen, Holland, pp. 116-117; "Greenhouse Industry Gains Ground in Canada," *American Vegetable Grower*, November 1972, p. 32.

80. P. G. Allen, "Growing Glasshouse Crops on Straw: A Survey of Recent Developments," *NAAS Quarterly Review* (U.K.), Summer 1968, pp. 167-169.

81. Stewart Dallyn, et al., "Growing Media Comparisons for Greenhouse Tomatoes," *Proceedings of the North American Greenhouse Vegetable Conference, September 1970*, Pennsylvania State University (University Park), Department of Horticulture, p. 70.

82. Kato, *op. cit.*, p. 12.

83. *Nutriculture*, War Department Technical Manual, TM 20-590, July 1946, Washington, D.C., pp. 3-4. Also see: Hoagland and Arnon, *op. cit.*, p. 11; and R. B. Withrow and J. P. Biebel, *Nutrient Solution Methods of Greenhouse Crop Production*, Purdue University, Agricultural Experiment Station Circular No. 232 (revised), October 1938, 20 pp.

84. "Special Study of the Hydroponic Project in Japan," Headquarters, Eighth Army, 10th Information and Historical Service (1947), pp. 2, 4, 12, 15, 17. For more general detail on these operations, see: "Army Grows. . . ," *op. cit.*; Moore, *op. cit.*; Carleton Ellis, M. W. Swaney, and Tom Eastwood, *Soilless Growth of Plants*, Reinhold, New York, 1947, pp. 42-44 (illustrated); William D. Jackson, "The Farming Quartermasters," *The Quartermaster Review*, March-April 1952, pp. 30, 131-132; and "Cinder Farm," *The Quartermaster Review*, September-October 1945, pp. 42, 43.

85. Based on conversations with James Lynn, Army History Center, Fort McNair, Washington, D.C. Housing for the Olympic games was erected on the site. For further detail on the Chofu operation, see "Hydroponic Vegetable Production in Japan," *Market Growers Journal*, June 1957, pp. 16-19.

86. S. H. Wittwer and S. Honma, *Greenhouse Tomatoes; Guidelines for Successful Production*, Michigan State University Press, East Lansing, 1969, pp. 83-85.

87. Conversation with James Montelaro, Department of Vegetable Crops, University of Florida, Gainesville, February 25, 1972.

88. Gurgel, *op. cit.*, p. 40.

89. Based on information provided by M. L. Lentz, President, Hydroculture, Inc., Glendale, Ariz., May 27, 1972 (the gross area was 24 acres, but deduction of area between the houses reduces the net covered area to 14 acres); *Annual Report 1971-1972, Environmental Research Laboratory, University of Arizona/Arid Lands Research Center, Abu Dhabi*, pp. 18, 21.

90. Visit with Kent Ellis, Environmental Farming of the Pacific, Inc., Honolulu, March 30, 1973.

91. Based on information provided by S. H. Wittwer, Agricultural Experiment Station, Michigan State University, East Lansing, September 13, 1972.

92. Gurgel, *op. cit.*, p. 37; Wittwer, *op. cit.* (1972).

93. Lentz, *op. cit.*

94. R. H. Stoughton, *Soilless Cultivation and Its Application to Commercial Horticultural Crop Production*, FAO, PL:FVC/1, Rome, 1969, p. 27. For detail, see Franco Massantini, "Le Colture Idroponiche," *L'Italia Agricola*, November/December 1968, pp. 1137-1172.

95. This unit is being financed by UNDP/FAO and is part of Lebanon's Green Plan. It is discussed in greater detail in chapter V.

96. Yutaka Hori, "The Present Situation of Hydroponics in Japan and the Standard Formula for the Construction and Managements," *Proceedings World Congress on Hydroponics, November 1969*, Wageningen, Holland, p. 21.

97. *Kartofel i Ovoshchi* (Potatoes and Vegetables), Moscow, March 1968; Gardner, *op. cit.*, pp. 178-179; G. F. Sheard and L. A. Darby, "Report of a Visit to the U.S.S.R. . . .to Study Protected Cropping and Cognate Research or Experimental Work, 7-28 June, 1967," Glasshouse Crops Research Institute, Littlehampton, England, December 1968, p. 13 (some economic data for the Kiev operation are summarized on p. 14).

98. *Kartofel i Ovoshchi, op. cit.*

99. This section is based on discussions with Kent Ellis of Hawaii (*op. cit.*, March 30) and Merle Jensen of the Arid Lands Research Center, Abu Dhabi, April 9, 1973. Also see Merle Jensen, "The Use of Polyethylene Barriers Between Soil and Growing Medium in Greenhouse Vegetable Production," *Proceedings of the National Agricultural Plastics Conference*, 1971, pp. 144-150.

100. No attempt will be made to discuss in detail the many forms and relative merits of the many plastics used for greenhouses. Suffice it to say that the two major types from a chemical point of view are polyethylene and polyvinyl chloride (PVC): polyethylene is fabricated as a flexible film; PVC may be fabricated as either a film or as semirigid sheeting. Polyethylene film is easily the most widely used of the plastics. In the United States, fiberglass is more commonly used for sheeting than PVC. Further technical detail on plastics may be found, *inter alia*, in J. A. Sondern, *Plastic Films Used in Horticulture*, Instituut voor Tuinbouwtechniek, Wageningen, Holland, September 1972, pp. 1-12.

101. In this respect, the plastic house resembled the early glasshouses built out of sashes. Comparison is also suggested with the paper covered houses erected in England in the 1700's (see ch. II). Transparent coverings were available as early as 1920 for chicken houses, but it is not known whether they were used for commercial greenhouses.

102. D. J. Coker and C. E. Chaplin, "A Review of Plastic Greenhouses: The Problems, Prospects, and Possibilities," *Hort Science*, Spring 1967, p. 7. Also see E. M. Emmert, *Low-Cost Plastic Greenhouses*, Kentucky Agricultural Experiment Station Progress Report 29, 1955.

103. J. J. Doesburg and E. W. B. van den Muijzenberg, "Eenige Orienteerende Proeven met 'Dialux'," *Mededelingen Directeur van de Tuinbouw*, Wageningen, December 1945 (Vol. 8), pp. 248-251.

104. H. R. Spice, *Polythene Film in Agriculture,* Faber and Faber, London, 1959, pp. 20, 48.

105. Use of plastic is particularly heavy in the Mediterranean region. See Jean-Claude Garnaud, *L'Intensification des Productions Horticoles du Basin Mediterranean par la Culture Protogee,* FAO, Rome, AGPC: Mis/10, 1971, 146 pp.

106. See Spice, *op. cit.,* pp. 42-43. This situation is perhaps most critical in unheated houses. Spice indicated that crops in plastic houses were often 7 to 10 days later in reaching maturity. On the other hand, given equal ventilation, the houses might be cooler in the summer.

107. Ray Sheldrake, Jr., "Air Makes the Difference," *American Vegetable Grower,* January 1971.

108. *Annual Report 1971-1972 . . . , Arid Lands Research Center, Abu Dhabi, op. cit.,* p. 18.

109. I. G. Sobek, W. E. Matson, and D. Jordin, "Air-Supported Plastic Greenhouses," *1961 Washington Farm Electrification Committee Report,* Washington State University (Pullman). Agricultural Experiment Station, pp. 1, 9, 11.

110. William J. Roberts, "Air-Inflated and Air-Supported Greenhouse Structures," *Proceedings of the Tenth National Agricultural Plastics Conference November 1971* (ed. by J. W. Courter), University of Illinois (Urbana), pp. 103-109.

111. Articles about the Ohio structure appeared as follows in the *American Vegetable Grower:* June 1969, pp. 30, 32; November 1969, pp. 30, 32; November 1971, pp. 18, 22. The Houston structure was noted in: *The Wall Street Journal,* August 28, 1972; *The Houston Chronicle* and *The Houston Post,* August 24, 1972. Tests were also conducted with air-inflated structures in England (*The Grower,* October 23 and 30; *American Vegetable Grower,* February 1967, pp. 38-39) and in Germany.

112. Comparative capital cost data are provided in chapter IV.

113. "Tower Greenhouses. . .Is There a Future for Them in the U.S.?" *American Vegetable Grower,* November 1966, pp. 15, 42; "Canada's Tower Greenhouse," *American Vegetable Grower,* March 1968, p. 36. Also see: Donald C. Spelman, "Tower Houses are Practical and Sound," *The Grower* (London), October 3, 1964, pp. 588-591; E. W. B. van den Muijzenberg, "Klimaatvorming," *Kassenen Verwarming,* Instituut voor Tuinbouwtechnick, Wageningen, Holland, Mededeling No. 55, 1964, pp. 3-8; O. Ruther, "Tower Glasshouses," *Acta Horticulture* (The Hague), No. 2, 1965, pp. 55-58; Enzo Manfredi, "Meccanizzazione e Razionalizzazione del Lavro," *L'Italia Agricola,* November/December 1968, pp. 1085-1086.

114. L. G. Morris, "Conventional Greenhouse Admits More Light," *The Grower,* (London), October 3, 1964, pp. 591-592; letter from G. F. Sheard, Glasshouse Crops Research Institute, Rustington, England, November 14, 1972 (referring to the work of H. J. Daunicht in West Berlin).

115. See, for example: D. C. Spelman, "Conveyor Belt Growing is on Its Way," *The Grower,* October 10, 1964, p. 647; Muijzenberg, *op. cit.;* Manfredi, *op. cit.;* and J. C. J. Kuiken and C. P. Andrea, "Transportsystem in Kassen," *Jaarverslag 1971,* Instituut voor Tuinbouwtechnick, Wageningen, Holland, Publikatie 72, pp. 80-82 (2 drawings, English summary).

116. W. M. Bailey, et al., "CO_2 Systems for Growing Plants," *Transactions of the ASAE,* March-April 1970, pp. 263, 268.

117. G. F. Sheard, "Crop Production Under Glass," *Journal of the Royal Agricultural Society of England,* 1967 (Vol. 128), p. 187.

118. Hand and Soffe, *op. cit.,* p. 381; G. H. Germing, *Developments in the Control of the Glasshouse Climate,* Instituut voor Tuinbouwtechnick, Wageningen, Holland, Publikatie 46, November 1969, pp. 3-6.

119. Wittwer and Honma, *op. cit.,* p. 22; Stoner, *op. cit.,* pp. 17-18.

120. Two major research units are particularly worthy of historical note: the Boyce Thompson Institute in Yonkers, N.Y.; and the Earhart Plant Research Laboratory at the California Institute of Technology in Pasadena.

The Boyce Thompson Institute opened in 1924 with extraordinary facilities for the time. Greenhouses were provided with precise temperature and humidification control (temperature was controlled within 1° and humidity to 2%) and supplementary carbon dioxide (initially scrubbed gas from the boiler). Two greenhouses had powerful outside lighting from lamps placed on massive gantry cranes. The Institute also had two growth chambers with complete environmental control. ("Organization - Equipment - Dedication," *Contributions from Boyce Thompson Institute for Plant Research*, January 1925, 58 pp., illustrated; William Crocker, *Growth of Plants; Twenty Years' Research at Boyce Thompson Institute*, Reinhold, New York, 1948, ch. 9, pp. 285-342.)

The Earhart Laboratory, often referred to as a phytotron, was constructed in 1948/49; it incorporated two air-conditioned greenhouses built in 1939 (F. W. Went: *The Earhart Plant Research Laboratory*, Chronica Botanica, 1950 (Vol. 12, No. 3), pp. 91-108; *The Experimental Control of Plant Growth*, Chronica Botanica, 1957 (Vol. 17), 343 pp.). The Earhart phytotron was the forerunner of a number of other such units around the world (see R. O. Whyte, *Crop Production and Environment*, Faber and Faber, London, 1960, pp. 147-160).

121. The Puerto Penasco operation and early plans for Abu Dhabi are summarized in two articles in the February 1971 issue of *HortScience*: C. N. Hodges and C. O. Hodge, "An Integrated System for Providing Power, Water, Food for Desert Coasts," pp. 30-33; M. H. Jensen and M. A. Teran, "Use of Controlled Environment for Vegetable Production in Desert Regions of the World," pp. 33-36. Further details of the Puerto Penasco operation are provided in Merle H. Jensen and Hamdy M. Eisa, *Controlled-Environment Vegetable Production: Results of Trials at Puerto Penasco, Mexico, 1968-1970*, University of Arizona (Tucson), Environmental Research Laboratory, 1972, 118 pp. More current information on the Abu Dhabi operation is provided in Miguel R. Fontes, "Controlled-Environment Horticulture in the Arabian Desert at Abu Dhabi," *HortScience*, February 1973, pp. 13-16.

122. O'Leary and Knecht, *op. cit.* (fn. 45), p. 264; Merle H. Jensen, Miguel Fontes, and Roberto Sau, "Calcium and Phosphorus Availability and Uptake," in Jensen and Eisa, *op. cit.*, p. 82.

123. The simplest form of a growing room is known as a propagation unit. Drawings and pictures of growing rooms used commercially are provided in *Growing Rooms: A Guide to the Practical Design of Installations*, Growelectric Handbook No. 1, The Electricity Council (30 Millbank, London), May 1972, 72 pp. A simple propagation unit is described in *Propagation Unit for Plants*, U.S. Department of Agriculture, Miscellaneous Publication No. 1215, December 1971, 2 pp.

124. *Growing Rooms. . ., op. cit.*, p. 1; G. H. Germing, *Opkweek en Teeltresultaten van Kunstmatig Belichte Tomatenplanten* (The Raising and Cropping of Artificially-Illuminated Tomato Plants), Instituut voor Tuinbouwtechniek, Wageningen, Holland, Mededeling No. 53 (mid-1960's), 62 pp. (summary and picture captions in English); T. O'Flaherty, "Growing Rooms are Now Established in Early Tomato Production," *Farm and Food Research* (Agricultural Institute, Ireland), September-October 1971, pp. 119-120. In such chambers, the growing time is compressed from 6 to 8 weeks to about 2 weeks.

125. This research has spawned a large number of research reports, many of them relating to bedding plants. For a summary of some of the early work, see D. T. Krizek, W. A. Bailey, H. H. Klueter, and H. M. Cathey, "Controlled Environments for Seedling Production," *Proceedings of the International Plant Propagators Society*, 1968, pp. 273-280. Popular articles also appeared in the *1968 Yearbook of Agriculture*, pp. 4-8 and in *Agricultural Research* (both USDA), March 1969, pp. 3-5.

126. D. T. Krizek, W. A. Bailey, H. H. Kluter, and R. C. Liu, "Maximizing Growth of Vegetable Seedlings in Controlled Environments at Elevated Temperature, Light, and CO_2," *Acta Horticulture* (The Hague), in press (presented at a symposium in September 1972). A particularly interesting feature of this work was that growth chambers were provided with both standard and elevated levels of temperature, light, and CO_2; this was one of the first times that more than 2 of these factors were studied simultaneously. While

the growth (dry weight basis) was 5 to 7 times greater in the growth chamber with standard conditions, it was 10 to 25 times greater in the chamber with elevated conditions during the first 15 days.

127. Insulated growth rooms would be much cheaper to heat during low winter light conditions than would greenhouses (with the exception noted in ch. VI, fn. 5). The possibility of using growth rooms in extreme northerly locations was suggested as early as 1948 by E. W. B. van den Muijzenberg (*Mededelingen Directeur van de Tuinbouw*, Wageningen, Holland, Vol. 11, No. 8, pp. 514, 521). A modest growth chamber was actually used in Antarctica in the early 1960's (Jack Hill, "The Absolute Desert-Growing Vegetables in the Antarctic," *World Crops* (London), May/June 1969, pp. 94-98). In late 1972, the matter was being considered in Alaska.

IV. ECONOMICS OF ENVIRONMENTAL CONTROL

Although a wide range of environmental control methods is technically possible, the economies of their use are not clearly defined. Unfortunately, the biological and physical research has not been balanced by a comparable effort on the economic side. Very little study has been done on the economics of environmental control in greenhouses in the United States. Fortunately, the situation is somewhat better in Europe.

This chapter summarizes what little economic information is available and suggests areas where additional inquiry might be fruitful. Unfortunately, the data do not permit analysis of individual environmental control steps. Nor do they allow very sophisticated analysis. But at least they may give an idea of the general setting and provide a starting point.

I have made repeated references to the high intensity of greenhouse food production; the evidence for this viewpoint is presented in the first section of this chapter. The next two sections review the basic economics of greenhouse production and marketing. Finally, alternatives to traditional greenhouse food crops are briefly noted.

INTENSITY OF FACTOR USE

Greenhouse agriculture is probably the most intensive system of cropping in commercial practice when all three of the traditional factors of production—land, labor, and capital—are taken into consideration. Within the greenhouse category, food crops are exceeded in intensity only by floral crops.

INTENSITY OF LAND USE

Intensity is formally viewed by economists in terms of the amount of labor and capital required per unit of land. But both of these measures are conditioned by the cropping systems involved. And both are reflected by total annual yields achieved per acre.[1]

Multiple Cropping

Much of the greenhouse food crop is double or triple cropped. In addition, some of the area may be planted to flowers or bedding plants off season. We do not have good statistics on these matters. Some scattered figures are available on vegetables and small fruits which may provide a notion of the extent of the practice. They are summarized in table 1. Inclusion of nonvegetable crops would undoubtedly raise the multiple cropping ratios.

Table 1—Estimated area multiple cropped to vegetables in greenhouses in selected western countries

Item	U.S., 1969/70	U.K., 1968-70 average	Holland, 1970	France, 1970
		Acres		
Greenhouse area:				
Available	575 (1970)		13,820	2,726
Cropped	1,029 (1969)		22,200	5,117
Multiple cropped:				
Area[1]	454		8,920	2,391
Index[2]	1.79	1.52	1.67	1.88

[1] Obtained by subtracting available area from cropped area.
[2] Obtained by dividing cropped area by available area.

Sources:
U.S.: Table 8 and 9.
U.K.: J. A. L. Dench, *Financial Results of Horticultural Holdings, Average Results for the Three Crop Years, 1968-1970*, University of Reading, Department of Agricultural and Farm Management, January 1972, p. 5.
Holland: Table 11 (including lettuce).
France: *Statistiques Agricoles*, 1971, Paris.

Multiple cropping has long been practiced in American greenhouses. In the Boston area in the late 1800's, two crops of lettuce were always grown; as of 1869, there was an increasing tendency toward a third crop of lettuce or to follow two crops of lettuce with one of cucumbers. One farmer was reported getting five crops a year, starting in the early fall with two crops of radishes, followed by one each of lettuce, tomatoes, and cucumbers; he utilized a sash-covered house and removed the sash in midsummer.[2] Bailey noted in 1875 that while it is generally best to devote an entire house to one kind of crop, "...it is often advisable to grow an alternation or rotation of crops, in order to employ the house to best advantage, and to meet the requirements of the markets." Even then, he noted that vegetables were often alternated with flowers or plant stock.[3]

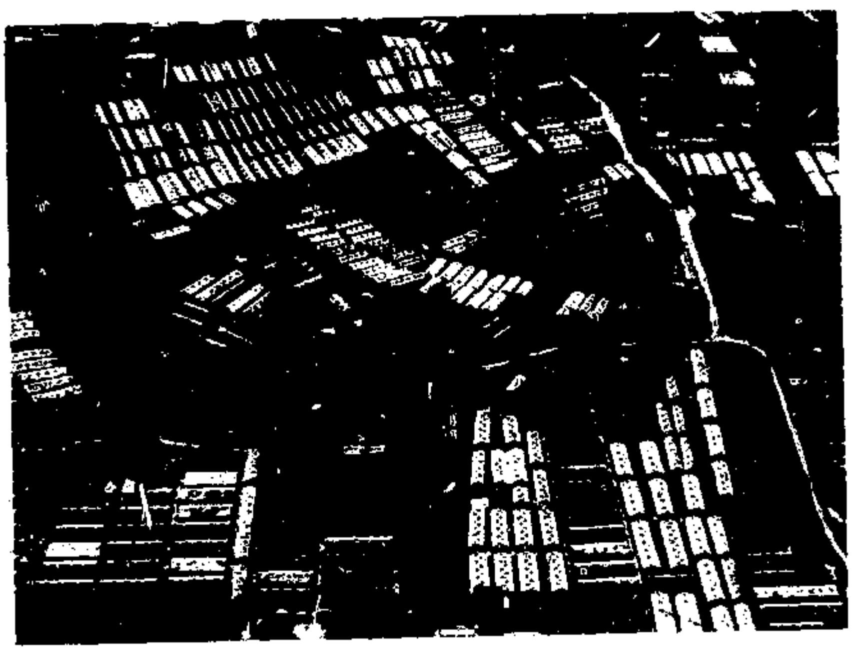
A number of different multiple cropping systems are used in the United States. The nine major patterns for greenhouse vegetable operations are outlined below:

Pattern	*Fall*	*Winter*	*Spring*
1			Tomatoes
2	Tomatoes		Tomatoes
3	Tomatoes		Cucumbers
4	Tomatoes	Lettuce	Cucumbers
5	Lettuce		Tomatoes
6	Lettuce	Lettuce	Tomatoes
7	Lettuce	Lettuce	Cucumbers
8	Lettuce	Lettuce	Lettuce

The seasonal breakdown is only approximate, particularly with respect to the spring season, when there may be early, mid, and late crops. Tomato rotations usually involve the same crop, but the pattern is somewhat mixed with the others.

Most of the greenhouse tomatoes are raised in the spring because environmental conditions are most favorable then. Fall crops neither yield well nor are generally profitable; they may often be utilized simply to keep labor employed. Winter crops raised in northern regions are handicapped by deficient sunlight and short days. Summer crops must compete with field-grown tomatoes. Normally, the spring tomato crop is transplanted in the winter and harvested during the spring and early summer. In some major regions, such as Ohio, growers often have only a spring crop. There are some exceptions to these patterns. Growers in Nevada have raised three crops a year to provide a

Plate 12–*An intensive greenhouse region in Belgium.*



continuous supply;[4] costs under this system, however, are higher. Also, some growers have simply tried to stretch out the harvest season from winter through the next fall. Any of these monoculture systems entail a substantially higher disease risk.[5]

Lettuce is about the only crop to do well in midwinter; it is tolerant of both lower light and lower temperature conditions. While the demand for lettuce during the early 1900's was quite strong, with the expansion of the field-grown industry into regions with mild winters, the demand for greenhouse-grown lettuce has generally declined.[6] It is now usually grown in rotation with or as a companion crop to tomatoes. Late spring tomatoes are often initially intercropped with lettuce and the two grown together for 2 to 5 weeks (in some regions, it is general practice to intercrop lettuce with tomatoes in late winter and early spring). Intercropping lettuce and tomatoes represents a compromise as to optimal temperature for each but has proven profitable in some areas. In those cases where three or four crops of lettuce are grown, the last crop may be intercropped.[7]

Cucumbers require considerable time to come to bearing size and generally do best as a spring crop. Sometimes short-season crops such as radishes, lettuce, or spinach are interplanted. In the American southwest, as many as three crops of cucumbers a year may be grown. Two are the maximum in the north. On the whole, greenhouse production has been less profitable with cucumbers than with tomatoes in the face of competition from outdoor production.[8]

Unfortunately, we do not have a great deal of comparable information on cropping systems outside the United States. Available reports show that in England and Holland, lettuce is planted during the fall and/or winter on land that is used for tomatoes and cucumbers during other periods. Many of the greenhouses are used during the summer as well as the spring for tomato production. A few Dutch and French growers have moved to year-round cropping of lettuce, obtaining seven or eight crops a year.

In general, it may be assumed that most heated greenhouses are on the average double cropped—either to a second vegetable crop or to a nonfood crop such as bedding plants or flowers. Given this near doubling in land use, how do yields compare?

Yields

Yields in greenhouses, as might be expected, are considerably higher than yields in field operations. Just how much higher depends on the cropping system and countries involved. Statistics are most readily available for tomatoes.

In the United States, double cropping of tomatoes has resulted in annual yields ranging from 60 to 120 short tons per acre, and averaging perhaps 75 to 85 tons; good yields often reach 100 tons.[9] Yields of the spring crop are about twice as high as the fall crop. By comparison, the average U.S. yield for single crop field tomatoes for fresh markets in 1971 was 6.7 tons, and the average for the highest mainland State (California) was 11.0 tons.[10] Thus, annual tomato production per acre in double crop greenhouses has easily run 10 times the U.S. average for single field crops. Yields for single cropping greenhouses have averaged 50 to 75 tons an acre, still well above averages for field culture.

What about tomato yields elsewhere? Canadian yields have probably averaged about the same as in the United States for single and double cropping of tomatoes.[11] European yields for single cropping have run, if the statistics are reliable, generally slightly less than U.S. yields except in Scandinavia, the Channel Islands, and Bulgaria (table 2). Comparable yield data for field culture for fresh market in the European nations are not in hand (indeed, in some of the more northerly countries the tomatoes are raised wholly or largely in greenhouses).

Compared with tomato yields in greenhouses, cucumber yields are considerably higher (double in some European countries) on a weight basis, while lettuce yields are only one-fourth to one-half as much.[12] Just how greenhouse

Table 2—Yields of greenhouse tomatoes in Europe, 1966

Country	Metric tons per hectare	Short tons per acre
England	90.3	40.9
Channel Islands	120.0	54.4
Ireland (1965)	113.0	51.2
Holland	[1] 91.5	41.4
Belgium	62.7	28.4
France	(100.0)	(45.4)
West Germany	78.0	35.4
Switzerland	65.0	29.5
Denmark	145.0	65.7
Norway	125.0	56.7
Sweden	120.0	54.4
Finland	110.0	49.8
Hungary (1957)	85.0	38.5
Romania (1957)	110.0	49.8
Bulgaria (1957)	131.9	59.8

[1] Sales.

Sources:

Western Europe: *Production, Consumption and Foreign Trade of Fruit and Vegetables in OECD Member Countries, Present Situation and 1970 Prospects, Tomatoes,* Organization for Economic Cooperation and Development, Paris, 1968, pp. 44, 45, 57, 94.

Eastern Europe: G. P. Shipway, *Agricultural Mechanization: Modern Methods of Cultivation and Harvesting of the Main Vegetables Under Glass,* United Nations Economic Commission for Europe, Geneva, Agri/Mech/19, 1961, p. 8.

yields of cucumbers and lettuce compare to field culture in the same regions is not known. Cucumbers require a high temperature and are not grown in the field in any quantity in some nations. Lettuce is more tolerant of lower temperatures.

Average greenhouse yields for all vegetables in the Soviet Union averaged 60.1 short tons per acre in 1965. By 1970, they had dropped to 47.3.[13]

These figures, plus those given earlier, suggest that we might take 50 short tons an acre (110 M.T. per ha.) a year as a rough but conservative overall yield figure for greenhouse vegetables. This can only be a multiple of several times over vegetables raised under the best field conditions except possibly in certain specialized areas in Asia. The tonnage figures per acre are, furthermore, considerably above those attained by any other food crops.[14]

INTENSITY OF LABOR USE

Greenhouse vegetable production requires large quantities of labor per unit of land. While greenhouse culture is technologically advanced in many ways, much of the work must be done by hand. This is because of the limits the structure places on natural processes (for example, rainfall and pollination) and on the use of large mobile equipment. Also, many vine crops must be tied up to obtain maximum yields. Greenhouses are still very much a handicraft industry.

Estimates of labor use for five countries are summarized in table 3.[15] It will be noticed that the range was from a minimum of 1.4 man-years per acre to a high of 3.9 (the upper figure may actually be considerably higher if we had better data on double cropping requirements in England and Japan). Individual crop requirements were highest for cucumbers and lowest for tomatoes. Review of crop combinations in Holland reveals, as might be expected, that inclusion of strawberries raised labor requirements substantially.

Only limited comparable data are available for field crops, but some from Japan may reveal the difference in requirements. In the case of tomatoes, greenhouse culture of single crops required 1.7 times as much labor as field culture. Cucumbers required 2.7 times as much. In turn, tomatoes and cucumbers grown in the field required far more labor than any other food crop (tobacco fell in between tomatoes and cucumbers; strawberries and floral crops were not listed).[16]

These labor uses, as noted, were on a per unit of land basis. If the higher yields obtained in greenhouses are taken into account, the amount of labor required per unit of product might not be higher; indeed, where very high yields are obtained it could be lower. Further data are needed to quantify this relationship.

How was the greenhouse labor utilized? In France, according to one study, it appeared to be divided between production and harvest as follows:[17]

	Production	*Harvest*	*Total*
		Percent	
Tomatoes	56.8	43.2	100
Lettuce	62.5	37.5	100
Cucumbers	64.5	35.5	100

Table 3—Estimated annual labor requirements for greenhouse vegetables in selected countries

Vegetable	Man-years of labor[1]				
	Canada, 1965 & 1966[2]	England & Wales, 1957[3]	Holland, 1970[4]	France, early to mid-1960's[5]	Japan, 1969[6]
	Per acre (Per hectare)				
Individual crops:					
Tomatoes	3.7 (9.1)*	2.2 (5.4)		3.0 (7.3)*	3.1 (7.7)
Lettuce				1.5 (3.6)*	
Cucumbers		3.3 (8.2)		3.2 (7.8)*	3.6 (9.0)
Crop combinations:					
Tomatoes and lettuce			1.4 (3.5)*		
Tomatoes and cucumbers	3.9 (9.6)*				
Lettuce, tomatoes, lettuce			1.6 (4.0)*		
Lettuce and cucumbers			1.5 (3.75)*		
Tomatoes and strawberries			2.8 (7.0)*		
Lettuce and strawberries			2.8 (7.0)*		

*Double cropping.
[1] Converted from actual hours on basis of 1 man year = 2,000 hours.
[2] Sample of 23 farms, Essex County.
[3] Norms.
[4] Heated greenhouse. Holland has traditionally minimized its labor input.
[5] Orleans area.
[6] Based on cost of production surveys.

Sources:

Canada. G. A. Fisher and Paul Hedlin, *Greenhouse Vegetable Production in Essex County, Production Costs, Returns and Management Practices, 1965 and 1966,* Ontario Department of Agriculture and Food, Farm Economics, Cooperatives, and Statistics Branch, February 1971, pp. 19, 34.

England & Wales. G. F. Shipway, *Agricultural Mechanization: Modern Methods of Cultivation and Harvesting of the Main Vegetables Under Glass,* United Nations Economic Commission for Europe, Geneva, AgriMech/19, 1961, pp. 5, 18.

Holland: *L'Evolution de la Production Fruitière et Légumière Sous Serres en Europe,* Centre National du Commerce Exterieur, Service des Produits Agricoles, Paris, 1971, p. 140.

France: J. de Bagneaux and J. Dujardin, *Evolution de la Rentabilite des Serres Maraicheres,* Centre Technique Interprofessionnel des Fruits et Legumes, Paris, CTIFL Documents 9, November 1966, p. 13.

Japan: Data compiled by Joseph Birse from the *Statistical Yearbook of the Ministry of Agriculture,* 1969-1970 (in Japanese), tables 60, 66.

Comparable data from a small sample of greenhouses in the United States which raised tomatoes indicated that the proportion taken by production labor was higher—ranging from 68 percent in California to 77 percent in New Jersey—while the proportion composed of harvesting costs was correspondingly lower.[18] Further study of these matters would be desirable.[19]

To convert hours of labor into cost of labor per unit of land, it is necessary to know greenhouse wage rates. It would also be useful to know how these rates compare with those paid to field laborers. Such data were not found for vegetable crops, but a Swedish study has summarized some data for national variations in wage rates in ornamental production. With U.S. wages placed at 100, index numbers for other nations were as follows: Sweden 119, Denmark 90, Holland 88, West Germany 83, northern Italy 59, England 56, northern France 55, southern France 45, southern Italy 24.[20]

In total, it is evident that greenhouse culture of food crops is very labor-intensive per unit of land compared with field culture. In one way, these ratios might understate the situation: if the construction of the greenhouse made the cultivation of these labor-intensive crops possible for the first time, the increase in labor requirements over former crops (such as grain) might be vastly higher. Because of the higher yields obtained in greenhouses the labor required per unit of product may not be much greater; it could even be less.

INTENSITY OF CAPITAL REQUIREMENTS

Greenhouses clearly require large amounts of capital per unit of land—probably more than any other form of crop production. As with other forms of agriculture, this consists of fixed capital and annual cash costs.

Fixed Capital

The costs of fixed capital, while clearly high compared with field culture on an area basis, are quite variable—depending mainly on type of structure and nature and extent of environmental control equipment. In addition, it is necessary to consider costs of (1) land, (2) fixed and mobile equipment, and (3) grading, packing, and office structures. A breakdown of the various cost items included in a recent analysis in California is presented in table 4.

Perhaps the most important variation in cost occurs between various types of structures. Metal truss framed glasshouses cost the most; wood frame or metal hoop (high tunnel) units covered with plastic film cost the least. It is relatively easy to quantify costs of the former because they are usually fairly standardized units constructed and erected by commercial firms. Wood/plastic houses, on the other hand, are often built by the farmer to his own design or adaptation, using local materials. Moreover, the plastic sheeting must be replaced every 1 or 2 years. Hence it is not possible to give an accurate idea of the relative capital cost of plastic houses, except to say that the simplest forms may be much cheaper. Houses using plastic panels may fall somewhere between houses using glass and plastic film, depending on the type of panels and

Table 4—Estimated total capital costs for a 1-acre greenhouse tomato operation in California, 1972

Item	Cost
	Dollars
Growing structure & equipment:	
Fiberglass/metal hoop structure & climate control equipment[1]	84,240
Land cost & site preparation	1,900
Utility connection	1,000
Fixed equipment[2]	2,170
Mixed equipment[3]	9,300
Subtotal	98,610
Grading, packing, & office structure:	
Structure	8,000
Grading table	[illegible],700
Office equipment	1,500
Subtotal	11,200
Total	109,810

[1] 9 connected 40' x 120' units (43,200 sq. ft.). Includes ventilating and heating equipment and provision for fan and pad cooling.

[2] Nutrient tanks $700; fertilizer proportioner $430; overhead support wires $180; trickle irrigation system $860.

[3] Tractor and equipment $4,000; pickup truck $4,000; vibrators for pollination, mist blower, carts, picking containers, thermographs, and small tools $1,300. The tractor and pickup truck could handle more than an acre; hence on a larger operation, the per acre cost of these items would be reduced.

Source: Hunter Johnson, Robert Rock, and Paul Moore, "Estimated Costs for Producing Greenhouse Tomatoes in California," University of California (Riverside), Agricultural Extension Service, May 1972, p. 4; and letter from Rock, January 5, 1973.

framing (given the same metal truss framing, the cost of glass and fiberglass may be similar).

While, for these reasons, it is not possible to give a broad or comprehensive set of estimates of fixed capital costs for greenhouse, it is possible to cite some cost figures for units at the upper end of the range—the new commercially manufactured glass and metal units with environmental control equipment. As noted in table 4, they form the major but not the total capital cost for producers using them.

United States. Approximate costs estimated by three firms in late 1972 for glass and metal truss units (which are more elaborate in design than the unit cited in table 4) with equipment suitable for the northern United States ranged from $2.86 to $5.00 per square foot, or $125,000 to $218,000 per acre

($309,000 to $539,000 per ha.).[21] These figures correlate fairly closely with an estimate of $3.00 to $5.00 per square foot noted in a recent report from Washington State University.[22] Narrower span units imported from Holland may be lower in price. (Air inflated units in late 1972 were priced at $2.60 to $2.75 per square foot, or $113,000 to $120,000 per acre.)[23]

— England. In 1972, fully equipped glasshouses ranged in cost from $76,800 (£32,000) per acre for multispan blocks of Venlo design (a type commonly used in Holland) to $96,000 (£40,000) for single widespan houses; both figures exclude land cost.[24]

— Mainland Europe. The average cost of a widespan glasshouse and environmental control equipment as of early 1971 was estimated as follows by a French group:[25]

	Francs per hectare	*Dollars per acre*
Holland	1,100,000	86,950
France	1,450,000	114,610
Sweden	1,500,000	118,640
Denmark	1,600,000	126,470
Germany	1,700,000	134,373
Switzerland	1,800,000	142,277

Venlo-type houses were less: 700,000 francs per hectare ($55,330 per acre) in Holland and 900,000 francs per hectare ($71,140 per acre) in France. In the past, there has been a geographic difference in the type of houses generally utilized in Europe. As one writer put it in 1965:

> The Netherlands and France use relatively low cost houses in large blocks. . .In contrast, Scandinavia, Germany, Belgium and Britain prefer wide houses in small blocks. . .which are more costly to build and operate.[26]

In any case, it is clear that new fully equipped metal truss and glass greenhouses represent a very substantial initial capital investment. Obviously, the investment in older houses, which have been partially or completely depreciated, is considerably less. And it is clearly less in plastic-covered houses or in those with little or no environmental control equipment. But at the very least, the investment is considerably above that in an open field.

Annual Cash Costs

Annual cash costs are also substantial. These are made up of fixed costs and operating (or variable) costs. Fixed costs include taxes and maintenance.[27] Operating costs include labor, fuel, utilities, farm chemicals, packaging materials, and so forth (and will be discussed in more detail in a following section). Although the data are far from conclusive, annual costs are probably correlated to some degree with capital investment: a more intensive culture is possible in a more advanced structure.

The very limited data we have for glasshouses for the United States and Canada suggest that for double cropping, the annual cash costs have run roughly 40 percent of the value of the fixed investment in a modern house.[28]

That is, in a glass or fiberglass house in North America representing an initial capital investment of about $100,000 per acre, the annual operating costs for double cropping have run around $40,000 per acre. The capital investment in older glasshouses (some of which may be fully depreciated) and in plastic houses may, of course, be considerably less. Annual operating costs may also vary widely and will be less if only one crop is involved. Both sets of costs may be less in other nations.

Despite the wide variations, the initial and annual capital costs for greenhouse operation are clearly high per unit of land compared with other forms of crop production.

COMPOSITE COMPARISONS

The previous sections have shown that greenhouses are an extremely intensive form of crop production, whether measured by output per unit of land or by labor or capital required per unit of land. We have not looked at the question of whether greenhouses have significantly higher requirements than field culture in terms of (a) labor or capital requirements per unit (quantity or value) of output, or (b) capital requirements per worker (the capital/labor ratio) than field production.

English and Dutch studies suggest that the labor cost per unit of product may not be much different, while the capital cost is much higher per unit of output. The English investigation compared different forms of vegetable farming necessary to produce a given income (£650/per year) in the mid-1950's. The results are summarized in table 5. Compared with intensive field production, heated greenhouses required about the same labor, and over twice as much capital. The capital differential was narrowed when the comparison was drawn with extensive vegetable production (probably because of the need to introduce larger tractors in the extensive system). Similarly, the Dutch study of pickling-cucumber production in 1967 indicated that labor requirements in greenhouses were about 32 percent less than in the field (the Dutch make particularly efficient use of greenhouse labor), while capital costs were about 84 percent higher per unit of product.[29]

Despite their high labor requirements, most people would probably expect the capital/labor ratios for greenhouses to be greater than for other forms of agriculture. Examination of table 5 reveals that the capital/labor ratios are not sharply different, except in the case of heated houses—in which case, the investment per employee was about twice as high. In the United States, the fixed capital investment per worker might average about $50,000 in relatively new heated glasshouses (assuming fixed investment of $100,000 per acre and a need for the equivalent of two full-time employees). While figures of this magnitude seem high, they are actually less than the average capital investment per worker on all U.S. farms in 1971 ($56,000).[30] The capital/labor ratios would, of course, be even lower for older houses or plastic-covered structures.

Both of these sets of comparisons with field culture need considerably further study before firm conclusions can be drawn.

Table 5—Labor and capital required for different vegetable cropping systems producing income of £650 per year, England, mid-1950's[1]

System	Land	Labor-regular workers	Capital[2]
	Acres	*Number*	*Pounds sterling*
Unprotected:			
Extensive[3]	18.0	2+	2,500
Intensive[4]	3.5	2+	2,000
Partly protected:			
Frames[5]	2.5	3+	2,700
Glasshouses:			
Unheated	0.6	3	4,000
Heated	0.4	2+	4,200

[1] £350 in addition to proprietor's labor.

[2] Excludes land; if land included, capital requirements are about the same.

[3] Brassicae, beetroot, runnerbeans, some lettuce.

[4] Asparagus, herbs, lettuce, spring onions, bunched carrots.

[5] Includes one-half acre covered by frames. Lettuce, celery, tomatoes, melons, chrysanthemums.

Source: R. W. Folley, *Management Aspects of Horticultural Production Under Glass*, Wye College (University of London), Studies in the Economics of Intensive Horticultural Holdings, Report No. 2, February 1958, p. 16.

ECONOMICS OF PRODUCTION

Given intensive use of the principal factors of production, what can be said of the economics of greenhouse food production? The available data are limited but do provide an idea of the costs and returns, the major conditions influencing returns, and the effect of returns on location of the industry. Hopefully, the data assembled here, while meager, will provoke further research on this key subject.

COSTS AND RETURNS

Clearly greenhouses require a lot of capital. Do they produce correspondingly high returns? Few general answers can be given at this point. But by examining data for tomatoes, the most commonly grown crop, we can gain some idea of the nature of costs, prices, and profits. The information reported is largely for North America, but it is augmented, where possible, with data from Europe.

Costs

The cost structure for greenhouse vegetable production was well set forth as early as 1897 by Liberty Hyde Bailey.[31]

The person who desires to grow vegetables under glass for market must, first of all, count up the costs and the risks.

- Glass houses are expensive and they demand constant attention to repairs.
- The heating is the largest single item of outlay in maintaining the establishment. Moreover, it is an item upon which it is impossible to economize by means of reducing temperature, for a reduction of temperature means delayed maturity of the crop. . . .
- Labor is the second great item of expense. . . . This, however, may be economized if the proprietor is willing to lengthen his own hours; but economy which proceeds so far that each one of the plants does not receive the very best of care is ruinous in the end.

Since Bailey's time, wage rates have evidently risen more than heating costs, for wages are now easily the greatest single item of expense, both in the United States and Europe, followed by fuel costs where heating is practiced.

Fairly recent estimates of fixed, operating, and marketing costs in the northern United States and Canada are summarized in table 6.[32] On balance, it appears that about one-third of the total production costs were fixed costs and about two-thirds were operating costs. Depreciation and interest on investment accounted for most of the fixed cost and roughly one-fourth of total costs. Labor represented about half of the variable costs and nearly a third of total production costs.[33]

The cost structure for individual houses may vary widely. For older houses, the depreciation and interest on investment charges may be far less: some may have been fully depreciated. On the other hand, in some advanced houses the current costs in all categories, except possibly heating, may be higher. For instance, one leading Ohio grower who had very high yields in 1971 (114 short tons per acre) had much higher total labor and supply costs than reflected in the table.

Plastic houses in the same locations would have lower fixed costs but possibly higher operating costs. In addition to the lower construction costs, the taxes on plastic houses are usually much lower (the houses are often classified as temporary structures). Maintenance costs can be high because of the need to replace the plastic covering every 1 to 3 years. The heating cost will also be higher if only one layer of plastic is used. Other expenditures may not be much different.

What do European studies of the cost of greenhouse operations show? It is difficult to make direct comparisons on the basis of the data available because every study seems to follow a different system of calculation. Still, it is possible to check a few proportions for labor and fuel (depreciation is included; interest on investment is excluded). Cost data from England for the 1970/71 crop year for glasshouses indicate that about 35 percent of production costs were represented by labor and 14 percent by fuel.[34] During 1971 in Holland, labor costs for tomatoes and cucumbers were about 29 percent of total costs and fuel was nearly 20 percent.[35] In the Orleans area of France in 1963/64, labor costs for greenhouse vegetables averaged 21 percent and fuel bills averaged 28.5 percent.[36]

Another English study specifically examined the relative costs of producing one crop of early tomatoes in glasshouses in England, Guernsey, and Holland in

Table 6—Estimated per acre costs of greenhouse tomato production in Michigan, Ohio, and Ontario

Type of cost	Glasshouses, 2 crops		
	Michigan, 1964[1]	Ohio, 1967[2]	Ontario, 1965 & 1966[3]
	U.S. dollars	*U.S. dollars*	*Can. dollars*
Fixed costs:			
Depreciation	5,000	6,000	4,430
Interest on investment	5,400	6,000	3,680
Taxes & insurance	1,250	2,000	1,720
Maintenance	600	1,500	1,480
Subtotal	12,250	15,500	11,310
Operating costs:			
Labor	11,000	[2] 16,000	10,080
Fuel	[4] 8,200	[4] 8,250	6,740
Utilities & telephone	1,300	950	900
Chemicals/supplies	[5] 1,700	[6] 2,500	[5] 1,140
Other	2,920	2,500	[7] 4,280
Subtotal	25,120	30,200	23,140
Total production costs	37,370	45,700	34,450
Marketing costs	NA	[2] 6,500	[8] 7,660
Total costs	NA	52,200	42,110

NA = not available.

[1] Estimated by growers attending greenhouse meeting.

[2] Estimated based on records of several growers with yields of 100 short tons per acre. Labor and marketing costs would be less with lower yields.

[3] Based on 23 farm records: 9 from 1965 and 14 from 1966; 5 growers from each group were the same. Includes some cucumbers.

[4] Includes sterilization.

[5] Farm chemicals.

[6] Supplies.

[7] Of this, Can. $2,198 was for interest and bank charges.

[8] Estimated at 20 percent of gross returns.

Sources:

Michigan: "Production Costs," *American Vegetable Grower*, March 1965, p. 48.

Ohio: M. E. Cravens, "The Glasshouse Agribusiness," Ohio State University (Columbus), Department of Agricultural Economics, 1968, p. 2.

Canada: G. A. Fisher and Paul Hedlin, *Greenhouse Vegetable Production in Essex County: Production, Costs, Returns and Management Practices, 1965 and 1966*, Ontario Department of Agriculture and Food, Farm Economics, Cooperatives and Statistics Branch, 1971, pp. 17, 19.

1960. Total costs were less in Holland, principally because of lower labor and fuel bills, but yields were also less there. On balance, the cost per ton was about the same in Holland and Guernsey and 8 percent higher in England.[37]

Few data were found on costs in other areas. In regions where (a) less heating is needed, (b) plastic is used, and (c) labor is cheaper, the costs may well be considerably less. Differences in labor productivity, however, must be taken into account. While total cost calculations provide an idea of working capital needed and the nature of costs, it is necessary to convert time to a cost per salable unit basis—as was done in the above study—to make interregional and international comparisons. Prices must then be considered.

Prices

The gross returns from greenhouse production clearly must be high on a per acre basis if they are to match or exceed costs. This in turn means that yields and/or prices must be high. Relative yield levels have already been discussed. Therefore, this section focuses on prices—both annual and seasonal.

First, however, the subtle factor of product quality should be mentioned. Greenhouse food crops are less subject to damage by adverse weather conditions than field crops; therefore, the proportion of both (a) the marketable product and (b) the higher grades of product is apt to be greater. There is less waste. Therefore, the average price per unit of overall greenhouse production is apt to be higher than for total field production.

(1) *Annual Prices.* Although good price series are not available, it would appear that greenhouse tomato prices per pound in the United States have not changed much in 80 years, despite a fivefold increase in the general price level. Bailey reported in 1891, for instance, that winter tomatoes "always find a ready sale at prices ranging from 40 to 80¢ per pound."[38]

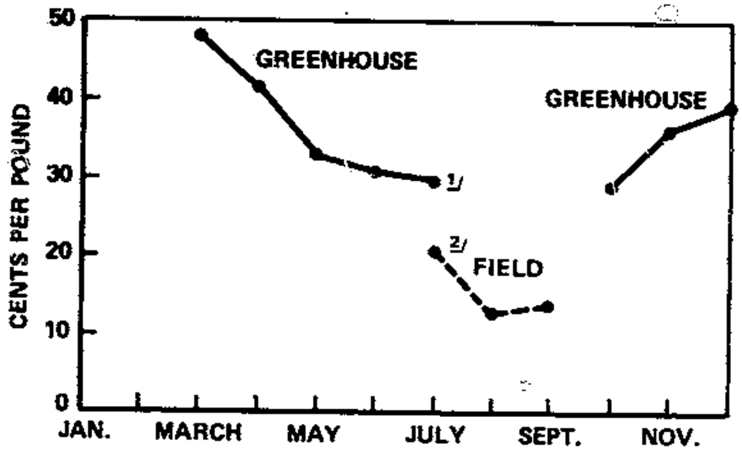
More recently, during the spring of 1961, average retail prices for greenhouse tomatoes in 214 Ohio retail stores ranged from 45.6 to 46.7¢ per pound for U.S. No. 1 medium fruit. Wholesale prices ranged from 31.8 to 32.0¢, indicating a retail margin of 30.3 to 31.5 percent. This grade accounted for 68 percent of the total display space. Other grades had retail prices ranging from 37.9 to 39.5¢ per pound and wholesale prices of 19.1 to 26.1¢ per pound.[39] Wholesale prices on the Cleveland market during 1970 ranged from 29 to 48¢ per pound for greenhouse tomatoes and from 12 to nearly 21¢ for field tomatoes (fig. 2).

During 1945-68, the average price to a number of growers for greenhouse tomatoes in the United States and Canada, exclusive of marketing costs, averaged from 20 to 25¢ per pound with no clear trends.[40] If the increase in the cost of living is considered, there was a decreasing trend. By comparison, the average annual farm and retail price for all fresh tomatoes in the United States increased about 75 percent from 1950 to 1970.[41]

Times series data for greenhouse produce in other countries were obtained only for Great Britain. Data for 1953-69 indicate an increase of 34.6 percent in monetary terms but essentially no change when the increased cost of living is taken into account.[42]

(2) *Seasonal Variation in Prices.* Greenhouse products undergo sharp seasonal variations in price. An indication of the variation for tomatoes at the

AVERAGE WHOLESALE PRICES FOR TOMATOES, CLEVELAND, 1970



1/ First half of month. 2/ Last half of month.

Source: Calculated from data reported in *Cleveland, Fresh Fruit and Vegetable Wholesale Market Prices, 1970*, USDA, Market News Service, Cleveland, February 1971, p. 21.

Figure 2

wholesale level is provided for the Cleveland market in figure 2. During the spring, the greenhouse price dropped from 48¢ to about 30¢ per pound. In the fall months, it increased from about 29¢ to 39¢ per pound. By comparison, the price of field tomatoes in the summer dropped from 20¢ to about 13¢. Canadian prices over 1960-67 have consistently run lower in the fall than in the spring.[43]

The sharp seasonal changes in greenhouse prices noted earlier for the United States are probably also found in other nations. Tomato prices in Paris, for instance, show a roughly comparable pattern.[44] The magnitude and timing of the fluctuations, however, may vary.

It would be useful to have more systematic price data available at the farm, wholesale, and retail levels for greenhouse produce both seasonally and over a longer period of time. It is hoped that such data will emerge in the future.

Profits

Vegetable and fruit production is generally a financially risky business, partly because of the sharp variations in product prices. This is no less true of greenhouses, despite their reduction of environmental uncertainties over field production. The greenhouse producer, if anything, is more vulnerable to price changes. His high overhead costs mean that he cannot easily let his horse lie idle. He also has a rather limited selection of alternative crops. Thus he does not have much short-term production flexibility when faced with low prices.

For these and other reasons, it is doubtful that many fortunes have been made in the long-established greenhouse areas in recent years. In the northern United States, some firms are in business only because the greenhouse was inherited and is fully depreciated. In Canada's leading greenhouse area in 1965 and 1966, the average firm lost $4,280.[45] In England in 1953 and 1954, the returns to greenhouse growers in one study were not much greater, acre for acre, than returns to those practicing far less intensive forms of agriculture.[46] In Holland in 1971, 12 percent of the greenhouses producing vegetables lost money.[47] Similarly, a number of greenhouses in Europe are probably operating on the economic margin or are facing unfavorable profit trends.[48] Although specific data are not available, past experience suggests that hydroponic operations have generally been especially marginal.

There are undoubtedly many exceptions. The better and more efficient houses in many locations are probably making a good return. And in some countries, the proportion of farmers included may be fairly large; for instance, in a sample of Dutch greenhouse operations (vegetables and fruit) in 1971, 62 percent had incomes of over $7,800 (f25,000); and 26 percent had incomes of over $12,500 (f40,000).[49] Incomes are also reported to be generally good in areas undergoing rapid expansion, such as southern Turkey; but in these cases, the profit can be a fleeting thing and may disappear rapidly as supply begins to exceed domestic demand.

In some areas of the United States, it was a rule of thumb in 1972 that a successful grower should gross $1 or more per square foot of total greenhouse area, or $43,600 per acre. A Texas greenhouse specialist estimates that probably half the operators in his State are successful on this basis.[50] This measure provides a starting point but is inadequate in that it does not take yields into consideration.

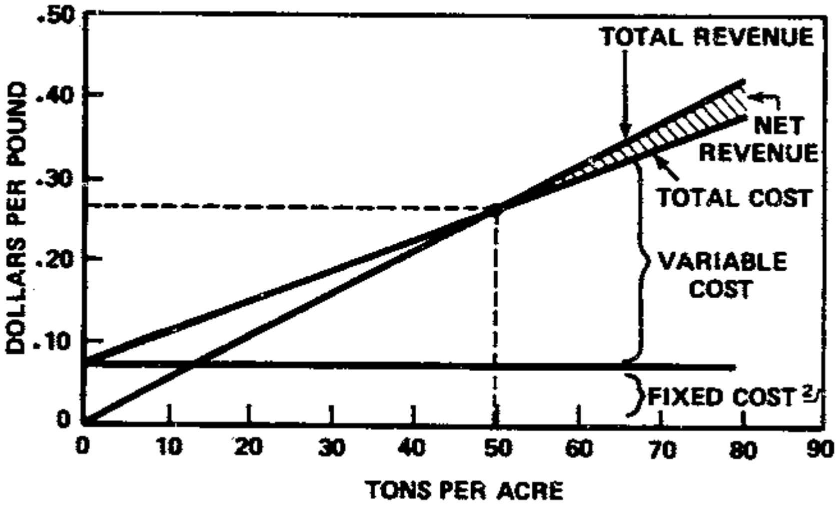
A slightly more precise rule of thumb might be the price needed to break even. For Ontario growers to cover production costs for greenhouse tomatoes in 1969, they needed to receive 21.5¢ per pound; this was the equivalent of 28.1¢ per pound wholesale at the Ontario food terminal.[51] The break-even price for an outstanding Ohio tomato grower in 1971 was 26.7¢ per pound excluding interest on investment, and 29.2¢ including interest (yield of 114 short tons per acre). In California in 1972, the break-even price was placed at 26.4¢.[52]

Break-even levels vary widely with differing yields and cost levels. This is indicated in figure 3. The break-even price in Indiana in 1970 was about 27¢ per pound at a yield of roughly 50 short tons per acre. Most growers operated at about this level. At higher yields or prices, net revenue became positive. Fixed costs were unusually low because most of the greenhouses were fully depreciated. It would be useful to have similar data for other States and countries.

Two further points suggested earlier need to be kept in mind in considering costs per unit. They are the proportion of marketable production and the

AVERAGE BREAK-EVEN POINT FOR 22 GREENHOUSE TOMATO OPERATIONS, SINGLE CROP, INDIANA, 1970 [1]

Greenhouses Less Than 1.15 Acres



1/ Data compiled in 1970 and adjusted to 1973 price levels.

2/ Fixed costs are unusually low in Indiana because most of the greenhouses are fully depreciated.

Source: Jerry Robertson and Glenn Sullivan, "The Greenhouse Tomato Industry: Production Trends, Production Economics, and Competitive Position," Purdue University (Lafayette, Ind.), Department of Horticulture, manuscript, February 1973.

Figure 3

distribution of the marketable production between various grades. In general, the more expensive methods of production tend to produce higher quality products which have less waste and which bring higher prices. Thus, cost comparisons should be drawn on the basis of marketable production, not total production, and preferably should also take grade distribution into account.

CONDITIONS INFLUENCING RETURNS

Returns to greenhouse operators are influenced by a number of variables which may not show up in the yearly financial balance sheet. In turn, these variables have economic dimensions of their own. We shall look at four in this section: economies of scale, physical facilities, cropping patterns, and government incentives. Factors having a competitive aspect will be reviewed in a following section.

Size and Economies of Scale

In the non-Communist nations, greenhouse operations tend to be of a size that can be operated by a family. The precise area generally ranges from 1 to 2 acres in the developed nations. In Canada, for instance, the greenhouses are "predominantly family size and very few exceed one acre."[53] In Holland, where particular emphasis is placed on labor efficiency, the average heated vegetable holding is about 2 acres.[54] The reasons are related to family characteristics and economies of scale.

In many developed nations, a unit of an acre or so can be operated by about two laborers (one in Holland) with some additional help at periods of peak activity. This amount of labor can usually easily be provided by the owner and his family. Moreover, the owner may be expected to pay close attention to management—a most important factor (a Japanese study has indicated that diseconomies of scale in cooperative greenhouses are mainly due to inefficiencies in decisionmaking).[55]

It is also generally thought that there are few significant economies of scale for units much above the family size. First, there is no particular economy in building larger units. Second, most of the greenhouse tasks have traditionally been carried out by hand; beyond the use of garden tractors, relatively few operations have normally been mechanized. Third, and closely related, variable costs such as labor account for a large proportion of annual costs; few of these costs drop significantly with increased size of operation. Indeed, labor costs may rise significantly if it is necessary to recruit labor outside the family.

Empirical evidence of the effect of size of operation on profitability is not plentiful. However, one recent study of 33 greenhouse vegetable operations in Indiana provides some data. The study indicated that profits were highest in firms around 1 acre in size, and lower in either smaller or larger units.[56]

Economies might accrue with increased size when (1) there is a unique opportunity to mechanize certain operations, (2) labor can be more efficiently utilized, (3) low-cost capital is available, (4) there are economies in the purchase of packaging materials and in marketing, or (5) some special management skills are available. The Communist nations clearly prefer large units, but this may be due more to an ideological commitment to large scale agriculture than to economics.

In any case, technological advances in greenhouse operations are gradually increasing the size of unit which may be handled by a family. The average size of Dutch vegetable houses, for instance, increased 17 percent from 1966 to 1970, and it is now thought that the optimum size is a three-man unit, or about 1 hectare (2.47 acres).[57] Modest further increases in size may be expected in Holland as well as in other countries.

Physical Facilities

Closely related to the question of economies of scale is the matter of intensity of production. Intensity, in turn, can be influenced by the type of structure and the degree of environmental control equipment. When a grower puts up a new house, should he make it as simple or as complex as possible?

The answer depends on many things, including the availability and cost of capital, land, construction and operating costs, climatic factors during the anticipated production season, and the existing price structure. Clearly, the simpler unit with the least environmental control equipment is less expensive to build and decreases the amount of capital needed. But the more complex structure offers more complete environmental control, making it possible to reach the higher prices of earlier or later markets, and/or to increase the frequency of cropping.

Whether to choose a simple or a complex unit has been a question even in quite different settings. Turkey and Holland are two examples. In Turkey, both the individual grower and the agricultural credit bank were concerned with whether they would get the greatest return on capital by building simple plastic houses or by continuing to construct the more expensive glass and metal buildings.[58] At a different level, growers in Holland in the late 1950's were faced with the question of whether they should build a better grade of house and add heating in order to reach an earlier market.[59]

In each case, the more expensive structure and environmental control equipment would make it possible to reach an earlier market and thus obtain higher prices. The question then was how much earlier and at how much higher a price. Analysis in Turkey suggested that the advantage of a glass house over a well-heated plastic house was not significant enough to offset the substantially higher capital investment. In Holland, it was noted that skilled growers in improved houses picked 25 percent more tomatoes 6 days earlier than in ordinary (Dutch light) structures; considering prices, every day that the tomato crop was earlier gave "a surplus return of 3 percent of the total value of the crop for the marketing period." It was tentatively concluded that the improved houses were worthwhile.

The problem with calculations of this nature is that a sudden shift in the price structure could throw the conclusions off. Moreover, not all groups have a long planning horizon. In Ireland prior to 1966, for example, the pattern for growers was to under-invest because they were uncertain about the future and wanted to repay borrowings within 5 years.[60]

Cropping Patterns

The type of structure and environmental control available will obviously have considerable influence over the kind of cropping pattern followed. In the most elementary structures, only single cropping may be possible. But the more elaborate facilities, as we have noted, make multiple cropping a definite prospect. The increased cropping alternatives in turn may make the question of crop selection more important and more difficult.

Relatively little attention has been given to formal determination of most profitable cropping patterns in greenhouses.[61] In the past, there have not been many economic alternatives. Increased attention, however, is being given to the selection of alternative crops, and the range may widen in the future (this point is discussed later in this chapter). While limits to the range of crops will be set by physical and biological factors, economics can be of use in selecting among those cropping patterns which pass the first screening.

One very appropriate technique is linear programming. Sophisticated theoretical programming techniques have been developed for crop selection and planning analysis in New Zealand and Israel; but in the case of each nation, both field and greenhouse crops are involved.[62] Only limited practical application of linear programming solely to greenhouses has been noted. One application, to one farm, was conducted in Pennsylvania and included vegetables, geraniums, and bedding plants; most profitable individual crops and cropping combinations were determined.[63]

Few public agencies could do individual farm analyses on a widespread basis. But they might be able to use data from selected farms to make generalized tests of various potential cropping systems. If some of these appear feasible, they could then be tested on a few individual farms. From that point, the computations would probably have to be put on a commercial or semicommercial basis and adapted to the differing management skills and resources of individual farms.

Government Incentives

Financial returns may also be influenced by government action. Several European governments seem to have taken an interest in stimulating greenhouse operations through grants or low-interest loans toward construction costs. Grants have been provided in England, Ireland, and France.[64]

Just exactly why the governments provided these incentives is not clear. Their actions may just be part of more general programs to aid agriculture, or they may be due to concern with reducing imports or expanding exports or to other factors such as political influence.

Greenhouses may not be the best investment: An English economist indicated in 1958 that ". . .as an agent in the promotion of wealth, capital in glasshouses (in England) is less productive than capital in farm machinery and livestock but more productive than capital in land and farm buildings."[65] On the other hand, the capital invested in inexpensive plastic greenhouses has probably been more productive. Still the record is a mixed one, and raises the question of justification for special government support.

The effects of these government programs have not, with one exception, been analyzed. The exception was a pilot study of 20 English growers who had received grants under the Horticultural Improvement Scheme. The author reported that:

> Most growers in the sample were not found to make a prior evaluation of new investment or to be concerned with its economic efficiency. They paid more attention to technical matters and their own relative efficiency (their comparative standing within the industry).[66]

It would be helpful to have an understanding of the greenhouse operators' attitudes toward investment in greenhouses with and without government incentive programs.

RETURNS AND LOCATION

The various factors influencing costs and returns have also had an influence on the location of greenhouse production within nations. Clearly, areas with a high solar radiation and warm temperatures are likely to experience greater plant growth and reduced heating costs. The interaction of these two factors has been used to compute measures of potential photosynthesis for various geographical regions.[67] These are summarized for the world on an annual basis in figure 4.

In the United States, greenhouses have been traditionally located near urban areas in the north-central and northeastern States. In recent years, however, there has been a much wider diffusion of new greenhouse construction throughout the country. The newer areas have a combination of at least several of the following factors which contribute to lowered costs:[68]

— High sunlight intensity undiminished by air pollution;
— Mild winter temperatures;
— Infrequent violent weather (tornadoes, high winds, hail, excessive snow);
— Low humidity during the summer for air cooling;
— A good water supply low in salt (chloride content).

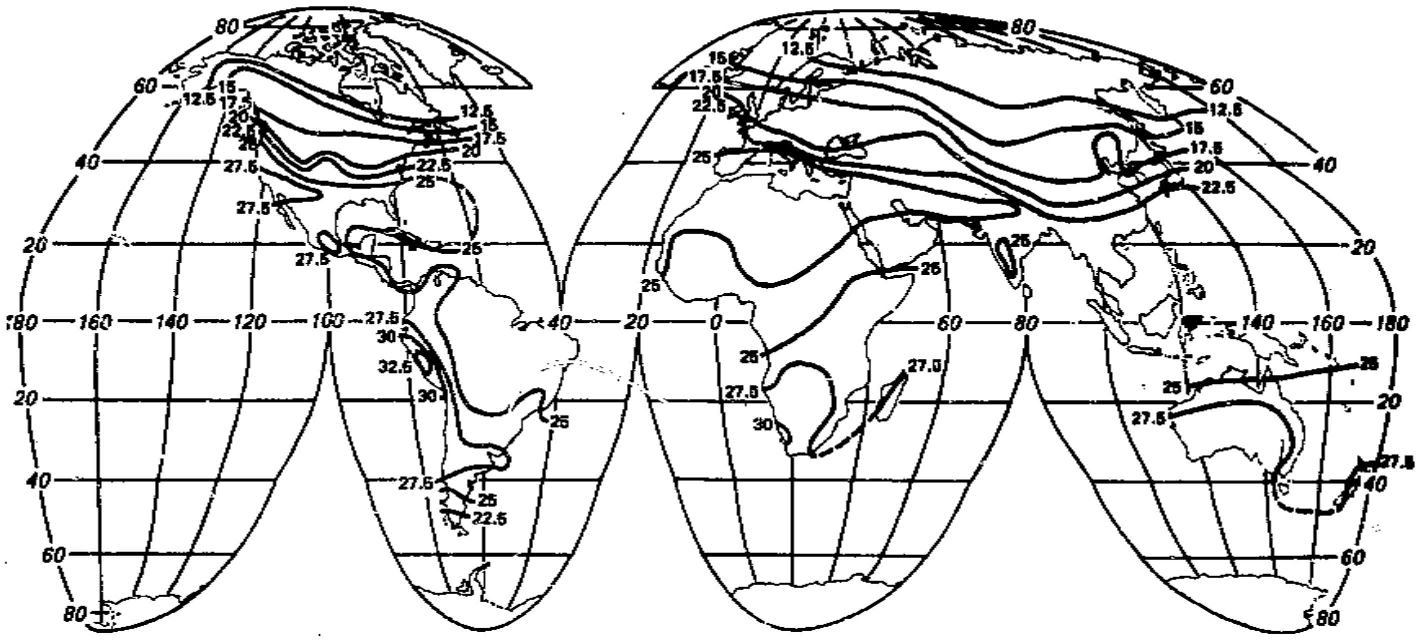
In addition, cheap fuel and electricity and low taxes are also desirable. Some of the areas which have recently met these requirements, as well as providing adequate prices, include the southwestern States of Texas, New Mexico, Arizona, and Nevada, as well as California. Most of the new construction in these areas is plastic.[69]

The situation is somewhat the same in Europe, although there are important differences. As noted earlier, much of the new construction of greenhouses has been in southern Europe, where the weather is milder and inexpensive plastic houses have been built. But at the same time, there has been a pronounced expansion in Eastern Europe; this expansion, however, is not so much related to product costs as to market prices (and the latter have in part been tied into the growth of export markets, of which more is said later).

Traditionally, European greenhouses have tended to be concentrated near urban areas. One geographer, extending the work of von Thunen, placed greenhouses in zone 1 nearest the heart of the city.[70] This pattern has recently changed in some cases. A huge greenhouse expansion in Italy in the 1960's was heavily concentrated in Sicily, where farmers, with a tradition of out-of-season vegetable cropping, made vast use of plastic greenhouses.[71] Conversely in England, there is reportedly no one low-cost area of production, and hence the British greenhouse area has "sought the consumer rather than the sun."[72] In the Soviet Union, which has a much wider geographical range, it seems to have been agreed that the majority of new glass will be located in the vicinity of the large centers of population; some additional houses, however, will be built in the south for the production of limited amounts of winter and spring crops (particularly tomatoes) for export to the north.[73]

It is almost anomalous that despite the many recent technical advances in

AVERAGE ANNUAL POTENTIAL PHOTOSYNTHESIS
Grams Per Square Meter Per Day



Source: Reproduced from: Jen-hu Change, "Potential Photosynthesis and Crop Productivity," in *Annals of the Assoc. of Am. Geographers*, March 1970, p. 96.

Figure 4

the provision of artificial environment, the environment still has enough influence, through cost of production, to be important in the locating of greenhouse production.

ECONOMICS OF MARKETING

Just as the production of greenhouse crops entails special economic problems, so does the marketing process. Some of the financial aspects of marketing—the costs of the process and the variations in prices—have been touched upon in the previous section. Here, the focus will be on the nature of demand and the competitive aspects involved in marketing greenhouse food products within and between nations.

NATURE OF DEMAND FOR GREENHOUSE PRODUCTS

The demand for greenhouse products—the quantity that will be purchased at a given price, time, and place—is a key element in determining the success of the greenhouse industry. Although the nature of demand for greenhouse food appears to be somewhat different from that for other products, it has not been the subject of much formal study. The following can only be an outline of the general framework, augmented with a few details.

Initially, however, it might be useful to review two basic characteristics of greenhouse food crops. First, they are mainly salad crops. Such crops, whether from the open field or a greenhouse, are much more in the nature of luxury goods than basic foods like grain. They are not necessary to life but are highly regarded for the variety they lend to meals. Second, the greenhouse forms are normally marketed only when local field production is not readily available; the added costs involved in making the product available during this period add up to higher costs at retail than for in-season production. The combination of these two factors tends to limit consumption of greenhouse products to wealthier people or to those with a special desire for the product. Any development which lowers the cost or increases the consumer's level of income will tend to encourage purchases of such products—or of similar shipped-in produce.

Elasticity of Demand and Demand Curves

As a tool in analyzing these and other effects on demand, economists use a measure known as elasticity of demand. It reflects the percentage change in quantity purchased in response to a percentage change in price or income. Greenhouse products tend to have both high price and high income elasticities of demand. This means that with a decrease in price of 1 percent, the quantity purchased will usually increase more than 1 percent. With an increase in income of 1 percent, the quantity purchased would increase by perhaps nearly as much (the exact proportion is not known; few food products will increase more than 1 percent).[74]

The precise elasticity of demand for a given product will vary over a range of economic conditions. This relationship may be summarized graphically in the form of a demand curve, such as in figure 5: Price elasticity is a function of the slope of the demand curve; changes in elasticity may be shown by movements up and down the demand line. Income elasticity is expressed in the position of the curve—that is, in its distance from the axis (the greater the distance, the stronger the demand).[75]

Demand curves are useful for demonstrating the variation in price elasticity of demand for greenhouse products through the season, as well as the effect of longer term changes in economic variables. These are shown, respectively, through (1) a movement along the demand curve, and (2) a shift in the demand curve.

Movement Along Demand Curve

The nature of demand at retail for greenhouse products probably varies with the season and price. During the winter, total supplies are at their lowest and prices are high; as the season progresses toward summer, supplies increase from a number of sources and prices decrease. Hence demand is probably less elastic in the winter and more elastic in the summer.[76] This situation could be depicted by a movement down the demand curve in figure 5 (the actual curve may be kinked or discontinuous).

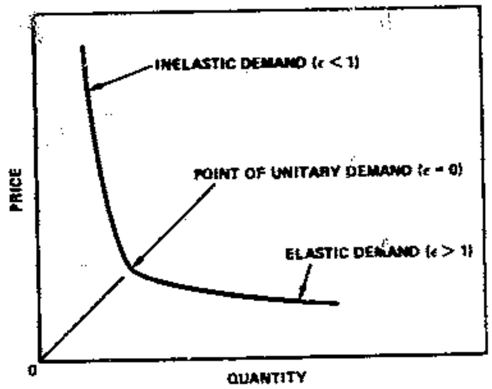
The question is, where does one start—in the inelastic or elastic portions of the curve? This depends on the specific product, the specific country, and probably the location of the retail sale. Data from several studies in Ohio indicated that the elasticity of demand in the spring for greenhouse tomatoes at retail is quite high (from −1.8 to −2.0).[77] Comparable data are not available for earlier and later in the season. To better appraise the effect of price changes on purchases, it would be desirable to have a more detailed seasonal breakdown for the United States as well as for other nations.

Shift in Demand Curve

There is also the possibility of a shift in the demand curve for greenhouse produce over time. This is most likely to occur when there is a marked and widespread increase in income, a drop in price relative to other goods, or a change in consumer preference. Such a shift appears to have taken place in Italy between the 1950's and the 1960's. The change in curves is depicted in figure 6. Note that there was not only a shift to the right but also a change in the slope of the curve to a more elastic (or horizontal) position.

How one views this change depends on his point of view. The original growers of the 1950's probably would have preferred to keep production at the same level and retain the higher prices of the period. But on the other hand, the lower prices of the 1960's considerably widened the market. Whereas formerly only the rich purchased greenhouse tomatoes, by the 1960's moderate income groups were also in a position to buy. A similar shift apparently

GENERALIZED DEMAND CURVE FOR GREENHOUSE VEGETABLES



Technical note: This curve is designed to fit under a rectangular hyperbola. In a straight-line demand "curve," the elastic and inelastic portions would be reversed.

Figure 5

took place in Turkey in recent years. From a social point of view, the broadening of the market is most desirable. It is doubtful, however, because of the costs of greenhouse production, that the process will ever go far enough to benefit lower income groups.

Greenhouse products, as was suggested earlier, do not usually have the market all to themselves, despite their special timing. Demand for them is strongly influenced by the availability and prices of substitutes. These substitutes can come from within or outside the country and may take many forms. This competition is the subject of the next two sections. The discussion is limited to salad produce.

INTRANATIONAL COMPETITION

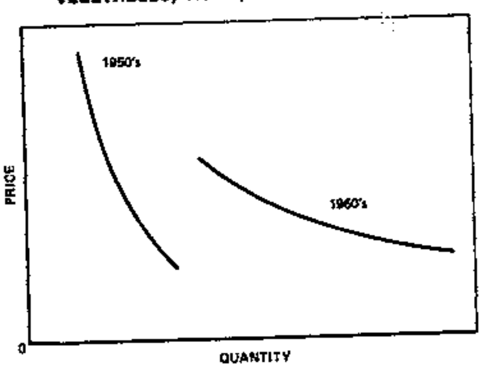
Greenhouse products can face a wider range of intranational competition from domestic production than might at first be evident. The two major forms of competition are with fresh and processed products.

Fresh Products

Greenhouse products may compete with field production or with output of other greenhouses.

(1) *Field Production.* Field production is undoubtedly the most important type of competition, particularly in nations with a wide range of climates. Greenhouse production seldom attempts to compete against local field production of the same crop during the same time period unless (a) the greenhouse product has a marked quality advantage, or (b) field production is a marginal proposition because of climatic conditions.

CHANGE IN DEMAND CURVE FOR GREENHOUSE VEGETABLES, ITALY, 1950'S AND 1960'S



Source: Lorenzo Venzi, *Il Mercato Delle Produzioni Serricole*, University of Naples, Centro di Specializzazione e Ricerche Economico-Agrarie Per il Mezzogiorno, Saggi e Ricerche 7, 1970, p. 81.

Figure 6

An example of the quality advantage is provided by the hydroponic production of tomatoes in greenhouses in the American southwest during the summer despite the presence of large quantities of much cheaper field tomatoes. There is evidently a certain sector of the market with a strong preference for the product because of real or imagined quality differences.

The field production of cucumbers and tomatoes outdoors in northern Europe is a marginal activity because of cool summer weather conditions. Greenhouse production, therefore, represents a significant proportion of total production. Cucumber output in Europe was concentrated in greenhouses as follows in 1968: Sweden, Netherlands, Belgium/Luxembourg, and the United Kingdom, all; Germany, about three-fourths; France, about half. The breakdown for tomatoes was: Sweden and Netherlands, nearly all; Belgium/Luxembourg and United Kingdom, about two-thirds; Germany, about a third. Lettuce is also largely raised in greenhouses in the Netherlands and Belgium/Luxembourg.[78]

Since greenhouse crops are for the most part grown out of the local season, the major form of competition usually comes from shipped-in produce. In the northern hemisphere, the shipped-in produce has come from more southerly regions in the same country or continent (the reverse would of course be true in the southern hemisphere).

Historically, southern-grown produce has had a marked influence on greenhouse growth in the United States. As early as 1904, Galloway wrote:

> Since the rapid expansion of vegetable growing in the South and the better facilities afforded for the shipment of such crops as lettuce, cucumbers, etc., the field for the growth of vegetables under glass has been considerably restricted.[79]

More than a decade later, Watts stated that "Southern competition is unquestionably the most serious obstacle to the development of vegetable forcing in the north." But he added, perhaps rather wishfully, that the "superior quality of greenhouse vegetables is becoming more generally recognized every year." Noting that the shipped-in produce was sometimes dumped because of a lack of markets, he indicated that the greenhouse products were generally sold, though sometimes at very low prices.[80] In subsequent years, tomatoes have emerged in the strongest competitive position, followed by lettuce and cucumbers.[81]

Similarly, in Australia, the improvement of internal transportation systems has led to increased production in the north and decreased production in the traditional glasshouse areas in the south. In particular, the opening up of standard gauge railroad links has increased the movement of tomatoes from the north to the south in the populous eastern half of the country during winter/spring.[82]

A key matter in such a setting may be the nature of demand for the greenhouse product compared with the shipped-in field product. The situation at retail is confusing in the northern United States. Greenhouse operators may feel that their product has a quality edge because of variety, protected growing conditions, greater maturity at harvest, and nearness to market. But these differences may add up to only subtle visual differences at retail.

Greenhouse products, moreover, are often not labeled as such. Tomatoes are a good case in point. Many consumers think that tomatoes packed in cardboard and cellophane tubes are greenhouse tomatoes; in fact they are usually field-grown tomatoes shipped in from other areas and then repacked by a local firm. Greenhouse tomatoes are more likely to be packed in plastic overwrapped trays in the retail store and may be higher in price. But even these generalizations may not hold in every case.[83]

Hence, it is not surprising that consumer tests in Ohio and Michigan in 1962 and 1963 revealed a lack of differentiation of demand for tomatoes:

– In the first Ohio investigation, price elasticities of demand were calculated for both local greenhouse and Florida tomatoes on the basis of retail sales; they proved to be essentially the same.[84] The second Ohio study indicated that "consumers are confused and don't really know what a greenhouse tomato is"; they did, however, indicate a preference for greenhouse tomatoes based on visual appearance and taste.[85]

– While 80 percent of those surveyed in one Michigan study said they could recognize a greenhouse tomato, most when put to the test could not.[86] Yet in another survey, 65 percent of the consumers selected the greenhouse tomatoes over ripened Florida tomatoes on the basis of appearance and taste.[87]

Thus while American greenhouse growers may be convinced of the superiority of their product over shipped-in produce, and while some consumers may share this view, the situation at retail in the northern States is such that greenhouse tomatoes may hold an initial edge solely on the basis of appearance. Many potential customers may not find appearance alone worth the extra price. And some who buy tube tomatoes thinking they are greenhouse tomatoes may not emerge with a very favorable conception of the greenhouse product. As we shall see, however, the situation is not so confused in the southwestern States.

(2) *Other Greenhouse Production.* In a purely national context, there is probably no great interregional competition in greenhouse food crops. They tend to be picked at a fairly mature stage and are generally not shipped far. An exception is provided in the case of Europe (to be discussed in a following section). And an Arizona firm is thinking of enlarging from 10 acres to 50 acres and shipping produce by air to the east coast.[88]

(3) *Stored Produce.* The current leading greenhouse crops are generally highly perishable and can be stored for only short periods of time. Therefore, they face little direct competition from other production which has been placed in refrigerated storage for later marketing. (In fact, very few fresh vegetables are stored for any length of time.)

Processed Products

One of the main characteristics of the greenhouse food crops presently grown, as noted in the introduction, is that they are purchased and consumed almost entirely in fresh form. The processed counterparts are largely quite different (tomatoes) or nonexistent (cucumbers, lettuce). The fact is that the major current items are salad vegetables, and salads, virtually by definition, are consumed in fresh form. The only exception is provided by gherkins or pickling cucumbers in Europe.

As production expands into other crops which have processed counterparts, such as frozen strawberries, the matter of competition could become of greater importance.

INTERNATIONAL COMPETITION

Perhaps the most severe competition for the greenhouse sectors in many countries comes from fresh production, both in the field and in greenhouses, in other nations. The situation in North America is somewhat different from that in Europe, so the two regions will be treated separately.

North America

The major international competition in the United States and Canada is provided by Mexico. A large irrigated winter vegetable area along the northwest coast of Mexico has been the source of sizable quantities of tomato exports to the United States and Canada since the early 1960's. Early in the period, tomatoes were shipped in the mature green stage; emphasis has since shifted to slightly more mature tomatoes which are known as "vine ripes."[89]

Mexico has several production advantages—relatively low labor costs, a favorable climate, and highly advanced production and marketing systems. A further factor has been the development of cherry tomato production:

> The cherry tomato can be harvested red and shipped without bruising, has high quality, is hardy, firm when ripe, prolific, and high yielding, and may be the first type of tomato to be harvested mechanically for the fresh market.[90]

All of these points add up to strong competition.

(1) *United States.* American imports of Mexican "vine ripe" tomatoes during the winter season increased from 9.1 million 40-pound units in 1963/64 to 16.0 million units in 1969/70. Their share of total U.S. tomato supplies increased from 14 percent to 37 percent during this period.[91] Part of the increase was at the expense of Florida tomatoes, but inevitably this shift has also meant increasing competition for greenhouse tomatoes.[92]

Still, domestic greenhouse tomatoes are evidently thought by some consumers to hold a quality edge over Mexican imports—enough so that they are willing to pay the higher price. Moreover, the region which one might think would suffer the most severe competition—the American southwest—has been a rapidly growing greenhouse area. Part of the answer in the southwest may lie in product differentiation: the greenhouse tomatoes are picked at a more advanced stage of maturity and are often labeled as hydroponic or greenhouse tomatoes.[93] Part of it is also timing: the Mexican shipments peak during February and March, southwest greenhouse production peaks later (though it begins to increase in March).[94]

Mexican tomatoes, therefore, have probably had more influence on the demand for Florida tomatoes than on demand for domestic greenhouse tomatoes. But the Mexican tomatoes may also have picked up the least affluent of the consumers who once bought greenhouse produce. And they may have cut into the U.S. export market in Canada.

(2) *Canada.* Despite their more remote location, Ontario growers have also felt the force of Mexican competition, both for cucumbers and tomatoes.

Mexican cucumbers are shipped in the earlier parts of the year and usually drop off as Canadian production comes on. They are considered more of a threat to field-grown cucumbers from the United States than to Canadian greenhouse cucumbers.[95]

As of 1969, Mexican vine ripe tomatoes were reaching the grocer's shelf in Canada about 2 weeks after picking. The cost at the Ontario Food Terminal in Toronto was just a little over half that for Canadian greenhouse tomatoes. The Mexican tomatoes normally begin to arrive in quantity in mid-December, after the Canadian fall crop, and continue through the winter. They have pushed into the early market for spring tomatoes—but may have cut as much into U.S. exports of greenhouse tomatoes to Canada as into Canadian production (which reaches the market slightly later).[96]

Europe

The international competition in North America may be mild compared with that in Europe. The situation is so complicated that it is a bit difficult to do justice to it in summary form. So let this section really be considered but an initial introduction. The major participants are listed in table 7.

It might be helpful to delineate three different competitive patterns: (1) that which has long existed between the developed European nations; (2) more

Table 7—Principal exporters and importers of greenhouse vegetables in Europe, 1970

Country	Quantity
	Metric tons
Exporters:	
Holland	505,000
Belgium	35,000
Bulgaria	33,000
Rumania	27,000
Importers:	
West Germany	440,000
United Kingdom	71,000
France	60,000
Sweden	30,000
Switzerland	11,000

Source: *L'Evolution de la Production Fruitiere et Legumiere Sous Serres en Europe,* Centre National du Commerce Exterieur, Paris, 1971, p. 19.

recent competition between southern and northern Europe, and (3) equally recent competition between Eastern and Western Europe. As before, the focus will be on tomatoes.

For many years, Holland was the primary source of greenhouse imports for the rest of Europe.[97] West Germany was the major importer, followed, at some distance, by the United Kingdom.[98] Over time, there was a shift to earlier spring marketings by the Dutch. The winter market was largely supplied by the Canary Islands and Spain.[99] Through the 1960's, the greenhouse area in Belgium and northern France expanded, increasing competition somewhat.

While winter vegetables have long been grown in the countries bordering the Mediterranean, competition has increased with a sharp expansion in the use of plastic greenhouses and row covers. The greenhouse expansion has been most pronounced in southern France, Italy, Greece, and Turkey. The use of row covers has been most important in Spain and Israel. Actual quantities exported through 1972 were not great, except for Spain and Israel, because internal demand largely absorbed production. But there is a threat of potential competition in the future as cultural marketing practices improve.[100] There is also a similar threat from outdoor production from southern Morocco, and more remotely from Tunisia and Egypt.[101]

But if the greenhouse competition from southern Europe is more potential than real at the moment, the same cannot be said for Eastern Europe. The various Eastern European countries have either rapidly expanded their greenhouse area or are now doing so. Area has already been expanded in Hungary, Rumania, and Bulgaria—largely to supply the export market in Europe during the winter and spring months; they have the potential to raise exports still further. Other East European countries seem less likely to emerge as exporters.[102]

Just how this overall pattern will be influenced by developments in the European Community is a question well beyond the scope of this study. Suffice it to say that the competitive situation of the late 1950's and early 1960's has subsequently undergone considerable change. The situation is unlikely to become less complex in the future.

* * *

In summary, it is clear that traditional greenhouse operators in northern regions have continually faced increasing competition from southern regions able to carry out lower cost field production. In the United States, this competition first came from southern States, but in the last 15 years it has grown to include sharp competition from Mexico. In Europe, competition has come from greenhouse areas in Eastern Europe and is increasingly likely to come from southern regions, some of which use inexpensive greenhouses and/or row covers.

This trend will undoubtedly continue. In the United States, increasing competition could conceivably come from Central America and northern

South America. Similarly, European operators could face increasing competition from north African nations. The extent of the developments, however, will depend on the nature and cost-reducing effects of production and transportation improvements.

ALTERNATIVES TO TRADITIONAL FOOD CROPS

Although a wide range of crops are raised in greenhouses, to a surprising degree greenhouse food production has centered on only a few. The reasons for this concentration have been alluded to in previous chapters, but it might be well to summarize them here.

– Desirable production characteristics: (1) comes into bearing or is ready for harvest within a short period, (2) fits in with existing crop patterns, (3) is responsive to intensive protected culture, and (4) can be produced reasonably economically.

– Desirable product characteristics: (1) high value, (2) consumed in fresh form, (3) no or quite different processed form, and (4) quality superior to field product.

Not all of these characteristics are of equal importance (superiority to field produce, for example, may not be so essential where there is little competition in an off-season market). And there are probably other factors in specific settings. But they are all reflected in the cost/returns balance.

Despite nearly 100 years of commercial food production in greenhouses, only three crops account for most of greenhouse production. But production and marketing patterns change. The sharply increased competition in European markets, for instance, has intensified the search for alternative crops. And additional alternative crops are beginning to appear. Some are food crops; others are not. The potential for the nonfood crops may well be better than for food crops—though the two could be tied together in rotations.

Among the food crops, perhaps the most promising at present are green peppers, green beans, and, in Europe, strawberries. They meet most of the preceding criteria. Both beans and peppers require growing conditions roughly similar to tomatoes, and have the advantage that they don't have to be picked so often. Peppers clearly fall in the salad class. Beans do not and are the only product (other than eggplant, which is sometimes raised) that normally is cooked before consumption. Strawberries have expanded in Holland; their main problem is the long time required to come into bearing (frozen strawberries are not yet common in Europe). Where adequate heat is no problem, eggplant, okra, and sweet corn might have possibilities. The present market for any of these crops, however, is not vast and new potential crops must be constantly sought.[103]

The nonfood crops with the greatest potential are cut flowers and bedding plants.

—Flowers. As noted earlier, flowers have come on very strongly in Holland as well as England. They are being given more serious attention in other traditional greenhouse areas. Flowers are probably the only type of crop which is more intensive than vegetables.

—Bedding plants. Near some of the metropolitan areas in the United States, there has also been a shift from vegetable crops to bedding plants. A portion of bedding plant output is composed of transplants for greenhouse use. According to one American authority, 25 percent of the bedding plants marketed are vegetables and, in turn, 50 percent of the vegetable plants are tomatoes (it is not clear, however, what proportion of the vegetable plants are used in greenhouses).[104] Some large firms in Holland specialize in the production of tomato, lettuce, and cucumber transplants for sale to greenhouse operators. Although no data are at hand, it appears that the proportion of transplants purchased from bedding plant firms compared with the proportion raised by the greenhouse operator may be rising.

But all of this is not to say that many growers will switch entirely to flowers and bedding plants. Some will, but others may increasingly integrate these crops into what are now purely food crop rotations. Where flowers and bedding plants can produce an extra crop during an otherwise idle or poorly used period, they may provide bonus income. Alternatively, we may see some growers swing mainly over to ornamental crops with food crops as minor elements in the rotation. More research attention is now being given to the matter of mixed rotations in Holland and probably in other nations as well. If the process works out, it is only to be welcomed, for it will increase employment and increase the profitability of investment of greenhouses.

* * *

This completes our general review of the economics of environmental control as found in greenhouse food production. It has taken us through four main areas: intensity of factor use, economics of production, economics of marketing, and alternatives to traditional food crops. Clearly much more research remains to be done on these issues.

REFERENCES AND NOTES

1. It has been noted elsewhere that the extent of multiple cropping alone is not a keen measure of land use intensity (Dana G. Dalrymple, *Survey of Multiple Cropping in Less Developed Nations*, U.S. Department of Agriculture in cooperation with U.S. Agency for International Development, FEDR-12, October 1971, p. 8). Total yields are difficult to handle if sharply different crops are planted. Probably the best measure would take into consideration number of days cropped *and* value of annual production. But this would require better statistics than are available for most nations. Until more sophisticated measures are developed, the material provided here may serve to give a fair idea of cropping intensity.

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GLOBAL REVIEW OF GREENHOUSE FOOD PRODUCTION. (~~Foreign~~ Agricultural Economic Report). / Dana G. Dalrymple. Washington, DC: Economic Research Service. Oct. 1973. (NAL Call No: A281.9/Ag8F)

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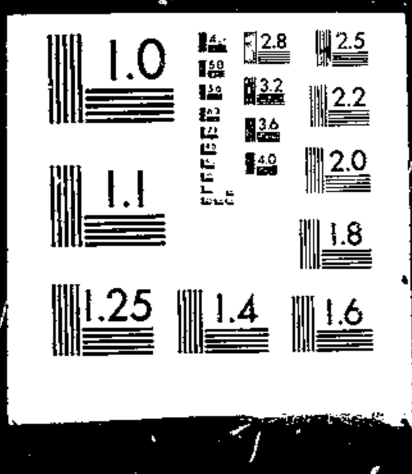

2. Henry A. Dreer, *Vegetables Under Glass,* Philadelphia, 1896, pp. 52, 55, 59.

3. Liberty Hyde Bailey, *The Forcing Book; A Manual of the Cultivation of Vegetables in Glass Houses,* Macmillan, New York, 1897, p. 7.

4. Letter from Linnis Mills, County Extension Agent-Horticulture, Southern Nevada Field Laboratory, University of Nevada, Logandale, March 17, 1972.

5. For details, see: S. H. Wittwer and S. Honma, *Greenhouse Tomatoes; Guidelines for Successful Production,* Michigan State University Press, East Lansing, 1969, pp. 8-10; Allan K. Stoner, *Commercial Production of Greenhouse Tomatoes,* U.S. Department of Agriculture, Agriculture Handbook No. 382, January 1971, pp. 10, 11.

6. R. C. Thompson, S. P. Doolittle, and T. J. Henneberry, *Growing Lettuce in Greenhouses,* U.S. Department of Agriculture, Agriculture Handbook No. 149, November 1958, p. 1.

7. S. W. Wittwer, S. Honma, and W. Robb, *Practices for Increasing Yields of Greenhouse Lettuce,* Michigan State University (East Lansing), Agricultural Experiment Station, Research Report 22, October 1964, pp. 1, 3, 4; Wittwer and Honma, *op. cit.*, pp. 11, 12.

8. James H. Beattie, *The Production of Cucumbers in Greenhouses,* U.S. Department of Agriculture, Farmers' Bulletin No. 1320, May 1923, pp. 5-6; Merle H. Jensen, "Take A Look at Seedless Cukes," *American Vegetable Grower,* November 1971, pp. 20, 22.

9. Stoner, *op. cit.*, p. 30; Wittwer and Honma, *op. cit.*, pp. 2, 9; Elton S. Banta, "Acres. . .of Tomatoes and Lettuce Under Glass," *American Vegetable Grower,* December 1955, p. 8; "Garden Farms Tries Double Cropping," *American Vegetable Grower,* January 1968, p. 28; "Sunripe, Inc.," *American Vegetable Grower,* November 1968, p. 22; letter from M. E. Cravens, Department of Agricultural Economics and Rural Sociology, Ohio State University (Columbus), October 27, 1972.

10. *Vegetables, Fresh Market, 1971 Annual Summary,* U.S. Department of Agriculture, Statistical Reporting Service, December 17, 1971.

11. A small survey taken in Essex County, Canada, in 1965 and 1966 revealed average yields of about 62 short tons for the spring crop, 19 for the fall crop, and 81 tons for both crops. (G. A. Fisher and Paul Hedlin, *Greenhouse Vegetable Production in Essex County; Production Costs, Returns, and Management Practices 1965 and 1966,* Ontario Department of Agriculture and Food, Farm Economics, Cooperatives, and Statistics Branch, February 1971, p. 20.)

12. G. P. Shipway, *Agricultural Mechanization: Modern Methods of Cultivation and Harvesting of the Main Vegetables Under Glass,* United Nations Economic Commission for Europe, Geneva, Agri/Mech/19, 1961, p. 8; Banta, *op. cit.*, p. 8; A. H. Gill, *Cucumber Production in the Lea Valley. 1969,* University of Reading, Department of Agricultural Economics and Management, Agricultural Enterprise Studies in England and Wales, Economic Report No. 2, November 1970, p. 5.

13. *Selskoye Khozyaystvo SSR*, Moscow, 1971, p. 217.

14. The highest total rice production attained in the world as of 1969 was 23.6 metric tons per hectare. This was achieved under triple cropping on an experimental farm in the Philippines. (*The International Rice Institute Annual Report, 1969,* pp. 110-111.)

15. To simplify the presentation, I have—as indicated in footnote 1 of table 3—converted actual hours into man-years on the basis of 2,000 hours = 1 man-year. It should be realized that the labor requirements are not evenly spread through the season, so that more men may actually be required at one time and less at another. Although factual data are not at hand, labor requirements in a double cropped greenhouse should be considerably more even than in field culture. As noted earlier, some U.S. growers raise a fall tomato crop in large part to keep labor employed over a longer period.

16. Data compiled by Joseph Barse from the *Statistical Yearbook of the Ministry of Agriculture, 1969-1970* (in Japanese), tables 60, 66.

17. J. de Bagneaux and J. Dujardin, *Evolution de la Rentabilite des Serres Maraicheres,* Centre Technique Interprofessional des Fruits et Legumes, Paris, CTIFL Documents 9, November 1966, p. 13. Data from Orleans area in the early to mid 1960's.

18. Hunter Johnson, Robert Rock, and Paul Moore, "Estimated Costs for Producing

Greenhouse Tomatoes in California," University of California (Riverside), Agricultural Extension Service, May 1972, p. 5; P. S. Dhillon and P. J. Kirschling, *Profitability of Tomato Production Under Plastic Greenhouses,* Rutgers University (New Brunswick, N.J.), Department of Agricultural Economics and Marketing, A.E. 335, June 1971, p. 7.

19. Individual task times have been studied in detail in Holland (*Taaktijden voor Sla, Tomaten en Komkommers,* Instituut voor Tuinbouwtechnick, Wageningen, Holland, Publicatie 71, December 1971, 68 pp.).

20. Cited by James K. Rathmell, Jr., "Rathmell Reports from Europe 4: Parting Observations," *Florists' Review,* January 27, 1972, p. 25.

21. The firms were located in Ohio, Indiana, and Illinois. The units would be quite different in design from those noted in table 4.

22. R. A. Norton, "Factors to Consider in Growing Greenhouse Tomatoes," Washington State University (Pullman), Cooperative Extension Service, EM 3699, October 1972, p. 6.

23. This is the prorated price of a 50,000 square foot structure, including an entry building and a standby power plant. It assumes construction on a level plot in a rural non-union area. It does not include primary power installation, lighting, plumbing, "or other appurtenances not specifically relating to the function of the bubble proper." (Letters from Harvey B. Leaver and W. Sidney Sugg, Environmental Structures Inc., Cleveland, March 6, November 16, 1972.)

24. Information provided by G. F. Sheard, Glasshouse Crops Research Institute, Rustington, Littlehampton, Sussex, England, February 18, 1972.

25. *L'Evolution de la Production Fruitiere et Legumiere Sous Serres en Europe,* Centre National du Commerce Exterieur, Department des Etudes de Marches Agricoles et Alimentaires, Paris, 1971, p. 31. More detailed estimates of investments in various types of structures in Holland are provided by P. G. A. Weber in *Investeringen en Jaarkosten van Kastypen in de Groenteteelt (Prijspeil Winter 1971/1972),* Landbouw-Economisch Instituut, The Hague, Mededelingen & Overdrukken 85, 24 pp.

26. G. F. Sheard, "Expectations About Technical Aspects of the Development of Protected Cropping" (Symposium on Vegetable Growing Under Glass, June 1965), *Acta Horticulture* (The Hague), June 1966, p. 188.

27. Here we exclude depreciation and interest on investment as they do not represent annual out of pocket costs. They will, however, be included in subsequent calculation of fixed costs.

28. This estimate is based on data subsequently presented in table 6 and in Johnson, *op. cit.,* p. 6.

29. A. J. de Visser, *Bedrijfseconomische Aspecten van de Augurkenteelt in Onverwarmde Kassen,* Landbouw-Economisch Instituut, The Hague, No. 4.9, August 1968, 44 pp.

30. *Balance Sheet of the Farming Sector,* U.S. Department of Agriculture, Agricultural Information Bulletin 356, December 1971, tables 23, 24.

31. Bailey, *op. cit.* (1897), p. 2.

32. It is not clear whether interest on operating capital is fully reflected in the U.S. figures. It is included in the Canadian estimates. The Canadian dollar was worth slightly more than the U.S. dollar in the 1960's, but no adjustment has been made.

33. A recent study of 33 greenhouse vegetable operations in Indiana indicated roughly the same breakdown for multiple cropping involving tomatoes and lettuce, but with labor costs representing slightly higher proportions (Jerry Robertson and Glenn Sullivan, "The Greenhouse Tomato Industry: Production Trends, Production Economics, and Competitive Position," Purdue University (LaFayette, Ind.), Department of Horticulture, manuscript, February 1973).

34. J. A. L. Dench, *Financial Results of Horticultural Holdings, Average Results for the Three Crop Years 1968-70,* University of Reading, Department of Agricultural Economics and Management, January 1972, p. 10. The data include small areas of outdoor crops (less than 10 percent of gross crop output). It is not clear how many glasshouses

were included in this sample, but it was drawn from a group of 170 horticultural holdings. Summary data for 8 houses are provided in W. L. Hinton and W. C. Housden, *Economic Results from Horticulture, 1970 Harvest Year,* University of Cambridge, Department of Land Economy, Agricultural Economics Unit, April 1972, table 1.

35. L. van Noort, *Rentabiliteit van de Tuinbouw in het Zuidhollands Glasdistrict,* Landbouw-Economisch Instituut, The Hague, Mededelingen and Overdrukken 78, 1972, p. 15. The data apply to greenhouses which receive more than 65 percent of their income from vegetables and hence may include small quantities of fruit and flowers. Interest is included.

36. de Bagneaux and Dujardin, *op. cit.,* p. 12.

37. R. R. W. Folley, *Tomato Growers' Interests in a West European Market,* Wye College (University of London), Department of Agricultural Economics, 1964, p. 20.

38. Liberty Hyde Bailey, *Experiments in the Forcing of Tomatoes,* Cornell University, Agricultural Experiment Station, Bulletin 28, June 1891, p. 45. For further historical price references see: Bailey, *op. cit.* (1897), p. 153; and George E. Stone, *Tomatoes Under Glass,* Massachusetts Agricultural College, Bulletin No. 105, August 1905, pp. 1, 9.

39. J. D. Brown and M. E. Cravens, *Retail Margins on Tomatoes,* Ohio Research and Development Center (Wooster), Research Bulletin 984, February 1966, pp. 12-14. The period covered was March to June.

40. See Wittwer and Honma, *op. cit.,* p. 68.

41. Data provided by Charles Porter, Vegetable Section, Economic Research Service, U.S. Department of Agriculture.

42. See *L'Evolution, op. cit.,* p. 323.

43. H. Blum, *Marketing of Ontario's Greenhouse Vegetable Products in Competition with Imports from Mexico,* Ontario Department of Agriculture and Food, Farm Economics, Cooperatives and Statistics Branch, Toronto, May 1969, p. 3.

44. W. Cadet, *Le Marche des Legumes de Serre Francais,* Centre Technique Introprofessional des Fruits et Legumes, Paris, CTIFL Documents No. 15, July 1967, p. 15.

45. Fisher and Hedlin, *op. cit.,* p. 35.

46. R. R. W. Folley, *Business Aspects of Horticultural Production Under Glass,* Studies in the Economics of Intensive Horticultural Holdings, Wye College (University of London), Report No. 1, August 1967, p. 13.

47. van Noort, *op. cit.,* p. 18.

48. The latter, for instance, was the case in the Orleans area of France from 1961/62 to 1967/68 (see *L'Evolution, op. cit.,* p. 65).

49. van Noort, *op. cit.,* p. 18.

50. Letter from John E. Larsen, Extension Vegetable Specialist, Texas A&M University (College Station), March 7, 1971.

51. Blum, *op. cit.,* p. 65.

52. Johnson, *op. cit.,* p. 6.

53. Blum, *op. cit.,* p. 86.

54. van Noort, *op. cit.* Dutch growers, on the other hand, avail themselves of more contract and hire services such as custom spraying and the purchase of transplants.

55. T. Shimizu, "Onshitsu Kyogyo Keiei ni Okeru Kibo no Keizai" (Economies of Scale in Cooperative Greenhouse Farming), *Noringyo Mondai Kenkyu,* Kyoto, 1971, pp. 1-13. (Abstract in *World Agricultural Economics and Rural Sociology Abstracts,* December 1971, item 5069.)

56. Robertson and Sullivan, *op. cit.*

57. *Tuinbouwcijfers, 1972, op. cit.,* p. 28; D. Meijaard, "De Glasgroenteteelt in Nederland," *Economische Statistische Berichten,* Rotterdam, 1971 (56, 2783), pp. 100-104. (Abstract in *World Agricultural Economics and Rural Sociology Abstracts,* June 1972, item 2333.

58. This matter is discussed in further detail in ch. IV. The key original reference is *Report on Early Vegetable Production,* Project 14A, 1968-69, T. C. Tarim Bakanligi, Antalya, Research Report No. 2, pp. 5E-11E.

59. Based on K. J. DeVries, "The Economical Comparison of Greenhouse Types," in *Advances in Horticultural Science and Their Applications* (Proceedings of the XVth International Horticultural Congress, Nice, 1958; ed. by Jean-Claude Garnaud), Permagon Press, 1962, Vol. 3, pp. 338-340.

60. *Report of the Survey Team Established by the Minister for Agriculture and Fisheries on the Glasshouse Industry*, Department of Agriculture and Fisheries, Dublin, 1966, p. 24.

61. Some farm management studies have, however, revealed *ex post* profit variations between different combinations. One Canadian study indicated differing levels of losses as follows: tomatoes/cucumbers/tomatoes—$3,219; tomatoes/tomatoes—$4,169; and tomatoes/cucumbers—$6,262 (Fisher and Hedlin, *op. cit.*, p. 35. The sample included 21 records for 1965 and 1966; 7 of the same farms were in each group).

62. Allan N. Rae, "An Empirical Application and Evaluation of Discrete Stochastic Programming in Farm Management," *American Journal of Agricultural Economics*, November 1971, pp. 626-636; D. Yaron and U. Horowitz, "A Sequential Programming Model of Growth and Capital Accumulation of a Farm Under Uncertainty," *American Journal of Agricultural Economics*, August 1972, pp. 441-451. Also see D. Meijaard: "The Importance of Farm Comparison and Linear Programming in Farm Management Research of Greenhouse Crops" (meeting on Horticultural Economics, July 1968), *Acta Horticulture* (The Hague), April 1969, p. 108.

63. R. F. Fletcher and Reed D. Taylor, "Making Decisions With the Help of Computers," *American Vegetable Grower*, November 1965, pp. 16, et seq. In the case of the farm studied, the most profitable pattern essentially involved double cropping of tomatoes with part of one crop devoted to bedding plants and geraniums.

64. These programs are summarized in *L'Evolution, op. cit.*, pp. 34, 35. In addition, information on the Irish program has been provided by the U.S. Agricultural Attache in Dublin, and the existence of a program in Austria was noted by the Office of the U.S. Agricultural Attache in Vienna.

65. Folley, *op. cit.*, (1968, *Investment Aspects. . .*), p. 9.

66. R. R. W. Folley, "Investment in Practice: With Special Reference to Grant-Aided Production of Crops Under Glass," *Journal of Agricultural Economics* (U.K.), January 1972, p. 25.

67. See Jen-hu Chang, "Potential Photosynthesis and Crop Productivity," *Annals of the Association of American Geographers*, March 1970, pp. 92-101. Chang presents summary maps based on data from 644 weather stations throughout the world, based on periods of 4, 8, and 12 months.

68. Wittwer and Honma, *op. cit.* (1969), p. 3.

69. *Ibid.*; Sylvan H. Wittwer, "The Greenhouse Industry. . .Where Are We Headed?" *American Vegetable Grower*, November 1971, pp. 34, 54; D. J. Coulter and C. E. Chaplin, "A Review of Plastic Greenhouses: The Problems, Progress and Possibilities," *HortScience*, Spring 1967, p. 9.

70. O. Janasson, "Agricultural Regions of Europe," *Economic Geography*, October 1925, p. 286. Discussed by Howard F. Gregor in *Geography of Agriculture: Themes in Research*, Prentice Hall, Englewood Cliffs, N.J., 1970, p. 60.

71. Lorenzo Venzi, *Il Mercato Delle Produzioni Serricole*, Universita di Napoli, Centro di Specializzazione e Richerche Economico-Agrarie per il Mezzogiorno, 1970, pp. 137-138.

72. R. R. W. Folley and R. A. Giles, *Locational Advantage in Tomato Production*, Wye College (University of London), Department of Economics, 1966, pp. 4, 5, 31. While yields tend to diminish and heating costs increase in a northerly direction, northern growers have tended to plant for later picking, for which they received the same or better price in their local markets.

73. R. Gardner, "Some Aspects of Horticulture in the Soviet Union," *NAAS Quarterly Review* (U.K.), Summer 1968, p. 180. For a more recent discussion of this matter, see *Pravda*, October 10, 1972, p. 10 (translation in *Current Digest of the Soviet Press*, November 8, 1972, p. 5).

74. These comments are based on a survey of price and income elasticities of demand for fruits and vegetables which I prepared several years ago and which are reported in *A Handbook on the Elasticity of Demand for Agricultural Products in the United States*, Western Extension Marketing Committee, WEMC Publication No. 4, July 1967, pp. 82-129.

75. The position of the curve, as will be noted subsequently in the text, can also be influenced by changes in consumer preference or in the price of competing products.

76. This hypothesis is supported by a study of the seasonal price elasticity of demand for lettuce in the United States during the 1930 to 1955 period (excluding 1942-46). Elasticities changed as follows: winter–1.02; spring–1.99; summer–2.15. (R. S. McGlothlin, *Price Relationships in the Western Lettuce Industry*, University of Arizona (Tucson), Agricultural Experiment Station, Bulletin 287, June 1957, p. 25.)

77. Marshall R. Godwin and William T. Manley, *Demand and Competitive Relationships for Florida and Greenhouse-Grown Tomatoes*, University of Florida (Gainesville), Agricultural Experiment Station, Bulletin 703, December 1965, p. 16 (data gathered in spring of 1963); Glen J. Vollmar, "An Analysis of the Retail Sales of Ohio Greenhouse Tomatoes for the 1955, 1956, and 1957 Spring Crops," Ohio State University, Department of Agricultural Economics, MS thesis, 1959, pp. 13, 14. Over the 1932 to 1956 period, the average price elasticity of demand of spring tomatoes at wholesale on the Toledo market was computed as –2.45 (maximum likelihood) and –4.32 (least squares) (Abbas Ghezelbash, "An Econometric Analysis of the Greenhouse Tomato Market in Ohio," Ohio State University (Columbus), Department of Agricultural Economics, Ph.D. dissertation, 1957, p. 123).

78. *The Fresh Fruit and Vegetable Markets in Seven European Countries, Vol. 2, Selected Fresh Vegetables*, International Trade Center, UNCTAD-GATT, Geneva, 1968, pp. 11, 79, 98, 115, 138, 183. Another reference suggests that the figures for cucumbers in 1966 were: Germany, 2/5; France, 2/3 (Cadet, *op. cit.*, p. 1).

79. B. T. Galloway, "Growing Crops Under Glass," *Agriculture Yearbook, 1904*, U.S. Department of Agriculture, 1905, p. 165.

80. Ralph L. Watts, *Vegetable Forcing*, Orange Judd Co., New York, 1917, p. 6.

81. R. C. Thompson, S. P. Doolittle, and T. J. Henneberry, *Growing Lettuce in Greenhouses*, U.S. Department of Agriculture, Agriculture Handbook No. 49, November 1958, p. 1; Jensen, *op. cit.*, p. 20.

82. Letter from L. V. Kavanagh, Chief, Division of Plant Industry, Department of Agriculture, New South Wales, June 2, 1972.

83. Based on discussions with Eugene Cravens, Department of Agricultural Economics, Ohio State University (Columbus), November 1972.

84. Godwin and Manley, *op. cit.*, p. 16. The study was conducted in the spring of 1963. An earlier study in Ohio revealed very high cross elasticity of demand between greenhouse and repacked tomatoes (Ghezelbash, *op. cit.*, pp. 119, 123-125).

85. Fred K. Buscher, "What's Your Image?" *American Vegetable Grower*, March 1964, p. 52. Based on a survey by Paul R. Thomas and Edgar Watkins in suburban Cleveland in the fall of 1963.

86. *Ibid.* Based on a survey by John Tocke in Grand Rapids in December 1963.

87. H. E. Larzelere and R. R. Dedolph, "Consumer Acceptance of Greenhouse Grown and Southern Field-Grown Tomatoes," *Quarterly Bulletin*, Michigan State University (East Lansing), Agricultural Experiment Station, February 1962, pp. 554-558.

88. "Superior Farming Company Proudly Presents Environmental Farms, Inc.–The Latest Industrial Concept in Controlled Environment Agriculture," January 29, 1973.

89. The tomatoes actually show only a pinkish core which is reflected on the outer side by coloration around the calyx. The more pinkish tomatoes are shipped to California.

90. Wittwer and Honma, *op. cit.*, 1969, pp. 86, 87.

91. M. E. Cravens, "Competition in the Winter Tomato Industry," *Greenhouse Vegetable Day*, Ohio Agricultural Research and Development Center (Wooster), Research Summary 50, April 1971, pp. 45, 46. U.S. imports of cherry-type tomatoes from Mexico are excluded.

92. Florida growers at first responded by increasing the area of tomatoes grown on trellises and harvested in the "vine ripe" gas to hasten the coloring of mature green tomatoes in refrigerated chambers. By 1973/74, it is expected that nearly every large operator in Florida will have such facilities. Some Mexican tomatoes have also been similarly treated in Mexico or in Nogales, Ariz. (Based on material provided by John Brooker, Economic Research Service, U.S. Department of Agriculture, Gainesville, Fla., January 15, February 5, 1973.)

93. See, for example, William Spencer, "Spotlight on Economics at North American Greenhouse Conference," *American Vegetable Grower*, November 1972, pp. 56, 58.

94. Larsen, *op. cit.*

95. Blum, *op. cit.*, pp. 7-11.

96. *Ibid.*, pp. 11, 15, 17, 20, 45, 55, 65, 77.

97. For further details on the Dutch export market as of the early 1960's, see M. T. G. Muelenberg, "A Quantitative Investigation into the Dutch Tomato Market: A Seasonal Analysis," *Netherlands Journal of Agricultural Sciences*, August 1964, pp. 170-185.

98. English imports of Dutch tomatoes are discussed by Folley, *op. cit.* (1964), pp. 16, 17, 47. England also receives early tomatoes from Guernsey. In fact, the Guernsey imports compete to some extent with those from the Canary Islands (see "Guernsey Tomato Supplement," *Fruit Trades Journal*, May 5, 1972, p. 20).

99. Details on exports by the Canary Islands and Spain are provided in *Production, Consumption and Foreign Trade of Fruit and Vegetables in OECD Member Countries, Present Situation and 1970 Prospects, Tomatoes*, OECD, Paris, 1968, pp. 42, 94.

100. Developments in these areas will be discussed in greater detail in the next chapter. A useful background reference is provided by Jean-Claude Garnaud, *L'Intensification des Productions Horticoles du Bassin Mediterranean par la Culture Protegee*, FAO, AGPC: Misc. 10, 1971, 146 pp.

101. This comment is based on personal visits in Morocco and Tunisia in June 1972 and on two FAO publications: *Horticulture in the Mediterranean Area: Outlook for Production and Trade*, FAO, Commodity Bulletin Series 42, 1963, p. 20 (para. 58); and Garnaud, *op. cit.*

102. Developments in Eastern Europe will be discussed in greater detail in the next chapter. Also see: *Horticulture in. . ., op. cit.*, p. 20 (para. 59); and *Production, Consumption. . ., op. cit.*, p. 95.

103. This discussion is based in part on: "Guernsey Tomato Supplement," *op. cit.*, pp. 14, 18; various papers by A. A. M. Sweep and a visit to Holland; Folley, *op. cit.* (1964), pp. 24, 31, 47; Gibson, *op. cit.*, p. 16 and a visit to Turkey; and Venzi, *op. cit.*, p. 137.

104. Wittwer, *op. cit.* (1971), p. 38.

V STATUS IN INDIVIDUAL NATIONS

This chapter reviews the status of greenhouse food production in 42 nations. Major emphasis is placed on current statistical measures, particularly those relating to crop area, production, or value. Some more general historical and economic material is included for several of the larger nations.

The degree of coverage varies considerably—from several pages for Holland to a short paragraph for Malta. In general, the amount of text is roughly proportional to the importance of greenhouses in the 42 nations. There are exceptions: in a few cases, such as Turkey, I was able to visit the nation and was able to obtain additional information directly; in some cases, such as Mainland China, data simply do not seem to be available.

Because greenhouse food production in neighboring nations often shares some of the same characteristics, the countries have been placed in regional groupings. The regions are North America, Europe, North Africa, West and East Asia, and Oceania. With one exception (the Philippines), the known greenhouse food crop area is either north of the Tropic of Cancer or south of the Tropic of Capricorn; the boundaries might even be extended to 30° north and 30° south.

Since detail, some of it of a fairly routine nature, is included here for a large number of countries, the general reader may wish to skip over portions of the chapter. Countries which might be of special interest are: The United Kingdom, Holland, France or Italy, the USSR, Bulgaria, Turkey, Abu Dhabi, Japan or South Korea, and the Philippines.

Where reference is made to total greenhouse area, nonfood crops such as flowers and potted plants may be included. The total food crop area is identified as such.

NORTH AMERICA

Greenhouses are found in virtually every U.S. State and Canadian Province, but commercial vegetable production has traditionally been concentrated southeast and north of Lake Erie. In the United States, this was partly historical accident.[1] In Canada, it represented an attempt to find the most favored growing area.

United States. Despite a long background in greenhouse vegetable production in the United States, the industry is quite modest in size. This is because, as suggested earlier, a wide variation in growing conditions exists in the United States, making outdoor culture of food crops feasible any time of year. Furthermore, transportation is highly developed. While the discussion in this section will focus on the 48 mainland States, greenhouses are also found in Alaska[2] and Hawaii.[3]

One unfortunate side effect of the small size of the industry is that few statistics are available. In fact, the only comprehensive data are gathered by the U.S. Census every 10 years--and they have included vegetables only four times. Census data for the past 80 years are summarized in table 8. In 1969 and 1970, the vegetable area represented only about 11 percent of total greenhouse area, perhaps the lowest proportion of any country with a significant greenhouse industry. In 1969, the planted area was 1,029 acres (table 9), as opposed to 575 acres of greenhouses used primarily for vegetable production in 1970 (table 8); this meant a multiple cropping index of 1.79. Compared with 1959 area, the greenhouse area declined but the cropped area increased, suggesting a sharp increase in multiple cropping.

Table 8—Greenhouse area in the United States, selected years, 1889-1969[1]

Year	All crops		Vegetables	
	Acres	*(Hectares)*		
1889	891	(361)	NA	
1899	[2] 2,209	(894)	[3] 103	[3] (42)
1909	[2] 2,632	(1,065)	NA	
1919	[2] 3,727	(1,508)	NA	
1929	[4] 3,980	(1,611)	1,285	(520)
1939	4,709	(1,906)	NA	
1949	4,394	(1,778)	629	(255)
1959	5,227	(2,115)	709	(287)
1969	5,202	(2,105)	[5] 575	(233)

NA = not available.
[1] Excludes Alaska and Hawaii.
[2] Area under glass; includes sashes and cold frames.
[3] Not directly based on U.S. census (see source below).
[4] This figure was reported as 4,098 acres in a subsequent census.
[5] 1970 (from Census of Horticulture).

Sources: U.S. Census reports except for the 1899 vegetable estimate, which is from B. T. Galloway, "Progress of Commercial Growing of Plants Under Glass," *Yearbook of the United States Department of Agriculture*, 1899, p. 586.

Independent estimates of greenhouse area have been compiled by an American trade journal for 4 recent years. They lump both vegetable and bedding plants together for 3 of the years, but do sort them out for 1971. The total estimated areas, including Alaska but excluding Hawaii, were as follows:

	Total area		Proportion covered with--		
			Glass	Plastic	Other[1]
	Acres	(Ha.)	Percent		
1965	1,686	(682)	72	23	5
1966	1,807	(731)	68	27	5
1967	1,872	(758)	65	28	7
1971	2,920	(1,182)	49	44	7

[1] Fiberglass, PVC.

In 1971, about 51 percent of the total area, or 1,490 acres, was reportedly devoted to vegetables. At least some of this total is believed to have represented cropped area: still, it is well above the highest census figure. The other 49 percent of the area was made up of bedding plants, which accounted for most of the expansion in total area by 1971. Much of the growth in area was in plastic houses.[4]

As mentioned, four censuses have reported the farm value of major greenhouse crops. The total value of greenhouse vegetable production increased as follows: 1929, $9.66 million; 1949, $13.0 million; 1959, $19.5 million; and 1969, $24.0 million. Inflation accounted for most of the increase.[5] The detailed breakdown for 1969 is presented in table 9.

Table 9—Area and value of leading greenhouse crops in the United States, 1969[1]

Crop	Total area[2]	Value per acre	Total value
	Acres	Dollars	Dollars
Tomatoes	651.4	29,555	19,252,038
Lettuce	272.0	12,638	3,437,606
Cucumbers	36.2	21,710	785,918
Other	69.3	17,749	1,230,037
All vegetables	1,028.9	24,012	24,705,599

[1] Excludes Alaska and Hawaii.
[2] Area planted.

Source: "All Farms; United States," Agriculture Division, Bureau of the Census, May 1972, table 25, p. 8.

Among the individual vegetables, tomatoes accounted for about 63 percent of the total area, had the highest value per acre, and accounted for about 78 percent of the total value. They were followed by lettuce with 26 percent of the total area and 14 percent of the value, and by cucumbers with 3.5 percent of the area and 3 percent of the value. Compared with 1959, the proportion of area devoted to tomatoes dropped 4 percent and the proportion of total value represented by tomatoes declined by 5 percent. In contrast, both the area and value of "other" vegetables (excluding cucumbers and lettuce) increased.

Traditionally, the U.S. greenhouse vegetable industry was located in the northeastern States (from Indiana eastward and northward). But in recent years, the industry in these areas has tended to stabilize, with much of the new construction taking place elsewhere in the country—particularly in the southwest. The reasons, noted earlier, are based on a number of technical, ecological, demographic, and economic factors. Some of the former vegetable houses are being used for flowers and bedding plants.

Canada. The overall greenhouse industry in Canada is relatively small compared with that in the United States, but vegetables appear to represent a larger portion of the total area. Total greenhouse area has expanded slowly in recent years:

	Acres	*(Hectares)*
1966	591	(239)
1968	667	(270)
1970	747	(302)

In 1970, about 77 percent of the area was under glass and 23 percent under plastic.[6] Just how much of the total area is used for food crops is not known. One estimate, however, suggests that in 1970, the area in Ontario (which represented about 80 percent of greenhouse area in Canada during 1960-66) was almost equally divided between vegetable and floricultural products.[7]

Data are available, however, on the farm value of the total greenhouse vegetable crop. These may be summarized as follows:

	Dollars (Canadian)
1966	8,989,000
1968	10,649,000
1970	10,794,000

Tomatoes have consistently been the leading crop since 1965, followed by cucumbers, lettuce, and other vegetables. In 1970, tomatoes accounted for 72 percent of total value, cucumbers 26 percent, lettuce 1 percent, and other vegetables 1 percent. The value of cucumbers dropped sharply from 1968 to 1970.[8] In 1966, greenhouses provided 16 percent of Ontario's fresh tomatoes and almost 20 percent of its cucumbers.[9]

Two crops of tomatoes are usually grown annually—one in the fall and one in the spring. One long-season crop of cucumbers is usually grown from mid-January to July.

Bermuda.[10] Bermuda is hardly known for its greenhouse industry. Yet it contains a plastic greenhouse operation which is of technical interest far beyond its modest area. The basic reason relates to its adaptation to a semitropical climate with saline ground water.[11]

The plastic greenhouse operation totals about 3 acres and is found on one of the less heavily populated islands. The structure is needed to provide protection from strong salty winds in the winter and from sporadic heavy rainfalls. Since groundwater is brackish, the roof is used to collect rainwater which is fed into man-made ponds (or cisterns) to be used for irrigation. In addition, the operators have recently purchased a small desalting unit which will be used as an emergency source of irrigation water (water from the unit is otherwise sold for drinking purposes).

The main crops are lettuce and tomatoes. Some 2¼ acres are used for lettuce and six crops are grown per year. Summer temperatures are high for lettuce even with the sides of the houses raised; the spray irrigation system provides some cooling and the operators are experimenting with the use of fans with a misting attachment. About three-fourths of an acre is devoted to tomatoes; two crops are raised. Both lettuce and tomatoes find a ready market out of the usual production season in the luxury resort hotels on the islands.

EUROPE

The greenhouse has a long history in parts of Europe. Yet commercial greenhouse food production, as in the United States, dates from only the late 1870's. And in many European nations it is more recent than that.

A great deal of published material is available on the greenhouse industry in individual European nations. The problems are to trace and translate it. Relatively few reports are available, moreover, which summarize data for Europe.[12] Hence the data presented in this section may represent only the tip of a much larger iceberg of information.

Two main geopolitical regions are discussed: (1) Western Europe and (2) the Soviet Union and Eastern Europe.

WESTERN EUROPE

Western Europe is the site of some long established greenhouse areas as well as some others which are relatively new. A higher proportion of the total greenhouse area has been used for vegetables than is true in the United States. Ornamentals were part of the glasshouse industry until World War II, when most of the production was shifted to food crops. Until recently, there has been only a slow return to floral crops. The situation as of the 1970's, however, is rapidly changing and ornamental crops are becoming increasingly important.[13]

The countries in Europe vary in their individual characteristics but can be placed into four main groups; the British Isles, Central Western Europe, Scandinavia, and Southern Europe.

British Isles

The British Isles include the United Kingdom and Ireland. The United Kingdom in turn includes England, Wales, and Scotland, North Ireland, and the Channel Islands of Guernsey and Jersey.

United Kingdom. The early development of protected agriculture in England was outlined in chapter II. The following section briefly updates the developments and reviews current statistics.

Recent History. The greenhouse industry in the United Kingdom expanded through the first part of the 20th century. By 1925, a total of 47,750 tons of greenhouse foods were produced with a farm value of £3.48 million. Tomatoes represented 67.5 percent of the value, followed by cucumbers with 21.6 percent, grapes with 3.7 percent, and other crops 7.2 percent. By 1935, the tonnage had increased to 60,015 but the value—probably reflecting the worldwide depression—rose only to £3.76 million. The crop proportions were about the same.[14]

With the onset of World War II and the loss of normal imports, it was decided to emphasize the production of tomatoes and leafy greens (lettuce, mustard, cress) in greenhouses. A series of Cropping Orders were issued requiring growers of cucumbers, grapes, and flowers to switch to these products. Fruit growers were allowed to retain grape vines and trees as long as they were undercropped, while flower growers were allowed 10 percent of their 1939 acreage to preserve their stock. By the summer of 1942, the majority of houses were turned over completely to tomatoes in the summer and leafy greens in the winter. Resulting output, together with the produce from an outdoor crop, offset the deficiencies caused by the loss of imports from Holland and the Channel Islands.[15]

Area Statistics. Assembling recent area statistics for the United Kingdom as a whole is not as easy as might be expected because there is no one central and systematic source of information. While extensive data are available for England and Wales, based on two censuses each year, the statistics for Scotland, Guernsey, and Jersey are more limited and are reported separately by the official agencies concerned. And no official data were found for Northern Ireland. Hence I will report on each of the regions individually.

– England and Wales.[16] The total greenhouse area in England and Wales has expanded only gradually in recent years:

July	*Total greenhouse area*		*Area used for food crops (excluding lettuce)*	
	Acres	*(Hectares)*	*Acres*	*(Hectares)*
1966	3,912	(1,583)	2,548	(1,031)
1968	4,601	(1,643)	2,568	(1,039)
1970	4,210	(1,704)	2,635	(1,066)
1971	4,267	(1,727)	NA	NA

Just how much of this total greenhouse area is used for food crops is not entirely clear. But if we add the area of individual food crops together—except for lettuce, which is normally grown in between tomato or cucumber crops—the total is equal to about five-eighths or 63 percent of the total area.

If the area of lettuce is added to the preceding total to get cropped area, we find that it has exceeded 4,000 acres (1,620 ha.) over the past three seasons. The breakdown by individual crop is as follows:

	Tomatoes	Cucumbers	Lettuce	Other vegetables	Fruit
			Acres		
1966	2,092	408	1,199	32	16
1968	2,142	373	1,384	40	13
1970	2,180	380	1,614	62	13
1971	2,228	418	1,730	NA	NA

The lettuce area obviously has increased sharply in recent years (the figure represents cropped area and because of multiple cropping production may have taken place on a smaller physical area).[17]

– Scotland. Total greenhouse area in 1969 was 265 acres (107 ha.). Combined tomato and cucumber area was 207 acres; lettuce occupied 52 acres. In 1970, the tomato and cucumber area remained at 207, while the lettuce area increased to 65.

– Guernsey. In 1970, total greenhouse area was 1,144 acres (463 ha.). Tomatoes accounted for 889 acres.

– Jersey. Total greenhouse area in 1971 was 112 acres (45 ha.); the tomato area was 78 acres and the lettuce area 3 acres. Comparable figures in 1970 were 73 and 5; in addition, 2 acres of cucumbers were included.

– Northern Ireland. In 1970, the total area was about 52 acres (21 ha.), of which about 30 (12 ha.) were used for vegetables.

If the crop data are grouped together, we find that the total cropped area in 1970 for the three crops, excluding Northern Ireland's, was 5,402 acres (2,186 ha.). The composition was: tomatoes 3,342 acres (or 62 percent of the total); lettuce 1,671 (31 percent), and cucumbers 389 (7 percent).

Volume and Value Statistics.[18] Although the area data are fragmented, comprehensive statistics are available for the United Kingdom on the quantity of production and its farm value. The tonnage figures show an increase from 121,000 short tons in 1964/65 to 136,000 short tons in 1969/70. The value figures, which may be more useful, are as follows:

	1964/65	1969/70
	Pounds sterling	
Tomatoes	11,433,000	14,465,000
Cucumbers	3,636,000	3,968,000
Lettuce	1,917,000	3,944,000
Fruit (grapes)	63,000	67,000
Other	880,000	1,440,000
Total	17,929,000	23,875,000

Again, the sharp increase in the lettuce crop is evident; in absolute terms it doubled in value; in relative terms it rose from 10.7 to 16.5 percent of the total. The total value of food crops rose by one-third from 1964/65 to 1969/70; some of this was, of course, accounted for by inflation.

Environmental Control. Although much of British greenhouse production is carried out in the summer, heating is now fairly widespread. In 1971, 73 percent of all the greenhouse area in England and Wales could be heated. During the 1970/71 crop year, about 57 percent of the tomato area and 43 percent of the lettuce area were heated (one might have expected more of the lettuce area to be heated since lettuce is largely grown in the winter).[19] In Guernsey in 1970, 87.5 percent of the area was heated.[20]

A sample survey of the use of other environmental control devices in England and Wales was carried out in March 1971. It revealed that of the total greenhouse area, 65 percent had an automatic or semiautomatic watering system (controlled from a central point), 15 percent had CO_2 enrichment, and 20 percent had automatic ventilation.[21] Over the 1971/72 season, about 20 percent of the tomato crop (mainly the early crop) and 40 percent of the lettuce crop were enriched with CO_2.[22]

Data for Guernsey revealed that in 1970, 28 percent utilized CO_2 enrichment and 10 percent had automatic ventilation.[23]

Government grants under the Horticultural Improvement Scheme have reportedly done much to help the greenhouse industry to modernize since the program was started in 1960. The scheme provides a cash grant equal to 38 percent of the cost of any approved modernization, rebuilding, or reequipping. In the first decade of its operation, the greenhouse industry received grants totaling £17.7 million.[24]

Ireland. Greenhouse vegetable production in Ireland is primarily aimed at the period from May to October, but there is some winter production. The total area under glass has expanded as follows:[25]

	Acres	*(Hectares)*
1960	188	(76)
1962	215	(87)
1964	248	(100)
1966	300	(121)
1968	385	(156)
1970	460	(186)

The proportion heated rose from 37 percent in 1960 to 59 percent in 1970.

About 95 percent of the area is occupied by tomatoes. The other 5 percent is accounted for by cucumbers and flower crops. Lettuce is grown as a second crop on some 25 percent of the tomato area. Tomato output was 16,500 metric tons in 1969, 20,500 in 1970, and 23,000 in 1971. Respective crop values were: £3.7, 4.2, and 4.6 million. Tomato production is reportedly adequate to meet domestic demand from the third week of April to mid-November; in addition, nearly 16 percent of output was exported in 1971.[26]

In March 1967, the Irish Government introduced a grant program for the construction and modernization of greenhouses and equipment. The basic grant is for one-third of the cost, but it goes up to 40 percent for heating systems. The maximum grant payable to any applicant is £25,000.[27]

Central Western Europe

This category is a bit of a misnomer, but it is used here to include the continental countries of Holland, Belgium, France, West Germany, Austria and Switzerland. For the most part, the industry in this area is mature, and the rate of growth of food production in greenhouses is either slow or was slowing down as of the early 1970's. France was perhaps an exception. Outside of France, nearly all of the area is in glasshouses and environmental control is relatively advanced.

Holland.[28] Holland has long had the largest greenhouse vegetable area in the world. The country's cool summers led initially to the use of unheated houses for summer production of tender crops such as tomatoes and cucumbers. Over time, increasing use was made of heated units to extend the season earlier in the spring and later in the fall. Dutch greenhouse production is very much oriented to the export market: in 1969/70, 61 percent of greenhouse production of five major crops was exported, principally to West Germany.[29]

Trends in Production. The growth of the greenhouse industry in Holland is shown in statistical terms in table 9. Early in the century, the greenhouse area was modest. But it grew rapidly from 1912 to 1940, the area of vegetables and fruits each expanding by about 10 times. There was little change from 1940 to 1950, no doubt a period of recovery from the war. However, from 1950 to 1970, there was a very sharp expansion in vegetable area and in the area used for flowers.

In retrospect, the period from 1950 to 1963 was probably the golden era for greenhouse vegetable production in Holland. Competition from other greenhouse areas was limited, especially in the early markets. And early in the period, transportation was not sufficiently improved, so that competition from southern outdoor producing area was not particulary severe. Equally important, the European market for greenhouse products underwent a very pronounced period of economic growth

In the mid-1960's, the European market began to get much more competitive. This was particularly due to expanding greenhouse production in the Eastern Bloc countries. Many of these greenhouses, incidentally, were built by Dutch firms.

So by 1971, the Dutch greenhouse vegetable area dropped for the first time in the postwar period. This decline was more than matched by an increase in the production of flowers and ornamental plants. Also, there is, strangely enough, a limited use of greenhouses which have been painted black for mushrooms.

Most of the original vegetable expansion through 1965 was in tomatoes, cucumbers, and lettuce (table 10).[30] The tomato expansion was coincidental with growth in the proportion of the tomato area heated–from 32.6 percent in 1950 to 65 percent. Thus the expansion in area was largely in the earlier season production, which was mainly exported.[31] The lettuce area, which represents winter production, probably expanded correspondingly. Strawberries were first planted in greenhouses in 1963 and had expanded moderately by the

Table 10—Estimated utilization of greenhouse area in Holland, selected years, 1912-72[1]

Year	Total		Vegetables		Fruit		Flowers & ornamentals	
			Acres (Hectares)					
1912	480	(194)	270	(109)	210	(85)	---	
1940	5,850	(2,367)	3,000	(1,214)	2,140	(866)	710	(287)
1950	5,788	(2,342)	3,138	(1,270)	1,950	(789)	700	(283)
1960	10,003	(4,048)	7,603	(3,077)	1,170	(474)	1,230	(498)
1965	14,727	(5,960)	11,717	(4,742)	780	(316)	2,230	(902)
1970	[2] 17,902	(7,245)	13,279	(5,374)	521	(211)	4,102	(1,660)
1971[2]	18,206	(7,368)	13,037	(5,276)	477	(193)	4,692	(1,899)
1972 (prelim.)[2]	18,243	(7,783)	12,437	(5,033)	413	(167)	5,394	(2,183)

--- = no data reported.
[1] Data are for greenhouse area only; they do not include multiple cropping.
[2] Excludes very small enterprises.

Sources:

1912-65: A. A. M. Sweep, Research and Experiment Station for Glasshouse Crops, Naaldwijk.

1970, 1971: *Tuinbouwcijfers, 1972,* Landbouw-Economisch Instituut, Central Bureau voor de Statistik, The Hague, p. 28.

1972: A. J. de Visser, Research and Experiment Station for Glasshouse Crops, Naaldwijk, October 1972.

mid-1960's.[32] The same was true of gherkins (pickling cucumbers)[33] and other vegetables.

What of more recent trends? From 1965 to 1970, tomato area dropped off while that of other vegetables continued to expand. The decline in tomato area was even more pronounced from 1970 to 1971, at which time the cucumber area also dropped. The area of lettuce (see fn. 2 to table 11) and other vegetables, including green peppers, continued to increase.

Throughout the postwar period, the area of fruit has dropped steadily. The major fruit crops originally consisted of grapes and tender tree fruits such as peaches and plums. These have declined in importance because of increased competition of shipped-in produce and because of production difficulties. The major production problems centered about the limited possibilities for more efficient production, the obsolescence of the glasshouses and plantings, and the difficulties of obtaining large quantities of labor for the short period involved in grape thinning. Further declines in fruit production are expected.[34]

Environment Control and Cropping Patterns.[35] Although the original cropping pattern in Dutch greenhouses consisted simply of one crop, greater use of environmental control devices has made it possible to extend the growing season and to expand multiple cropping. By 1971, 67 percent of the vegetable area was heated; the comparable figure for fruit was 17 percent. As of 1968, about 15 percent of the total area was equipped with automatic

Table 11—Acreage distribution of vegetable area in greenhouses in Holland, by crop, selected years, 1950–72

Calendar year	Total, excluding lettuce	Tomatoes	Cucumbers	Lettuce[1]	Gherkins	Strawberries	Other
	Acres (Hectares)						
1950	3,138 (1,270)	2,765 (1,119)	126 (51)	NA	---	---	247 (100)
1960	7,603 (3,077)	6,397 (2,589)	677 (274)	NA	---	NA	529 (214)
1965	11,717 (4,731)	8,559 (3,464)	1,727 (699)	NA	148 (60)	259 (105)	1,024 (414)
1970	13,279 (5,374)	8,251 (3,339)	2,137 (865)	[2]8,924 (3,612)	576 (233)	596 (241)	1,719 (696)
1971	13,035 (5,275)	7,870 (3,185)	1,851 (749)	NA	746 (302)	600 (243)	1,968 (796)
1972 (prelim.)	12,437 (5,033)	7,294 (2,952)	2,078 (841)	NA	734 (297)	618 (250)	1,712 (693)

NA = not available. --- = no data reported.

[1] Grown during the winter on land cropped to tomatoes and cucumbers at other times of the year.

[2] Average of land harvested and planted under glass in 1970. The lettuce area by crop years is reported elsewhere as follows: 1969/70, 9,266 acres (3,750 ha.); 1970/71, 9,592 (3,882).

Sources:

1950-65: A. A. M. Sweep, Research and Experiment Station for Glasshouse Crops, Naaldwijk. (Also source of data on lettuce in fn. 2.)

1970, 71: *Tuinbouwcijfers, 1972,* Landbouw-Economisch Instituut, Central Bureau voor de Statistik, The Hague, pp. 29, 32. (Data on gherkins and strawberries provided by A. J. de Visser of Naaldwijk.)

1972: A. J. de Visser, Research and Experiment Station for Glasshouse Crops, Naaldwijk, October 31, 1972.

ventilation and 29 percent with automatic irrigation (a little less than half of this was also equipped to deliver fertilizer in solution form).

Probably the most common cropping system is the late winter or early spring planting of tomatoes or cucumbers which bear through the summer, followed by a fall or early winter planted crop of lettuce. The lettuce area is less than the combined tomato and cucumber area, so that the total area for the three crops declines in fall and midwinter: during the 1970/71 crop year, the total area was highest on July 1 (10,550 acres) and lowest on December 1 (4,750 acres).

Both the tomato and the cucumber plant can bear fruit over an extended period of time. The lettuce plant, however, disappears with its harvest. Because of this, and the fact that lettuce grows rather quickly, more than one crop of lettuce may be grown. A few growers started year-round cropping of lettuce in 1971 and attained seven crops within a year. Multiple cropping of lettuce is expected to expand.[36]

Many other cropping patterns are practiced or are possible. Increasingly, these will probably involve flowers. Dutch economists have calculated 120 different multiple cropping combinations which are possible in terms of timing.[37] Not all are feasible at this point, however.

As multiple cropping expands, there is increased interest in shortening the growing period of individual crops. One way of doing this is to make use of transplants which have been grown to a more advanced age than has been the case in the past. Dutch economists are studying this matter.[38] Increasingly, transplants are being grown from seed by specialized firms and then purchased by farmers in pre-cut block form.

Labor Requirements. The Dutch greenhouse industry is heavily concentrated in a small area southwest of The Hague known as the "Westland." One of the reasons for this concentration was the availability of a labor force. And within the area, according to one Dutch dissertation:

> The greater the number of resident sons, the stronger the stimulus to intensive culture... Thus the use of greenhouses and heating became more frequent among Catholic gardeners than among Dutch Reformed ones.[39]

It is also said that compared with cultural practices in England and Guernsey, Dutch glasshouse tomato techniques are extensive—that is, relatively little labor and expenditure are applied over a big area of glass. As a result, yields are not unusually high. Still, as an English economist states, it may well be that:

> The Dutch growers have found a superior balance between fruit quality, fruit yield and work requirement than elsewhere, and this enables them to excel in value of output per man, which is what matters in commerce.[40]

Our earlier comparisons of labor requirements (ch. IV) did confirm that less labor seemed to be used than in other nations.

In any case, labor productivity in Dutch greenhouses has clearly increased sharply since the mid-1950's. According to one set of estimates, the amount of labor needed to produce an acre of tomatoes in 1968 was only 56 percent of that required in 1954; the amount needed for an acre of cucumbers in 1968 was only 16 percent of that needed in 1954. Since yields per acre went up during this period, the output per hour of labor rose even more sharply—about three times for tomatoes and six times for cucumbers. More specifically, the number of man-years required for an acre of tomatoes dropped from 2.37 to 1.32, while the comparable decline for cucumbers was from 5.26 to 1.26.[41]

Still, a considerable amount of labor is needed for vegetables (and the needs for flowers are 50 to 100 percent higher). Distribution of these needs is considered in the choice of crops; the variation in needs for fruit crops is much greater than for vegetables. In the case of tomatoes, labor requirements peak in June, when harvesting of the early tomatoes begins and the late crop is still growing. Of total 1971 labor requirements, 58 percent were involved in growing, 33 percent in harvest, and 9 percent in planting and cleaning up the vines.[42]

Economic Statistics. For the most part in Holland, there are many growers that are of modest size. For example, in 1971 there were 12,378 greenhouse holdings with vegetables and 2,061 holdings with fruit. The average size of holding in southern Holland was 2.2 acres (0.90 ha.) for heated vegetables and 1.38 acres (0.56 ha.) for unheated vegetables.[43] The trend is toward gradually larger holdings. Cooperatives are increasingly common.

Through the early 1960's, greenhouse food production in Holland was considered quite profitable. With increasing production and competition from other nations in Europe, the level of profitability dropped sharply in 1964 and did not begin to rise again until the late 1960's. A review of greenhouse operations in southern Holland in 1968 led to the following breakdown of financial position: favorable 44 percent, fair 30 percent, unfavorable 14 percent and very unfavorable 12 percent.[44]

Recent levels of income distribution by major crop type are reflected in the results of a survey of about 150 growers in southern Holland in 1971 who raised principally vegetables or flowers:[45]

Income level	*Vegetables*	*Flowers*
Dollars[1]	*Percent*	
Negative	12	3
0-3,150	16	4
3,150-7,875	30	18
7,875-12,600	16	14
12,600-18,900	12	20
18,900 and over	14	41
Total	100	100

[1] Conversions on basis of 1 guilder = 31.5¢.

It is small wonder that there has been a shift to the production of flowers and ornamental plants.

The financial situation of Dutch growers is influenced by several unique factors. On the favorable side, the cost of metal and glass structures in Holland has long been relatively low per unit of area due to the type of construction and the fact that many internationally important greenhouse manufactures are located in Holland. (Costs, however, have been increasing rapidly and this differential may now be less than it once was.) The Government has been financially encouraging a transfer from heavy oil to natural gas for heating to help reduce a severe air pollution problem. Growers, on the other hand, have to pay 40 percent of the cost of the glasshouse experiment station through a tax of 0.15 percent of gross returns which is collected by the auction (essentially all of the Dutch produce is sold through auction).

* * *

On balance, we may see that greenhouse food production in Holland, for economic reasons, has probably passed its peak in terms of area occupied; whether value of the food crops will also decrease depends on future changes in yield and prices. The major tomato crop will increasingly be supplemented by other vegetable and floral crops.

Belgium. Belgium has a relatively large greenhouse food industry for its size. But as with Holland, much of the production is exported. There has been a slow but steady growth in greenhouse area devoted to fruit and vegetable crops since 1960. The official figures are:

	Acres	*(Hectares)*
1950	1,700	(688)
1960	2,385	(965)
1962	2,510	(1,016)
1964	2,770	(1,120)
1966	2,865	(1,160)
1968	2,985	(1,208)
1969	3,050	(1,232)

Essentially no plastic is used. About 50 percent of the houses are heated.[46]

A much higher proportion of the Belgian area is used for fruit than anywhere else. In 1969, for instance, the official figures show that about 1,100 acres (or 36 percent) was devoted to fruit and 1,950 acres (or 64 percent) to vegetables. The trend during the 1960's, however, has been a gradual decrease in fruit (down from 1,280 acres in 1960), and a substantial increase in vegetables (up from 1,100 acres in 1960).[47]

The major fruit crop has been grapes, which accounted for 930 acres in 1969, followed by strawberries with 156 acres, peaches with 7, and others with 3. Since 1965, there has been a downward trend in grapes and some minor fruits and an uptrend in strawberries.[48]

The actual vegetable area and its composition is a matter of some debate. The official figure for 1969 is, as noted, about 1,950 acres, excluding multiple cropping. On the other hand, data from a Belgian agricultural organization suggest a much larger area. The official figures are based on the taxed area, while the unofficial figures are based on data reported by farmers.

The variation in figures may most readily be understood by looking at individual crops. The official figure for tomatoes in 1969 was 2,560 acres, while the unofficial estimate of cropped area was 2,670 acres. Similarly, the respective cucumber estimates were 45 and 148 acres. The official figures—which exclude lettuce—listed only 318 acres of other crops, while the comparable unofficial estimates were 1,340 acres. Thus the unofficial estimate of cropped area was 8,485 acres; excluding lettuce, which is grown as a second and third crop, it was 4,160 acres. Since tomatoes and some of the other crops are in part grown as a second and third crop, this figure might be further lowered. Still, the total would appear to be well above the official figure.[49]

Despite these wide area differences, the unofficial figures for the distribution of vegetable production on a weight basis in 1969 vary only slightly from those reported in an official Belgian report for the 1968/69-1970/71 period:[50]

	1969	*1968/69-1970-71*
	Percent	
Tomatoes	49.0	48.2
Lettuce	31.4	31.1
Cucumbers	7.0	7.0
Other	12.6	13.7
Total	100.0	100.0

The seasonality of production of the three major vegetables is much like that found elsewhere in Europe. The bulk of the tomato production (67 percent in 1968/69-1970/71) is obtained in the July-August period. Most of the cucumbers are produced from March to August. Lettuce has two peaks: October-December (23 percent) and March-May (58 percent).[51]

Prices, as might be expected, reach their low points during these periods, except in the case of the first month of heavy tomato and cucumber production. On a seasonal basis, during 1968/69-1970/71, prices for greenhouse vegetables were well above those raised in the open:

	Glasshouse prices as proportion of field prices	
	Tomatoes	*Lettuce*
	Percent	
1968/69	227	197
1969/70	204	185
1970/71	280	159

In 1969/70, 83 percent of the tomatoes and 44 percent of the lettuce were raised in greenhouses.[52]

Exports, principally to France and Germany, accounted for about 22 percent of greenhouse tomato production, 9 percent of cucumbers, and 39 percent of lettuce in 1970.[53]

France. Although France, as was reported in chapter II, was one of the first countries to utilize protected agriculture, greenhouse food production has not been important there until recently. Only in 1954 did the current industry begin to take form with construction of greenhouses in Saint-Mihiel and in Orleans.[54] The industry grew slowly, reaching an area of nearly 300 acres (120 ha.) by 1961.[55]

The growth in greenhouse food area since then is shown in the following figures:[56]

	Acres	*(Hectares)*
1962	395	(160)
1964	620	(250)
1966	1,460	(590)
1968	1,980	(800)
1970	2,720	(2,200)

In 1968, about 1,000 more acres involved flowers.

Much of the recent construction has involved plastic; in 1970, the total area under plastic was about 865 acres (350 ha.).[57] Plastic is particularly important in the south, where it represents 67 to 80 percent of the total area: these houses are less often heated than is true in the north. Hence the proportion of area in the country which is heated dropped from 88 percent in 1966 to an estimated 69 percent in 1970.[58]

A significant portion of the greenhouse area is multiple cropped. If the cropped area of the three major crops—lettuce, tomatoes and cucumbers—plus strawberries is added, it far more than exceeds the greenhouse area devoted to vegetables. This is illustrated below for 1970:[59]

	Acres	*(Hectares)*
Lettuce	3,037	(1,229)
Tomatoes	1,213	(491)
Cucumbers	744	(301)
Strawberries	124	(50)
Total cropped	5,118	(2,071)
Total area	2,726	(1,103)
Cropping index	1.88	1.88

The cropping index represents total cropped area divided by total greenhouse area. In 1969 the index was 1.96; in 1968, 1.75. Actually, the index is low because it does not include such crops as melons, peppers, and celery; the area of these other crops totaled 400 acres (162 ha.) in 1968/69.[60] If their area was the same in 1970, their inclusion would raise the index from 1.88 to 2.02.

The harvest of tomatoes and cucumbers peaks in June and July, while lettuce harvest is at its maximum in the months of December, January, and February. Up to three lettuce crops may be grown in one season (which partly explains the high cropped figure for lettuce). A common rotation involves two crops of lettuce and one crop of tomatoes.[61]

Total production of food crops in 1969 was about 164,000 metric tons, of which tomatoes represented 62,000, cucumbers 60,000, lettuce 36,000, and others 6,000. Between 1964 and 1969, overall production of lettuce increased 3.6 times, and cucumbers went up 1.9 times. Average yields per acre per year (2 crops) were about as follows: cucumbers, 111 short tons (250 m.t./ha.); tomatoes 67 tons (150 m.t./ha.); and lettuce 12 tons (26 m.t./ha.).[62]

West Germany. For a country of its size and wealth, West Germany has a relatively small static greenhouse vegetable industry. Trends in estimated greenhouse vegetable area are as follows:

	Acres	*(Hectares)*
1956	1,890	(800)
1962	2,100	(850)
1966	1,800	(730)
1968	1,824	(738)
1970	2,128	(861)

From 1966 to 1969, the area devoted to ornamental crops expanded from 2,700 acres to 3,680.[63]

There is less concentration on one major crop than in other nations. In 1970, the area distribution was: tomatoes 21 percent, cucumbers 18 percent, lettuce 17 percent, kohlrabi 14 percent, horseradish 12 percent, radishes 11 percent, cauliflower 1 percent, and others 6 percent. No particular trends have been evident since 1966, except for an increase in horseradish and radishes.[64]

Part of the reason that tomatoes, cucumbers, and lettuce are not more important is that they are imported in great quantity (427,000 metric tons in 1970) from greenhouses in neighboring Holland; much smaller quantities (13,000 tons in 1970) are also imported from Belgium. Tomatoes, and to a lesser extent cucumbers, are also imported from greenhouses in Romania (23,000 tons in 1970) and Bulgaria (12,000 tons in 1970). Adverse climatic conditions, with their attendant costs, are evidently such that Germany finds it cheaper to import these vegetables than to raise them domestically in greenhouses.[65]

Austria. Like West Germany, Austria has a relatively small greenhouse vegetable industry. The estimated area in recent years has been:

	Acres	*(Hectares)*
1964	148	(60)
1966	180	(73)
1968	215	(87)
1970	237	(96)
1971	247	(100)

The growth since 1964 has been brought about in part by a Ministry of Agriculture support program for greenhouse operations.[66]

The principal vegetables are lettuce, peppers, and cucumbers. Crops of lesser importance include radishes, kohlrabi, chives, dill, and tomatoes. The main production seasons are March-July and September-November.[67]

Austria imports substantial quantities of greenhouse tomatoes (15,300 metric tons in 1970) from Romania and Bulgaria, smaller quantities of cucumbers (4,500 tons in 1970) from these two countries and Holland, and some lettuce from Holland. Again, weather conditions in Austria evidently make imports cheaper than extensive domestic production.[68]

Switzerland. Greenhouse vegetable production occupies only about one-fourth of the total greenhouse area in Switzerland. The vegetable area increased from 81 acres (32 ha.) in 1965 to 105 (43 ha.) in 1969.[69] Tomatoes are the main greenhouse crop, occupying about 88 acres in 1970 with a production of 19,500 metric tons. Cucumber production in 1969 was 4,400 tons. Greenhouse tomatoes are imported from Holland, Romania, and Bulgaria (7,400 tons in 1970); greenhouse lettuce is imported from Holland and Belgium (4,100 tons in 1970). The Swiss houses have a high degree of environmental control and double and triple cropping is practiced.[70]

Scandinavia

Greenhouse food production has been practiced in Scandinavia since the 1930's and the industry is now relatively mature. The areas involved are relatively small, little more than 1,600 to 1,700 acres as a whole for Scandinavia. On the other hand, the quality of environmental control is of a high degree; heating is practiced in nearly all of the houses. As in other developed nations, greenhouses are used for both food and floral crops, with the latter gaining in importance. Because of the northerly location, winters are dark and cold; few vegetables are harvested during this period but artificial lights are sometimes used for growing vegetable transplants or for flowers.

The limited statistical data obtained for individual Scandinavian nations are summarized in the following sections.

Denmark.[71] The area of greenhouse vegetables raised in Denmark changed but little through the 1960's.

	Total greenhouse area		*Total vegetable area cropped*[1]	
	Acres	*(Ha.)*	*Acres*	*(Ha.)*
1960	887	(359)	456	(185)
1965	1,275	(516)	517	(209)
1967/68	1,362	(551)	569	(230)
1969/70	1,409	(570)	576	(233)

[1] Including multiple cropping.

In terms of total greenhouse area, the proportion represented by vegetables declined slowly—from about 51 percent in 1960 to 33 percent in 1969/70. Early in the decade, the increase in other crops was due to flowers; later in the period, it was due to potted plants.

During the 1969/70 season, about 50 percent of the vegetable area was devoted to tomatoes, 23 percent to cucumbers, 12.5 percent to lettuce, 7 percent to melons, and 7 percent to other vegetables. The multiple cropping index was 1.23 and was largely due to lettuce.

Danish greenhouses tend to be fairly wide, and full-size tractors are sometimes used. Since manure is scarce, it was reported in the mid-1960's that cucumber beds were made largely of barley straw or a mixture of barley, straw and peat.

Norway.[72] As in Denmark, the area of greenhouse food crops increased only slightly during 1959-69:

	Total greenhouse area		*Total food crop area*	
	Acres	*(Ha.)*	*Acres*	*(Ha.)*
1959	358	(145)	260	(105)
1969	470	(190)	177	(112)

As a proportion of total greenhouse area, the proportion represented by food crops declined from 72 to 59 percent.

The major food crop in 1969 was tomatoes, which accounted for 56 percent of the total area, followed by cucumbers with 19 percent, lettuce 10 percent, and others, including strawberries, 15 percent. Production is carried on throughout the year except in midwinter. In 1969, about 9 percent of the total area was covered with plastic.

Sweden.[73] The total greenhouse area in Sweden in 1970 was 954 acres (386 ha.), of which about one-third to one-half (318 to 477 acres) was devoted to vegetable production. The large and medium-sized holdings reportedly specialize in tomatoes, cucumbers, carnations, roses, or pot plants; the smaller holdings usually have a mixed crop. Greenhouses are found as far north as the Arctic Circle.

Finland.[74] Of a total greenhouse area of 754 acres (305 ha.) in 1969, about 447 acres (181 ha.) or 59 percent were devoted to vegetables. Approximately 83 percent of the vegetable area was under glass and 17 percent under plastic. Tomatoes accounted for 68 percent of the vegetable area, followed by cucumbers with 23 percent, lettuce 3 percent, and other vegetables 7 percent. Some of the area under plastic is unheated and is used only during the summer. Very good results have been obtained from culture in peat.

Iceland.[75] Iceland differs from other nations in that all the heat for its greenhouses is provided by hot subterranean springs. Tomatoes and cucumbers are the main crops along with flowers. Grapes and bananas have been grown under experimental conditions.

Southern Europe

The southernmost countries of Europe bordering the Mediterranean—especially Italy and Greece—have sharply expanded their greenhouse vegetable production under plastic in recent years. The climate in these nations is mild, and environmental control mechanisms are usually simple. Plastic has been used more to facilitate or intensify existing winter production than to create an entirely new type of agriculture.

Portugal.[76] Vegetables are grown under plastic covers in Portugal, but as of 1970 they were classified as low plastic tunnels or frames. Nearly 200 acres of greenhouses existed, but they were used exclusively for flowers.

Spain.[77] In continental Spain, about 740 acres (300 ha.) of plastic-covered structures were used in 1970. It is not entirely clear whether they were wholly or partially of greenhouse size (high tunnels). In any case, they are found in the Barcelona area in the northeast, and in the southern Provinces. With the plastic units, earlier crops are obtained and more of the production is obtained during the first crop. (The Canary Islands, a Spanish possession, are reported on in the Africa section.)

Italy.[78] Although perhaps not well known, Italy has the second largest vegetable area under cover in Europe. Most of the growth has come in the past decade. Greenhouse area expanded as follows:

	Total greenhouse area		*Greenhouse vegetable area*	
	Acres	*(Ha.)*	*Acres*	*(Ha.)*
1960	1,542	(624)	588	(238)
1964	5,951	(2,408)	3,538	(1,432)
1969	12,700	(5,141)	9,190	(3,720)

The growth in greenhouse vegetables is unparalleled anywhere.

Much of the expansion was undoubtedly due to the availability of plastic in regions which were already familiar with vegetable production. The increase in area under plastic was fantastic: from essentially none in 1960 to nearly 2,500 acres (1,193 ha.) in 1964 and 9,870 acres (3,995 ha.) by 1969. In contrast, the area under glass dropped from 3,375 acres (1,366 ha.) in 1964 to 2,145 acres (868 ha.) in 1969. About 58 percent of the total area in 1969 was heated–more than might be expected.

While most of the greenhouse vegetable area in 1960 was in the north, the big spurt was in the Province of Lazio in the central part of the country and in Sicily. The specific growth figures were:

	1960		*1969*	
	Acres	*(Ha.)*	*Acres*	*(Ha.)*
Liguria	1,319	(534)	1,468	(594)
Lazio	30	(12)	2,902	(1,177)
Sicily	11	(5)	5,088	(2,059)
Campania	9	(4)	1,201	(486)
Other	173	(69)	2,044	(825)
Total	1,542	(624)	12,703	(5,141)

The growth was extraordinary in its concentration on vegetable crops. In 1969, over 98 percent of the greenhouse area in Sicily was in vegetables (at the same time, 98.1 percent of the area was under plastic); the comparable figure for Lazio was 82 percent. Sicily accounted for over half of the greenhouse vegetable area in Italy.

In terms of type of crop, tomatoes were in the lead in 1969 with 57.1 percent of the area. They were followed at some distance by chilli 14.4 percent, pumpkins 10.8 percent, eggplant 3.2 percent, cucumber 2.7 percent, lettuce 2.6 percent, and other 9.1 percent. (The nonvegetable crops were principally flowers, but included one unique crop: tobacco.) Production in Sicily was similarly heavily oriented to tomatoes and chilli.

Nearly all of the expansion in Italian vegetable production was absorbed internally. Imports were reduced and exports showed no particular growth. Apparently, Italian producers hold no great visions of exporting vegetables to European markets, in part because the varieties and fruit quality are not of export standard. Rather, there may be more interest in diversifying into flowers.

Malta.[79] A small greenhouse industry is found on Malta, just off the southern coast of Italy. By 1970, some 180 growers had constructed greenhouses totaling about 34 acres. Most are of plastic. Of the 34 acres about 14 acres were used for tomatoes and 20 acres for floral crops.

Plate 13–*Horticultural Demonstration and Training Center, Malta. Plastic covers or funnels are in the foreground; plastic-covered greenhouses are at the right.*

Greece.[80] A large plastic greenhouse industry has recently developed in Greece. Estimates of the growth are:

	Acres	(Hectares)
1966	620	(250)
1969	2,040	(826)
1970/71	2,965	(1,200)

A further expansion to 3,700 acres (1,500 ha.) was indicated for 1971/72.

Of the 1970/71 area, 707 acres (286 ha.) were on Crete. Nearly half the total area was in the Peloponnesus. In some areas, greenhouses have been built on land formerly planted to olive trees.

Because of the high cost of glass in Greece, as well as the low income of the vegetable growers, nearly all of the covering is plastic. The usual structures, therefore, are very simple, consisting of a simple wood frame with vertical support, or tubular curvilinear frames (high tunnels). Houses are not heated.

Precise data are not available on the crop breakdown, but it appears to be essentially all vegetables. The main crop is cucumbers (occupying 50 to 53 percent of the area), followed by tomatoes (40 to 43 percent), and others (5 to 7 percent; eggplants, peppers, squash, kidney beans, strawberries). The main growing season is from September to May. A small proportion of both cucumber and tomato production was exported in 1970.

In addition to greenhouse area, there was an additional area of about 3,128 acres (1,266 ha.) of plastic row covers or low tunnels in 1970. Most of this (75 percent), is used for watermelon.

SOVIET UNION AND EASTERN EUROPE

Since 1960, there has been a sharp expansion of greenhouse construction in the Soviet Union and the nations of Eastern Europe. In the Soviet Union, this has represented an effort to provide an improved standard of living; very little fresh produce had heretofore been available in other than summer months. The same may be true in Poland and East Germany. But in the more southerly nations of Hungary, Romania, Bulgaria, and Yugoslavia, there has also been a distinct interest in export markets. We will discuss each nation in the above order.

Soviet Union[81]

The glasshouse vegetable area in the Soviet Union is one of the largest in Europe. As of 1970, there were about 5,350 acres. The recent growth of glasshouse vegetable area has been as follows:[82]

	Acres	*(Hectares)*
1965	1,185	(479)
1966	1,546	(626)
1967	1,863	(754)
1968	2,265	(1,078)
1969	3,661	(1,482)
1970	5,352	(2,166)

Plastic houses are widely used, but no comparable national statistics have yet been noted. One estimate suggested that the area under plastic houses and tunnels in 1967 was about twice as great as the glasshouse area.[83]

The Soviet Five-Year Plan for 1971-75 envisages the construction of a further 2,810 acres (1,136 ha.) of greenhouses.[84] If accomplished, this would bring the total area by 1975 to over 8,000 acres (3,300 ha.). A Central Board for the mass production of prefabricated greenhouse blocks was established in 1969. To reduce growing costs, emphasis is being given to building large houses so that operations can be more fully mechanized. Productivity of labor is felt to be higher and costs of production lower in houses of 10 acres than in smaller units.[85]

About 80 percent of the greenhouse area is in the central and northern zones of the European part of the country; only 4 percent is in the southern regions. Generally, the houses are placed near the larger cities on large state or collective farms. The largest of these, the Moscow State Farm, has nine units, each of nearly 15 acres, for a total area of 133 acres (54 ha.). A greenhouse complex of nearly 300 acres (120 ha.) is being designed near Kirovabad. Other large greenhouse "combines" are found outside Leningrad (104 acres), Kislovodsk, Simferopol, Minsk, and Kiev. There are also a number of smaller specialized farms–39 around Moscow alone in 1970.

At least some of the greenhouses have quite advanced environmental control systems. During the construction of a large unit outside Moscow, it was stated that:

– "each crop will have its specific microclimate"
– "each section will have hundreds of artificial suns switched on and off automatically."

In the Russian Federation, almost all of the transplants for the winter greenhouses are grown under artificial light. But it does not appear that lights are widely used to raise plants to harvest (only 4 to 5 percent of annual cucumber production on the Moscow State Farm, for instance, is raised from November to March). Use of the lamps is acknowledged to be expensive.

The Soviet cropping composition is unlike that found in other countries. Instead of tomatoes, cucumbers are the major spring and summer greenhouse crop. The reasons can be traced to yields and price policy. According to an English visitor:

> The cucumber differs from the tomato in that growth and yield rise steadily with increasing day-length and plant performance is very satisfactory under continuous daylight such as occurs in June and July in northerly latitudes. Hence substantial yields, which compare favourably with yields from more southerly latitudes, can be achieved under glass in the far north.[86]

Cucumbers are sold at the same price as tomatoes; since cucumbers are easier to raise and yield more, farmers concentrate on them rather than on tomatoes.[87] Neither crop prospers in the northern part of the Soviet Union in the winter when days are short and light intensity low; therefore, the Soviets use bulb onions to produce crops of green salad onions. As a result, in the Russian Republic in 1967, cucumbers accounted for 57 percent of total production, onions 32 percent, tomatoes 3 percent and leafy greens 9 percent. This balance has led at least one Soviet writer to complain that "the assortment of vegetables grown in hot-houses is still inadequate." Increased attention may be given to the placing of more greenhouses in the southern regions in order to improve the winter crop selection.

Eastern Europe

It is difficult to obtain systematic data on the greenhouse industry in Eastern Europe. The statistics reported here were usually obtained from a variety of secondary sources, were not always clearly defined, and were not entirely consistent. They should, therefore, be viewed with caution.

No information was obtained on Czechoslovakia, except for one statement that the greenhouse area, presumably in the late 1960's or 1970, was about 1,480 acres (600 ha.), almost all constructed in the previous 4 years.

Poland.[88] Although often not included in estimates of European greenhouse area, Poland has a fairly substantial greenhouse industry. The total area reportedly has expanded as follows:

	Acres	*(Hectares)*
1950	278	(113)
1956	323	(131)
1960	499	(202)
1965	683	(276)
1970	1,075	(435)
1971	1,191	(482)

Out of a total area of 856 acres in 1967 (347 ha.), about 67 percent was in private hands, 29 percent in State farms, and 3.6 percent in cooperatives.

The crop-use pattern varies with type of holding. In 1967, vegetables were the most important category in terms of number of holdings:

Chief crop	*Private*	*State*
	Percent	
Vegetables	60	48
Flowers	13	33
Seedlings	24	19
Other	3	--
Total	100	100

Flowers were relatively more important on state than private farms. This was particularly true when the crops on state farms were broken down on the basis of area—in which case the proportion of flowers went up to 50 percent and vegetables and seedlings dropped; a comparable breakdown was not available for private farms. Within the vegetable category, the three main crops in the mid-1950's were the usual: tomatoes, cucumbers, and salads (presumably leafy vegetables).

Heating is widely practiced. In 1967, the proportion of the area heated was 91 percent on the state farms and 75 percent on private farms.

Continued greenhouse expansion is planned. The Government has contracted for the import of 25 large greenhouses (14.8 acres each) to be built on state farms near urban areas—a total area of 371 acres. It is expected that private greenhouses will expand by 198 acres. All of this may make it possible for Poland to triple per capita consumption of greenhouse vegetables by 1975.

East Germany.[89] Very few statistical data have been located on East

Germany. According to one estimate, the country had 410 acres (166 ha.) of greenhouse vegetables in 1957, principally lettuce and tomatoes. More recent data suggest a very sharp increase in the area under plastic in the late 1960's, reaching about 494 acres (200 ha.) in 1970 (the area under glass was not reported). Of the plastic total, about 25 percent was heated; the proportion is to be increased. Cucumbers appear to be the leading crop in the heated houses; others include lettuce, kohlrabi, chicory, chives, and parsley.

Hungary.[90] In 1969, nearly 2,000 acres (800 ha.) of greenhouse were estimated to be in use in Hungary. Of the total, about 1,730 acres (700 ha.) were believed to be plastic and nearly 250 glass (100 ha.). The plastic houses were mainly classified as high tunnels. These figures, if correct, represent a substantial growth from earlier periods. As of the early 1960's, the area was estimated as only 62 acres (25 ha.). The main crops grown under plastic are tomatoes, peppers, lettuce, spinach, parsley, and sorrel.

Romania.[91] The area of greenhouses in Romania is substantial: in 1970, it totaled about 4,570 acres (1,850 ha.), of which nearly 3,000 acres (1,200 ha.) were plastic and 1,600 acres (650 ha.) glass. The glasshouse area increased as follows: 1965, 250 acres (100 ha.); 1967, 545 acres (220 ha.); 1969, 1,120 acres (450 ha.). Most of the glasshouses were built by Dutch firms. Tomatoes were easily the most important crop grown in glasshouses in 1970, accounting for about 75 percent of the total area. They were followed by cucumbers 12 percent, peppers 5 percent, and others 8 percent.

There are several large greenhouse units on state farms. A British agriculturist who visited the country in February 1969 reported one unit north of Bucharest which totaled over 124 acres in area; it was built by a Dutch company in blocks of 12.4 acres each. Considerable heat is needed in the cold winters, and many crops are grown over buried hot water pipes which are used in addition to the normal above-ground piping.

Bulgaria.[92] The growth in greenhouse area in Bulgaria is more fully documented than in the immediately preceding countries. Yearly estimates are as follows:

	Acres	*(Hectares)*
1955	12	(5)
1957	19	(8)
1963	90	(36)
1965	355	(144)
1967	964	(390)
1969	1,483	(600)
1970	1,977	(800)

About three-fourths of the 1970 total was estimated to be glass and one-fourth plastic.

Of the nearly 1,500 acres in 1969, about 950 were state owned and the rest were operated by cooperatives. Within the state category, there were reportedly three farms in the 99-124 acres category and seven in the 62-99 acres group. The largest farm has 145 acres built as a continuous line of identical 7½ acre blocks. The larger units were erected by Dutch firms. The optimum size is considered to be 62 acres in the state sector and 15 to 30 in the cooperative sector.

Nearly all of the greenhouse area as of 1969 was devoted to vegetable crops; only about 75 acres were used for flowers. Within the vegetable category, around 80 percent of the area was used for tomatoes, 15 percent for cucumbers, and 5 percent for peppers. Cucumbers were largely raised on straw bales.

Production is not carried out in the summer because of extreme heat. Heating in the winter was originally provided by hot winter springs, then by hot water provided by industrial enterprises, and more recently by oil.

The primary purpose of the greenhouse building program is to provide produce for export to earn foreign exchange. Toward this end, about 80 percent of the crop has been exported in recent years, principally to Western Europe (largely West Germany, Austria, and Sweden), but with small quantities to Eastern Europe.

Yugoslavia.[93] The limited information shows that there apparently were about 300 acres (121 ha.) of greenhouses in Yugoslavia in the early 1970's. They are evidently largely in the hands of several firms in Macedonia and around Mostar. Vegetables, especially tomatoes, and flowers are both produced.

AFRICA

Greenhouses are not common in Africa. The few that seem to be used for food crop production are found in northwest Africa: Morocco and the Canary Islands. Some greenhouses are found in Uganda but seem to be entirely used for ornamental crops.[94] Tomatoes were grown in greenhouses during the wet season in Rhodesia in the early 1960's, but this practice ceased with the advent of more effective spray programs.[95] There was also some experience with greenhouse food production in the Medjerda Valley in Tunisia a few years ago, but the effort was discontinued and the project dismantled.[96]

Low plastic covers (low tunnels, plastic row covers, and so forth) are, however, fairly widely used in North Africa—both for their warming effect and for wind protection for seedling plants.[97]

Canary Islands.[98] The Canary Islands, which lie off the southern coast of Morocco, are an important factor in the winter vegetable trade in Europe. As of 1970, about 1,100 acres (450 ha.) were covered by greenhouses (one estimate places the figure as high as 1,480 acres or 600 ha.). The construction of large plastic-covered houses began in 1958. Older structures are now used largely for cucumbers, while more recent houses are used for tomatoes and eggplant. Strong winds provide adequate ventilation. Water is scarce and expensive so that many of the covered structures—especially those used for cucumbers—are irrigated with a spray system which reduces the quantity of water needed by 40 to 50 percent.

Morocco.[99] Field tomatoes are a major export from Morocco to Europe, particularly France, during the winter and early spring. One of the earliest growing regions is in the Sousse Valley in the southern portion of the country. In 1971, there were about 34 greenhouses in the Guerdene of the Sousse Valley which raised vegetable transplants for an area of about 150 acres (60 ha.). Three advantages have been noted for raising transplants in this way: protection from the climate, especially frost; a top quality transplant of assured variety; and early harvest and high yield. Other growers are reportedly becoming interested.

ASIA

Asian countries, except for *Israel*, have usually been left out of any global discussion of greenhouses. This is unfortunate, for greenhouse vegetable production in Asia is of some importance and is expanding. Moreover, the practices followed are different from those found anywhere else in the world except in the Mediterranean region. And while the techniques utilized may not find wide adoption in the developed nations, they could be most useful in other developing regions. For purposes of our discussion, we will look first at West and then East Asia.

WEST ASIA

Three of the West Asian nations with greenhouse food production are located at the eastern end of the Mediterranean: Turkey, Lebanon, and Israel. Their climatic conditions are not greatly different from those of other Mediterranean nations already discussed. The other two West Asian nations—Kuwait and Abu Dhabi—are located on the Persian Gulf and are largely deserts.

Turkey.[100] Although it is not widely recognized, Turkey has a large and expanding greenhouse area. The first houses were constructed around the coastal city of Antalya in the southwest in the late 1940's. Their use proved profitable and the area was expanded. By 1968, about 1,500 acres (600 hectares) were reportedly in use. The area further expanded to around 4,300 acres by the end of 1970 and as of 1972 was estimated at about 5,000 acres (2,000 hectares).[101]

Essentially all of the area as of 1972 was in the coastal regions, principally in the south. Most of the greenhouses are within 100 miles of Antalya (with the fastest growing and most intensive district in Demre to the east). Another large area is found near Mersin in the Adana area. Other greenhouses are scattered along the northwest coast from Izmir to Istanbul.

The locations are highly correlated with available sunlight and warm temperature, both available in greatest supply on the south coast. Because of lower temperatures, heating costs average perhaps a third higher in the Istanbul area and four times as high in Ankara in the Anatolean Plateau.

While heating is fairly widely practiced, environmental control practices are otherwise at a rudimentary level. Through the mid-1960's, the greenhouses were nearly all built of metal and glass. Their design left much to be desired: they were not structurally very sound and roof ventilation was limited or

Plate 14–*Plastic-covered greenhouses with glass end walls in southern Turkey. Note greenhouses on hillside terraces in background.*

nonexistent. Wood burning stoves placed at a height of about 4 feet provided an inefficient source of heat. And water was applied by flood irrigation. Cultural methods were more suitable to the open field than to greenhouses. Most growers raised only one crop a year, usually tomatoes.

In 1968, the United Nations Development Program sponsored, through the Food and Agriculture organization, the assignment of a greenhouse production specialist at the Government vegetable research station at Aksu, just outside of Antalya. Emphasis was placed on determining the "best" system of production under Turkish conditions. This led to investigation of improved methods of construction, heating, and watering.

In response to the greenhouse research and the changing economic conditions (expanded production led to lower prices which in turn increased interest in lowering cost of production), the industry has undergone some sharp changes. The most obvious has been a shift to the use of wood framing and plastic covering for greenhouse construction. The method is evidently about as effective as the old metal/glass system and much lower in capital cost. Also, some growers have started to use locally manufactured hot air heaters instead of the wood stoves; while more efficient, they also have a higher capital cost. In terms of crops, there has been increasing diversification of production involving cucumbers, peppers, green beans, and squash. And within the tomato category, small fruited European types–which are more easily grown in the winter than Turkish types–are becoming accepted.

Much, however, remains to be done in terms of environmental control and improving cultural practices. The UNDP/FAO greenhouse specialist estimates that yields could be doubled with the use of economically improved techniques. Seed improvement is seriously needed. Double cropping systems must be developed and adopted. A number of soil problems need to be solved—soil-borne root diseases and nematodes, lack of organic matter, high salt concentration, and poor drainage. At the vegetable research station, corn has been found to be a most suitable green manure crop for the summer (not the least of its qualities are its resistance to the usual greenhouse soil-borne diseases and its ability to prosper under high temperature conditions). Improved water control and more careful use of fertilizer may help alleviate some of the salt problems.

The economic merits of alternative types of greenhouses have received considerable attention in the UNDP/FAO work conducted at Aksu. Relative yields, costs, and returns on invested capital for five combinations were as follows for tomatoes:

	Yields	Cost		Return on invested capital
		Capital	*Annual*	
	Metric tons/decare	*Lira/decare*		*Percent*
Glass:				
Central steam	17	100,000	10,000	10
Wood stoves	11	75,000	7,500	13
Plastic:				
Hot air	17	36,300	4,300	40
Wood stoves	11	18,300	2,600	11
Unheated	7	16,300	2,300	11

The steam heated house not only had the highest yield, but it also came into production earlier in the season when prices were higher; hence it had the greatest gross income per unit of land. Yields in the hot air heated house were nearly as high, but since the capital cost was much less, the return on invested capital was much higher (the same advantage was not noted in the case of peppers and cucumbers). It was felt that type of heat was much more important than type of structure in determining yields—as is shown by the lower yields in each type of house heated by wood stove. Hence in terms of economics, the most logical type of structure for tomato production in Turkey is a hot air heated plastic house; the subsequent development of lower cost hot air heating systems might strengthen this situation.

The choice of system will, of course, be influenced by the resources available. For most farmers, capital is very limited. Hence there is a tendency for growers to start with an unheated plastic house and then subsequently install a wood heating system; the hot air system doubles the cost (again, the variability of low cost local systems may lessen this differential). But if land is a scarce resource or is expensive to purchase—and in one greenhouse area land prices tripled in the last 2 years—then the systems which offer higher yields begin to come into more favorable balance.

At the national level, there is a similar concern with stretching the return from capital. Much of the financing comes from the national Agricultural Bank. The bank realizes that with a given amount of capital it is able to finance many more farmers if less capital-intensive units are built. The more houses that are built, the wider the profits are spread and the greater the number of individuals that are employed.

As of 1971, about 25,000 greenhouses were in operation, providing employment for an equivalent of about 15,000 full time workers. They represented a total capital investment of about $35 million and an annual gross output of about $15 million. Greenhouse vegetables were found in most markets in the country. "Although the prices are still too high for the average and low income groups, it is expected that as production increases, the prices will tend to go down and more people will be able to buy them."[102]

Investment in greenhouses continues at a heavy pace; of the total loan funds provided by the Agricultural Bank which were outstanding at the end of 1971, about 63 percent was for loans made in 1971. Despite lower prices, greenhouse production continued profitable and repayment rates were considered to be good.[103]

The tightening in the domestic market for the major greenhouse vegetable crops has promoted increased attention to alternative crops (including flowers) and export markets. In early 1973, plans were initiated for two large glass-covered greenhouses to be built in the Izmir area, south of Istanbul, to produce winter crops for export to Europe. Both are to be owned and operated by cooperatives.[104] How successful these groups will be in competing with other nations remains to be seen.

Lebanon.[105] Simple plastic-covered greenhouses have been used in Lebanon for a number of years for vegetable production.[106] The first modern controlled environment greenhouse was completed at the American University of Beirut during the 1970/71 academic year. It was provided with climate control devices and was designed for both research and the teaching of greenhouse operation and management. Four other units are planned.

Shortly thereafter, the Government Green Plan took two significant steps toward the establishment of a modern greenhouse industry. First, a hydroponic greenhouse manufactured in the United States (see ch. III) was erected on the outskirts of Beirut. It was financed by the United Nations Development Program and FAO as an experimental and demonstration unit. Even before construction was completed in 1972, four units were sold to a large citrus firm in Lebanon; the firm was also named regional sales representative. Concurrently, the Green Plan asked for bids on seven regular greenhouses totaling about 20,000 square meters to be built in four regions of the country. The prospects included equipment for automatic ventilating, heating, and irrigation. The tender was subsequently revised to include houses of all different major types (glass, fiberglass, PVC, polyethylene).

Reasons cited for Government interest in greenhouses include the following: limited availability of highly productive land, increasing cost of labor necessitating year-round use, high prices for several horticultural products off season, stabilization of supply, and increased returns to farmers. Not everyone agrees on some of these points, but the seasonal rise in prices of some items has been documented. Beirut has a relatively higher proportion of wealthy consumers than many other nations in the Near East, and demand should be comparatively strong. Preliminary Government analysis suggested that cucumbers would make the most promising vegetable crop for local consumption; local production is not possible during the winter and imports are scarce and high priced. Tomatoes are considered a more marginal proposition; although there is typically a sharp seasonal rise in prices, low-cost imports are now available from Jordan.[107] Squash, string beans, and sweet peppers are being considered but are in need of further investigation.[108]

Should the greenhouses prove profitable, there is sufficient private capital available to insure expansion of production. The problem is that the domestic market, as in many developing nations, is not very broadly based. It is even thinner in neighboring nations. Supply could quickly exceed effective domestic demand--a matter that will have to be considered in future growth.

Israel. Although Israel raises a wide range of horticultural crops under cover, the area of greenhouses used for food crops is relatively small. Most of the covered vegetables are raised under low tunnels. One estimate suggests that during the winter of 1969/70, only about 65 acres (25 ha.) of vegetables were raised in greenhouses, while 5,440 acres (2,200 ha.) were raised in low tunnels.[109]

While some greenhouses used for vegetables utilize glass, most are plastic-covered wood frame structures or high tunnels. The frame houses generally have ventilation equipment and sometimes are used for heating. Houses with highly sophisticated climate control equipment are used almost exclusively for flowers. The advantages of greenhouses are well known in Israel, but they have not been more widely used for food crops because of (1) the competition and the good results obtained from the low tunnels, and (2) the large investment required for greenhouses.[110]

The main purpose of the low tunnels is to help protect vegetable plants from cold weather in the winter and from hail. Only a small proportion of these structures are permanent; they are mainly used during the winter and then taken down. Crops raised in these structures include bell peppers, artichokes, strawberries, squash, and melons. Some of the product is exported to Europe.[111]

A Centre for Research in Protected Crops has been established at Bet Dagan under the Agricultural Research Organization of the Ministry of Agriculture. To incorporate international knowledge in this work, a High Value Crops Project was set up in 1970 with the help of the United Nations Development Program and the Food and Agricultural Organization. A research facility is being established which will eventually include 10 refrigerated greenhouses. Both food and floral crops will be included in the research activities.[112]

Use of controlled environment enclosures as part of a desert agro-industrial complex is being considered for southern Israel.[113]

Kuwait and Abu Dhabi. Some of the most unusual greenhouse food production in the world is carried out in Kuwait and Abu Dhabi on the Persian Gulf. Both are small, oil-rich nations located in a desert area. An almost complete lack of fresh water has virtually ruled out commercial production. Hence, desalinized sea water is used for hydroponic or trickleculture vegetable

Plate 15--*Arid Lands Research Center in Abu Dhabi. The center was established through a grant from the Sultan to the University of Arizona.*

production. And because of generally high temperatures, they are provided with cooling equipment.

Kuwait built its first greenhouse in 1962, and by 1969 had erected seven more. The total area by then was 6.2 acres (2.5 ha.). All but one were located at the experimental farm. Of the eight, six are covered with polyester panels and five have artificial cooling. The structures are principally used for vegetable production but flowers are also raised.[114]

Abu Dhabi has probably the most advanced greenhouse cultural system of its type. The basic technique was developed by University of Arizona scientists and has been discussed in chapter III. The present installation, the Arid Lands Research Center, is located on Sadiyat Island and was placed in operation in early 1972. It consists of a 4.77-acre (1.93 ha.) trickleculture unit (sand substrate); of the total, 2.45 acres are covered by 48 air-inflated plastic structures and 2.3 acres by polyethylene over a rigid structure. Waste heat from engine-driven electric generators is used to desalt sea water. Evaporative cooling is used most of the year (but it is difficult to keep summer temperatures as low as desired because of the high humidity on Sadiyat). The use of trickleculture and the maintenance of a high humidity in the greenhouse reduce water use considerably below levels required for culture in the open.

Preliminary production and marketing experience in Abu Dhabi with 15 crops has indicated that those with the greatest profit potentials are tomatoes and cucumbers. In the future, about 70 percent of the total area will be devoted to these two crops. Other commercial crops include snap beans (bush), cabbage, Chinese cabbage, and radishes. Peppers are under study. Lettuce has not done well under prevailing temperatures, and eggplant, okra, and turnips were found unprofitable. Radishes are interplanted among other crops. Chinese cabbage is used as a replacement for lettuce. Yields for major crops have been as follows:

	Yield of 1 crop	Crops per year	Annual yield
	Short tons/acre	*Number*	*Short tons/acre*
Tomatoes	60	2	120
Cucumbers	80	3	240
Beans	4.5	4	18
Cabbage	23	3 to 4	70 to 90
Chinese cabbage	20	4+	80+
Radishes	9	9	81

These are quite respectable yield levels, especially for a desert. Still, the search for desirable heat-tolerant varieties continues.

Production is timed so as not to compete with the limited local supplies. The average wholesale price received has been about 27¢ a pound. The average per capita income in Abu Dhabi is one of the highest in the world and there has been a good market. In February 1972, a 1,000-pound trial shipment of vegetables was air-freighted to Beirut; a second shipment was sent in March. Prices received were sufficient to make such exports realistic. Formerly, Abu Dhabi imported a considerable portion of its higher quality vegetables from Lebanon.[115]

The techniques developed and tested in Abu Dhabi may well prove to be of value for other oil-rich desert areas with ocean shoreline. A 2-acre unit, similar in design to the Abu Dhabi installation, is planned for Kharg Island in the Persian Gulf, just off Iran.

EAST ASIA

Much of East Asia is intensively farmed, and multiple cropping is commonly practiced. Plastic-covered greenhouses have been used to facilitate this process in the northern part of the region—Japan, South Korea, and northern China (People's Republic)—by making possible the production of a winter crop of vegetables. Except for glasshouses in Japan, environmental control techniques are minimal. Recently, simple plastic houses have come into use in the Philippines for a quite different purpose—to produce tomatoes during the rainy summer season. One of the most intensive vegetable areas in the region, the new lands of Hong Kong, has not as yet utilized greenhouses.[116] Nor are they used on Taiwan.

Japan. Greenhouse food production in Japan is similar in some respects to that in Israel. That is, in addition to the usual glass and plastic covered houses, wide use is made of temporary structures. Essentially high plastic tunnels, they are used during the winter for one crop of an early variety and then taken down so that regular field culture can be practiced the rest of the year. No artificial heating is normally used in the temporary houses.

The area data for plastic do not distinguish between the regular and temporary structures. Hence the statistics should be taken with a considerable grain of salt in terms of quality of environmental control. The area of greenhouses of both glass and plastic construction used for fruits and vegetables has expanded as follows:[117]

Crop year	*Glass*		*Plastic*	
	Acres	*(Ha.)*	*Acres*	*(Ha.)*
1960/61	398	(161)	3,227	(1,306)
1962/63	561	(227)	8,485	(3,434)
1964/65	788	(319)	12,076	(4,887)
1966/67	754	(305)	17,687	(7,158)
1968/69	872	(353)	25,039	(10,133)

The total glasshouse area in 1970, including land used for flowers, was 1,480 acres (598 ha.).[118]

Within the glasshouses, 41 to 42 percent of the area has been used for fruit and 58 to 59 percent for vegetables. The fruit area is principally grapes. About 70 percent of the vegetable area is used for melons—a far higher proportion than anywhere else in the world. Several vegetable crops are usually grown each season. Division of the area planted by the area covered revealed the following multiple cropping indexes: 1962/63, 286; 1964/65, 241; 1966/67, 280; 1968/69, 292. These are the highest indexes found anywhere.[119]

Within the plastic houses, virtually all the area is used for vegetable crops. These usually include tomatoes, cucumbers, and eggplant. Strawberries (evidently classified as a vegetable) are one of the main crops raised in the temporary houses: the house is usually put up in January and removed in time for spring planting of other crops. In addition, vast areas are planted under low tunnels.[120]

The temporary structures are basically composed of prefabricated metal hoops covered with plastic (high tunnels). Such units can be erected or dismantled by two or three people in a few days. Some houses are rented from contractors, whose charge includes delivery to site, erection, and removal.[121]

The temporary plastic houses have probably made a significant contribution to providing relatively low-cost products out of season. One writer states that because of the temporary houses, "it is now possible to enjoy fresh strawberries at a reasonable price for nine months out of the year."[122]

The usual size of greenhouse holding is very small—less than 0.1 acre for glasshouses and less than 0.2 acre for plastic houses in the Aichi and Shizucka area. Individual houses are even smaller. Part of the reason is that some operators are also involved in upland and paddy rice farming.[123]

It is expected that many of the houses will have to be made larger to facilitate the introduction of labor-saving methods. Labor shortages are expected to be one of the major constraints on expansion of the greenhouse industry.[124]

South Korea. A large variety of winter vegetables is raised in plastic-covered, wood frame structures in South Korea. According to estimates compiled in the spring of 1972, the vegetable area totaled 3,205 acres (1,297 ha.).

The leading crops in terms of proportion of area occupied were: cucumbers 26 percent; Chinese cabbage 15 percent; tomatoes 13 percent; lettuce 13 percent; melons 10 percent; and red peppers 9 percent. The remaining 14 percent of the area was covered by more than a dozen other crops. The leading Provinces in terms of area were: Kyungnam 37 percent; Chungnam 22 percent; Kyunggi 15 percent; and Chunnam 13.5 percent.[125]

The amount of double cropping is not known. In some cases where temporary houses are used, the latter half of one crop and the first half of another is under plastic. This also occurs when the frame is left standing and the plastic applied only during the winter months. The season for covered production varies from year to year and from region to region but usually extends from about the first of November to about the middle of April.[126]

The area under plastic expanded sharply through 1969/70 but increased by only 62 acres between then and 1971/72. And during the 1971/72 season, there were signs of market saturation. Attempts to export to Japan have met a thin market.[127]

In addition to the acreage in plastic-covered houses, about 6,000 acres (2,428 ha.) were covered by tunnels in the spring of 1970. Watermelon, as in Greece, was the leading crop (28 percent of the area), followed by Chinese cabbage, tomatoes, yellow melon, and cucumbers.[128]

People's Republic of China. China is the big unknown in greenhouse food production. Although greenhouses have been used for many years in the northern part of the country, no national statistics on their area have yet been located by foreign analysts.[129]

The one news item that was found referred to the winter production of vegetables in the suburban areas of Peking. For 1971, 8,800 hot-houses and 95,000 plastic-covered cold frames were reported, the latter having an area of 180 acres (73 ha.). The Commune Evergreen, which was visited by Mrs. Nixon, was reported to have 1,300 hothouses producing 2,250 tons of vegetables. About 25 varieties of vegetables were grown, but cucumbers and tomatoes were the primary crops.[130]

It is to be hoped that more data can be found on China in the future.

Philippines.[131] The Philippines is the only tropical country in the world where greenhouse food production is known to be carried out commercially. The main reason is for protection from heavy summer rains, but the warming effect can also be important at higher altitudes. In addition to physically protecting the plant from the force of the rain, the structure provides other benefits of water control such as reduced leaching of fertilizer, less washing of insecticides, and reduction of disease incidence. Weed control is also made easier. And the harvesting period may be prolonged.

There are two main greenhouse areas in the Philippines: the highlands near Baguio, and the lowlands north of Baguio (La Union) and near Manila.

The highlands' greenhouses were first built near Baguio, a region of 4,000 to 6,000 feet elevation, after World War II. Both glass and plastic houses with open sides were in existence as of late 1972. The glass area was roughly 10 acres, and the plastic area was about 8 acres.

The lowlands' greenhouse industry was slower to develop because of the need to develop improved varieties which are both resistant to bacterial wilt and set fruit under high night temperatures. The first greenhouses were established in Rizal in 1967, in La Union in 1970, and in Laguna in 1973. As of early 1973, the total lowland area was probably about 20 acres, all under plastic. Further expansion is expected.

The use of plastic structures for tomato production in the Philippines was attempted as early as 1958 and several times thereafter. None of the early ventures succeeded, in part because of varietal problems and in part because of inappropriate design of the structures. In 1967, a variation of the high tunnel type, consisting of PVC plastic over bamboo, was tested and found to be suitable for the heavy rains and high winds of the region. It is open on the sides and ends. The newest units also allow for roof ventilation. One of the main technical problems is the low light intensity during the rainy season. Plastic films need to be treated with a fungicide at the factory to reduce mold growth and maintain maximum transparency.

Nearly all of the greenhouse area is devoted to tomatoes. In the glasshouses at Baguio, however, tomatoes are double cropped with cucumbers or other high-value crops. Monocropping is generally followed in the plastic units: after the tomato crop, the land is fallowed or planted to a legume cover crop. Furrow irrigation is utilized. Temperatures inside the houses get very high during the daylight hours in summer but the tomato plants do not seem to suffer unduly, except for fruit color, as long as the temperature drops off at night. Yields are low by international standards (10 metric tons per acre) but about twice those found under field conditions. They are expected to increase as management practices are improved and as varieties producing larger and heavier fruit are developed.

Since field production of tomatoes is very difficult during the rainy season, the greenhouse product faces little competition. As of early 1973, most of the tomatoes were being sold in the Manila region to supermarkets, hotels, and U.S. military bases. While foreign visitors generally consume the tomatoes in fresh form, Filipinos prefer to use them in cooking. Prices have tended to limit consumption to higher income groups. Should production expand and prices drop, the potential market is broad because tomatoes are popular.

The Philippine experience in using simple greenhouses for rainy season fruit production could well be instructive for other tropical nations.

OCEANIA

Essentially the only greenhouses used for food production in the southern hemisphere are found in Australia and New Zealand. They are principally, if not entirely, located below 30° south.

Australia.[132] National data on greenhouses are not available in Australia, so it has been necessary to build up information from the State departments of agriculture. Replies from the three most important States (New South Wales, Victoria, and Tasmania) indicate a total area of only 178 acres (72 ha.).

Tomatoes are easily the leading crop in area, followed by green peppers and cucumbers; peppers are increasing in importance. Small but increasing areas are used for nursery crops.

Of the three States, New South Wales has the largest area with 154 acres in 1970/71 (down 6 acres from 1969/70); 95 percent of its production is tomatoes. It is followed by Victoria with about 40 acres of unheated glass; peppers are the leading crop with 70 percent of the area. Tasmania is third with nearly 24 acres, 37 percent of which is heated; tomatoes are the major crop. In the State of South Australia, a substantial area of vegetables is raised under cold frames (643 acres or 260 ha. in 1971/72).

Nationally, the industry is relatively static in terms of growth. Improvements in transportation, principally the adoption of a standard gauge railroad system, have led to increased competition from earlier outdoor growing areas in Queensland. Also, water is a limiting factor in South Australia; it is either expensive in metropolitan areas or restricted in supply in country areas where river or subartesian water is used.

New Zealand.[133] New Zealand has a relatively large greenhouse industry for its size. This is because of its limited range of outdoor growing areas, relative isolation, and high level of income. Recent greenhouse area data are as follows:

Year ending January 31	*Total area*		*Area under crops*	
	Acres	*(Ha.)*	*Acres*	*(Ha.)*
1964	212	(86)	223	(90)
1968	248	(100)	250	(101)
1971	285	(115)	293	(119)
1972	288	(116)	291	(118)

Some multiple cropping was practiced, accounting for differences between total and cropped area. The proportion of greenhouse area heated increased from 35 percent in 1964 to 54 percent in 1972.

Tomatoes are by far the most important crop, accounting for 260 acres or nearly 89 percent of the total cropped area in 1972. They were followed at a considerable distance by: cucumbers 5.6 percent, grapes 3.7 percent, and beans 2.0 percent. Yields in 1972 (short tons per acre) were: tomatoes 60.3, cucumbers 71.9, grapes 17.5, and beans 14.9.

The usual marketing season for tomatoes is from May to February for heated houses (remember that the seasons are reversed in the southern hemisphere) and from November to March in unheated houses.

ANTARCTIC

Surprisingly, small greenhouses have been built by various Antarctic exploration teams.[134] The region, despite its low temperatures, experiences total daylight from mid-November to mid-February. One of the most recent efforts was by an English explorer in 1962-63. A small, insulated, double-glazed structure was built with only limited provision for ventilation (because of drifting snow). Since the buildings in the base were underground, entry and heat were provided from below. As it turned out, the problem with temperature was to keep it down on days of clear skies. Tomatoes were intercropped with lettuce and radishes; the tomatoes and radishes did well but the lettuce failed to head satisfactorily.[135]

* * *

This completes our review of the greenhouse situation in individual nations. Some statistics have no doubt been overlooked. And a few nations may even have been missed. The biggest gap in our knowledge is Mainland China. But perhaps enough information has been presented to give a reasonable idea of the size and nature of greenhouse vegetable production around the globe.

REFERENCES AND NOTES

1. It is not exactly clear why there has long been such a concentration in northern Ohio. As in other northern States, greenhouses tended to be established where cultural and marketing conditions favored outdoor vegetable production: growers then simply were looking for ways to extend their season and since they had long used hot beds or simple greenhouses to start transplants, the shift to off-season greenhouse production was not an unnatural one. Still, this doesn't explain the special concentration in Ohio. Winter growing conditions or markets were hardly any more favorable there than in many northern States. Possibly coal for heating was cheaper. Or possibly many farmers were of Dutch extraction. Or possibly it was just the agglomeration of skills, tradition, or infrastructure. The question would be an interesting subject for geographic study.

2. In 1971, there were about 6.5 acres under commercial production in Alaska (letter from John Burton, Associate Professor of Agricultural Economics, University of Alaska, February 21, 1972). In addition, many private homes have small backyard plastic houses (see *National Geographic*, September 1972, pp. 410-411). The main crops are tomatoes, cucumbers, and green peppers. The season normally extends from March through September.

3. Commercial greenhouse food production in Hawaii dates from only 1971. All the area in 1973, nearly 12 acres, was in hydroponic or trickleculture and was devoted to tomatoes. Two crops are grown on a year-round basis, and in part replace imports from California. No artificial heat is necessary but light is a limiting factor in some parts of the islands in the winter. One of the main purposes of the structure is to facilitate insect and disease control (visit with Kent Ellis, Environmental Farming of the Pacific, Inc., Honolulu, March 31, 1973).

4. *American Vegetable Grower*, November issue, 1965, 1966, 1967, and 1971. The 1971 data are not fully comparable to previous years' data because of the inclusion of additional States.

5. The wholesale price index for all commodities in the United States increased from a base of 100 in 1929 to 217 in 1969 (computed from data in various issues of the *Statistical Abstract of the United States*); the comparable index for value of greenhouse production increased from 100 to 248.

6. *Greenhouse Industry, 1969-1970*, Statistics Canada, Ottawa, December 1971, p. 6, and earlier issues. Also see "Greenhouse Industry Gains Ground in Canada." *American Vegetable Grower*, November 1972, p. 22.

7. H. Blum, *Marketing of Ontario's Greenhouse Vegetable Products in Competition with Imports from Mexico*, Ontario Department of Agriculture and Food, Farm Economics, Cooperatives and Statistics Branch, Toronto, May 1969, p. 1.

8. *Greenhouse Industry... op. cit.*, and data provided by the Agriculture Division, Statistics Canada, Ottawa, March 14, April 21, 1972.

9. Blum, *op. cit.*, p. 4.

10. Based on a personal visit to Bermuda in September 1972 and discussions with the following individuals: Idwal Hughes and Edward Manuel, Department of Agriculture; David Lovejoy and Jonathan Livingston, Pleasant Acres, Smiths Island.

11. The soil and rock structure of the island is very porous, so that rainwater is directly absorbed with very little runoff; there are no perennial streams. Yet because of the intrusion of surrounding salt water, well water is often brackish. A small hydroponics unit on the main island uses a reverse osmosis unit to purify brackish well water (letter from Norman Davidson, Bermuda Gardens, Hamilton, January 8, 1973).

12. Perhaps the most complete single source is *L'Evolution de la Production Fruitiere et Legumiere Sous Serres in Europe*, Centre National du Commerce Exterieur, Department des Etudes de Marches Agricoles et Alimentaires, Paris (10, Avenue d'Iena, Paris 16 eme), 1971, 432 pp. It concentrates on Western Europe, but does provide data for Romania and Bulgaria.

13. Letter from G. F. Sheard, Glasshouse Crops Research Institute, Rustington, England, November 14, 1972.

14. W. F. Bewley, *Commercial Glasshouse Crops*, Country Life, Ltd., London, 1950, p. 470.

15. *Ibid.*, p. 482; "Glasshouse Production," in *Horticulture in Britain*, Part 1, Vegetables, Ministry of Agriculture, Fisheries, and Food, 1967, p. 301. A similar policy was followed in Germany (personal discussion with H. E. Volkner, Bethesda, Md.; Volkner's father operated a large greenhouse in Germany during the war).

16. Based on data provided by G. F. Sheard, *op. cit.* 1972, and in *L'Evolution, op. cit.* pp. 300, 309 (contains detailed data back to 1956/57).

17. The growth represents a shift in consumer preference away from the tougher outdoor, over-wintered lettuce towards the glasshouse product. The shift was also aided by the availability of improved glasshouse varieties and an increase in the import duty in 1963 (*Glasshouse Lettuce: An Economic Survey in Lancashire*, University of Manchester, Department of Agricultural Economics, Bulletin 139/H2. February 1972, pp. 1, 5, 30.)

18. Compiled from data provided by the Agricultural Censuses and Surveys Branch, Ministry of Agriculture, Fisheries and Food, Guilford, Surrey, April 13, 1972.

19. *Ibid.*

20. "Census of Horticultural Properties, 1970," States Committee for Horticulture, Guernsey, pp. 8, 9.

21. "Statistical Information, Glasshouses and Glasshouse Equipment-England and Wales," Ministry of Agriculture, Fisheries and Food, Guilford, Surrey, August 3, 1971, 2 pp.

22. Letter from Sheard, *op. cit.* June 23, 1972.

23. "Census of Horticultural Properties. . . ," *op. cit.*, pp. 8, 9.

24. G. F. Sheard, "Greenhouse Vegetable Production in Britain," *Proceedings of the North American Vegetable Conference*, September 1970, Pennsylvania State University, (University Park), Department of Horticulture, p.52.

25. *Report of the Survey Team Established by the Minister for Agriculture and Fisheries on the Glasshouse Industry*, Department of Agriculture and Fisheries, Dublin, 1966, 15; *L'Evolution, op. cit.*, p. 357 (based on Irish data). (The first reference covered the 1960-64 period; the second the 1966-70 period.)

26. "Note on Irish Glasshouse Industry," Department of Agriculture and Fisheries, Dublin, May 17, 1972 (prepared for and forwarded by Eugene Ransom, Agricultural Attache, American Embassy, Dublin).

27. *Ibid.*: "Department of Agriculture and Fisheries Scheme of Grants for Glasshouse Nurseries," Department of Agriculture and Fisheries, Dublin, GGS/3, June 1970, 5 pp. (mimeographed).

28. Unless noted otherwise, the information in this section was obtained from: (1) a visit with A. J. Vijverberg and A. J. de Visser of the Research and Experiment Station for Glasshouse Crops in Naaldwijk, June 29, 1972; (2) letters from A. A. M. Sweep, Naaldwijk, February 22 and April 21, 1972; and (3) A. A. M. Sweep, "Research and

Culture- Glasshouse Vegetables in Holland," *North American Greenhouse Vegetable Conference*, 1970, *op. cit.*, pp. 31-38.

29. *L'Evolution, op. cit.*, pp. 125, 137. The proportions of each crop exported were tomatoes 81 percent, cucumbers 68 percent, lettuce 62 percent, strawberries 15 percent, and grapes 26 percent.

30. I do not have statistics for the full period for lettuce, but it is clear that an expansion took place. In 1950, only a small proportion of Dutch houses were heated and then they were seldom used for winter production, which is when lettuce is largely raised.

31. See R. R. W. Folley, *Tomato Growers' Interests in a West European Market*, Wye College (University of London), Department of Agricultural Economics, 1964, pp. 22, 49; M. T. G. Meulenberg, "A Quantitative Investigation into the Dutch Tomato Market: A Seasonal Analysis," *Netherlands Journal of Agricultural Sciences*, August 1964, pp. 172, 185.

32. For details, see R. K. Elema and D. Meijaard, *Economische Aspecten van de Aardbeienteelt onder Staand Glas*, Landbouw-Economisch Institute, The Hague, No. 4.15, November 1968, 67 pp. (Abstract in *World Agricultural Economic and Rural Sociology Abstracts*, June 1969, p. 325.) The strawberries are principally harvested in April and May.

33. For details, see A. J. de Visser, *Bedrijfseconomische Aspecten van deAugurkenteelt in Onverwarmde Kassen*, Landbouw-Economisch Instituut, The Hague, No. 4.9, August 1968, 44 pp.

34. The glasshouse fruit industry has been analyzed by J. Goedegenbure and J. Kuyvenhoven in *Economische Aspecten van de Teelt van Kasfruit*, Landbouw-Economisch Instituut, The Hague, No. 4.38, March 1971, 84 pp. (English summary).

35. The data in this section are from: *Tuinbouwcijfers, 1972*, Landbouw-Economisch Institut, Central Bureau voor de Statistic, Hague, pp. 28, 32: *L'Evolution, op. cit.*, pp. 152, 157.

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37. T. Hendrix, "Discussie-Nota Teeltplannen," Instituut voor Tuinbouwtechniek, Wageningen, Holland, undated, 16 pp.

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39. H. I. Oudshoorn, *The Market Gardners in Wateringen and Delier: A Geographic Study of the Religious Situation in the Westland* (in Dutch), Van Gorcurn & Co., Assen, 1957, p. 135.

40. Folley, *op. cit.* p. 23.

41. Based on data compiled by D. Meijaard, Landbouw-Economisch Instituut, The Hague, November 24, 1969, pp. 1-2.

42. Goedegebure and Kuyvenhoven, *op. cit.*. pp. 63, 64; *Teelt van Licht Verwarm de-en Koude Tomaten*, Research and Experiment Station for Glasshouse Crops, Naaldwijk, Informatjereeks No. 14, 1971, p. 14.

43. L. van Noort, *Rentabiliteit van de Tuinbouw in het Zuidhollands Glasdistrict*, Landbouw-Economisch Instituut, The Hague, Mededelingen & Overdrukken 78 (1972), pp. 4, 6.

44. *L'Evolution, op. cit.* pp. 152, 157.

45. van Noort, *op. cit.*, p. 18.

46. *L'Evolution, op. cit.*, pp. 201, 207 (also reported in *Statistique Agricole*, Office Statistiques Communautes Europeennes, *op. cit.*, pp. 192, 193).

47. *Ibid.*

48. *Ibid.*

49. *Ibid.*, pp. 201, 205.

50. "La Culture Maraichere Souse Verre," Belgian Ministry of Agriculture, 1971(?), p. 3. (Provided by U.S. Agricultural Attache, Brussels, February 18, 1972.)

51. *Ibid.*, p. 5.

52. *Ibid.*, pp. 8, 10, 11.

53. *Ibid.*, p. 27. Details on exports are found in *L'Evolution, op. cit.*, pp. 215-217.

54. A. Bry, "Implementation Actuelle et Evolution des Culture Legumieres en France et a l'Etranger," in *Les Serres Maraicheres* (Journees Nationales, March 1964), Institut National de Vulgarization des Fruits, Legumes et Champignons, Paris, 1964, p. 11. (This publication, which totals 160 pages, contains many useful technical articles on food production in French greenhouses.)

55. W. Cadet, *Le Marche des Legumes de Serre Francais*, Centre Technique Interprofessional des Fruits et Legumes, Paris CTIFL Documents No. 15, July 1967, p. 3.

56. Cadet, *op. cit.*, p. 3; *L'Evolution, op. cit.*, p. 45; *Statistiques Agricoles, 1970*, Ministry of Agriculture, Paris, pp. 222-223; *Statistique Agricole, op. cit.*, p. 179.

57. From estimates provided by A. A. M. Sweep, Horticultural Research and Experiment Station, Naaldwijk, Holland, February 22, 1972.

58. *L'Evolution, op. cit.*, p. 45 (a graphic presentation of the heated and unheated areas by district is provided in a figure on p. 47); data for 1970 provided by Thomas E. Street, Agricultural Attache, American Embassy, Paris.

59. *Statistiques Agricoles, op. cit.* pp. 222-223; *Statique Agricole, op. cit.* p. 179.

60. *L'Evolution, op. cit.*, p. 54.

61. *Ibid.*, pp. 49-53.

62. *Ibid.*, pp. 50, 51; Cadet, *op. cit.*, p. 3.

63. Sweep, *op. cit.* (1972); *Statistique Agricole, op. cit.*, pp. 177-178.

64. *Statistique Agricoles, op. cit.*, pp. 177-178.

65. *L'Evolution, op. cit.*, pp. 185, 187, 189.

66. Letter from Hans G. Stuckman, Agricultural Research Specialist, Office of Agricultural Attache, American Embassy, Vienna, March 23, 1972. The reference is to high-sided houses.

67. *Ibid.*

68. *L'Evolution, op., cit.*, p. 395.

69. *L'Evolution, op.cit.*, pp. 367, 368. (Based on data provided by the Swiss Federal Bureau of Statistics. According to data supplied by the U. S. Agricultural Attache in Switzerland, however, the 1969 census indicated that vegetable producers had 294 acres of high-sided greenhouses. Although some of the area might be used for other crops, the differential is almost too wide for comfort.)

70. *Ibid.*, pp. 365, 366, 372, 373, 381, 382.

71. Statistics compiled from various yearbooks (*Landbrugsstatistick*) of the Danish statistical office and provided by Harlan J. Dirks, Agricultural Attache, American Embassy, Copenhagen, March 29, 1972; P. G. Allen and D. J. Fuller, "The Danish Glasshouse Industry" *Agriculture* (London), March 1964, pp. 120-124.

72. *Jordbruksteljinga* (*Census of Agriculture*), June 1969, Central Bureau of Statistics of Norway, Oslo, 1971, pp. 174-177; June 1959, CBSN, 1961, p. 338. (Yearly data for tomatoes and cucumbers are now provided in the annual report on *Agricultural Statistics* by the CBSN.) Provided by Ivar Kristianslund, Lecturer in Statistics, Agricultural College of Norway, April 1972.

73. Letter from Gunnar Ledin, Ardelningsdirektor, Tradgarsavdelningen, Lantbruksstyrelsen, Solna, March 23, 1972; *Swedish Agriculture*, Ministry of Agriculture, 1968, p. 16; *L'Evolution, op. cit.*, p. 256.

74. Letter from Martti Halme, Director for the Bureau of Horticulture, The National Board of Agriculture, Helsinki, April 22, 1972. (Data from Agricultural Census of 1969); *L'Evolution, op. cit.*, pp. 272, 273, 276, 281.

75. Wright Britton, "Sailing Iceland's Rugged Coasts," *National Geographic*, August 1969, pp. 238-240.

76. *L'Evolution, op. cit.*, pp. 412, 413. The area under low tunnels or frames was estimated at 445 acres (180 ha.) in 1970.

77. M. Robledo, "Plastics Applications in Spanish Agriculture," *Plasticulture* (Paris), March 1971, pp. 10, 11, 18, 19; F. Buclon, "New Trends in the Use of Plastics in Agriculture," *Plasticulture*, March 1972, pp. 11, 12. The area of low tunnels or plastic row covers was 3,160 acres in 1968 (*L'Evolution, op. cit.*, p. 400).

78. The materials presented in this section is an amalgam of data obtained from the following sources: *L'Evolution, op. cit.*, p. 228; Antonia Bacarella, Le Coltivazioni in *Serra in Sicilia*, Instituto Nazionale de Economia Agraria, Osservatorio de Economia Agraria per la Sicilia, Palermo, 1971, pp. 12, 13, 15, 24; Lorenzo Venzi, *Il Mercato Delle Produzioni Serricole*, Universita di Napoli, Centro di Specializzazione e Richerche Economico-Agrarie per il Mezzogiorno, Saggi e Ricerche 6, 1970, pp. 23, 28; *Bollettino Mensile de Statistica*, Instituto Central di Statistica, Rome, July 1971 (as summarized by Office of U.S. Agricultural Attache, Rome). Further information may be obtained from: Ranieri Favilli, "Aspetti e Problemi Della Orticoltura Forzata in Serra," *I Georgofili, Alti Della Accademia De Georgofili*, Florence, 1961, pp. 320-358; and in the superb special number of *L'Italia Agricola* on "Colture Protette," November-December 1968, pp. 875-1349.

79. R. G. Siddall, "Tomato Production in Malta," UNDP/SF Horticultural Demonstration and Training Centre, Malta, 1970.

80. A. Bry, "Evolution dans l'Utilization et de Developpement des Matieres Plastiques dans l'Horticulture in Greece," *4th Annual Colloquium on Plastics in Agriculture*, June 1970, Paris, 1971, pp. 43, 46; Buclon, *op. cit.*, p. 12; data provided by James C. Frink Agricultural Attache, American Embassy, Athens, May 26, 1972. Another source places the area breakdown in 1970 as: tomatoes 54 percent, cucumbers 43 percent, and other 3 percent (*L'Evolution, op. cit.*, p. 407).

81. Considerable help was received in the collection and translation of materials used in this section. Among those who assisted were Roger Euler and Robert Svec of the office of the Agricultural Attache, American Embassy, Moscow. In Washington, assistance was provided by Fletcher Pope and Val Zabijaka, Economic Research Service, USDA.

82. *Selskoye Khozyaystvo SSR, 1971*, Moscow, p. 217. Greenhouse production during this period expanded from 63,600 metric tons to 225,900. (In addition vegetable production in hotbeds in 1970 totaled 40,100 m.t., while that on warmed ground and under plastic film was 92,800 m.t.)

83. G. F. Sheard and L. A. Darby, "Report of a Visit to the U.S.S.R. . . . to study Protected Cropping and Research or Experimental Work, 7-28 June, 1967," Glasshouse Crops Research Institute, Littlehampton, England, December 1968, p. 24.

84. *Planovoye Khozyaystvo*, January 1972 (translation in JPRS, February 9, 1972, item 55147). Targets cited earlier were slightly less (*Sovietskaya Russia*, April 23, 1971). Subsequently the target was placed at 3,954 acres (1,600 ha.) (*Pravda*, October 10, 1972, p. 2; translation in *The Current Digest of the Soviet Press*, November 8, 1972, p. 4).

85. Except as noted otherwise, the references for this paragraph and those which follow are: *Moskovskaya Pravda*, September 27, 1969; *Sovietskaya Russia, op. cit.*; *Kartofel i Ovoschchi*, March 1968; *Komsomolskaya Pravda*, July 13, 1969; *Pravda*, October 10, 1972; *Pravda*, October 27, 1972.

86. R. Gardner, "Some Aspects of Horticulture in the Soviet Union," *NAAS Quarterly Review* (U.K.), Summer 1968, p. 180.

87. *Ibid.*, p. 180. Despite the limited light, a satisfactory crop is produced from the reserves of food material stored in the bulb.

88. Data provided by Alan W. Trick, Agricultural Attache, American Embassy, Warsaw, March 9, 1972.

89. Shipway, *op. cit.*, (1961) p. 4, appendix; G. Vogel and H. Hildman, "Die Nachsten Ziele und Aufgaben fur die Gemuseproduktion Untur Glas und Plaste," *Dtsche. Gartenbau*, Berlin 1970, pp. 285-288 (noted in *World Agricultural Economics and Rural Sociology Abstracts*, December 1971, item 5354.); P. Klose, et. al., "Rationalle Nutzung

von Plasfoliengewachshausern" *Dtsche. Gartenbau,* 1971, pp. 12-15 (noted in *Horticultural Abstracts,* December 1971, item 8720).

90. Sweep, *op. cit.,* (1972); A. Samos, "Verwendung von Kuntstoffen beim Gemusebau in Ungarn," *4th International Colloquium on Plastics in Agriculture,* June 1970, Paris, 1971, pp. 50-54 (English summary); G. J. Schmidt, "European News Letter," *American Vegetable Grower,* June 1963, p. 50; Bagneaux and Dujardin, *op. cit.,* p. 4; F. Venter, "Der Einsatz von Folie im Ungarischen Gemusebau," *Gemuse,* July 1971, pp. 33-36 (noted in *Horticultural Abstracts,* December 1971, item 8721).

91. *L'Evolution, op. cit.,* p. 422; Sweep, *op. cit.,* (1972); Bujur Manescu, "L'Utilization des Matieres Plastiques pour les Cultures Maraicheres en Roumanie," *4th International Colloquium on Plastics in Agriculture,* Paris, 1971, pp. 69-77; F. W. Shepherd, "Horticulture in Rumania," *Agriculture* (U.K.), November 1970, pp. 504-506. Most of the area estimates for the country do not include the area under plastic.

92. G. J. Schmidt, "European News Letter," *American Vegetable Grower,* June 1969, p. 10. November 1968, p. 35; Shipway, *op. cit.,* (1961), p. 4; T. Mourtazor, "Achievements and Problems of Greenhouse Vegetable Growing in the Peoples Republic of Bulgaria" (Symposium on Protected Growing of Vegetables, May 1969), *Acta Horticulture* (The Hague), April 1971, pp. 11-17; D. J. Fuller, "Bulgaria Builds Glasshouses," *Agriculture* (U.K.), January 1970, pp. 15-19; Sweep, *op. cit.* (1972). V. Popova. "The General Improvement of Some Basic Economic Indicators of Greenhouse Vegetable Production" (in Bulgarian), *Ikonomika Selskoto Stopanstvo,* Sofija, 1971, pp. 51-64 (cited in *World Agricultural Economics and Rural Sociology Abstracts,* September 1971, item 3808).

93. James K. Rathmell, Jr., "Europe has Carnation-Growing Problems." *Florists' Review,* January 6, 1972, pp. 47-48; letter from Frank W. Ehman, Agricultural Attache, American Embassy, Belgrade, February 28, 1972.

94. Letter from R. Holliday, Head of Department of Crop Science, Makerere University, Kampala, November 1, 1972.

95. Letter from G. F. Buchanan, Horticulturist, Department of Conservation and Extension, Ministry of Agriculture, Salisbury, August 8, 1972.

96. Department of State Airgram from Tunis, TOAID A-010, January 19, 1973.

97. See Jean-Claude Garnaud, *L'Intensification des Productions Horticoles du Basin Mediterraneen par la Culture Protogee,* FAO, Rome, 1971, 146 pp.

98. M. Robledo, "Plastics Application in Spanish Agriculture," *Plasticulture* (Paris), March 1971, pp. 12, 13, 18, 19,; F. Buclon, "New Trends in the Use of Plastics in Agriculture" *Plasticulture,* March 1972, pp. 11, 12. For details on the structures used in the Canary Islands, see M. Morey and F. Gonzales, "Emploi de Serres Geantes en Plastique dans Climats Sub-Tropicaux," *Cong. Int. Appl. Mat. Plast. Agric.,* Pisa, 1967, pp. 105-108 (noted in *Horticultural Abstracts,* September 1967, item 4221, p. 500).

99. "Apercu sur le Developpement Economique de la Region du Souss-Massa et sur Les Perspectives en Matiere d'Exportation," *Bulletin Mensuel d'Information,* Office de Commercialisation et d'Exportation, Rabat, No. 258, March 1972, p. 30. (Provided by Norman Ulsaker, Agricultural Economist, US/AID, Rabat.)

100. This section is based on data I gathered in Ankara, Antalya, and Aksu, June 19-23, 1972. The principal written references were W. B. Gibson, "Greenhouse Production in Turkey," FAO, AGS/AGP:SF/TUR 13, Working Paper, October 1971, 26 pp.; "Report on Early Vegetable Production, Project 14A, 1968-69," Vegetable Research Station, Aksu, Research Report No. 2, pp. 5E-11#. Additional materials were obtained from numerous individuals, including the Food and Agriculture Office of US/AID and the Office of the U.S. Agricultural Attache in Ankara, and FAO advisors at Aksu, and from visits to numerous greenhouses in the Antalya area. Some of these and other sources will be noted in the footnotes which follow.

101. These are rough estimates based in part on data supplied by the State Planning Office in Ankara and in part by the estimates of the former FAO greenhouse specialist. As in so many nations, comprehensive data based on actual surveys are not available. Data

compiled by the Ministry of Agriculture in 1970 show a far lower figure of 1850 acres (750 ha.); it is felt that this information is complete (based on data gathered by S. Unal of US/AID and Y. Z. Durusoy of the Office of the U.S. Agricultural Attache).

102. Y. Z. Durusoy, "Winter Gardening in the Turkish Rivera," Office of U.S. Agricultural Attache, Ankara, June 12, 1972. (Draft of article subsequently published in *Foreign Agriculture*, January 22, 1973, pp. 15-16).

103. Loans are made on a 5-year basis at 9 percent for no more than 50 to 70 percent of the total cost. In 1971, 563 farmers were added on this basis. (Based on discussion with Ihami Sozen, T. C. Ziraat Bankasi, Ankara, June 21, 1972.)

104. Based on discussion with Sozen, *op. cit.*, Ankara, April 11, 1973. One house will be 24 acres; the other 12 acres.

105. Except as noted, this section is based on discussions in Beirut, June 16, 1972 with: William Horbaly, U.S. Agricultural Attache; Hasbim Jawad, Resident Representative, United Nations Development Program; M. Basbous, President, and Gabriel Boyorgi, Economist, Green Plan; Jack Latham, Vice President, Hydroculture, Inc.

106. For pictures of some of these structures, see Garnaud, *op. cit.*, photographs 10, 16, 17, 20, 12, 28, 29.

107. These imports, however, are not always allowed in the country; this evidently was the case during the winter of 1971/72.

108. "Economic Aspects of Producing Cucumbers in Greenhouses in Lebanon," Plan Vert, Beirut, September 1971, 15 pp.

109. Uzi Klosner, "The Use of Plastics in Israeli Agriculture," *4th International Colloquium on Plastics in Agriculture*, June 1970. Paris, 1971, p. 41.

110. *Ibid.*; letter from Duane W. Clark, Agricultural Attache, American Embassy, Tel Aviv, February 23, 1972.

111. Clark, *Ibid.*

112. L. Morris, "Environmental Control for High Value Crops," *Israel Agriculture, Winter Newsletter, 1972/73*, Ministry of Agriculture, Jerusalem, pp. 27-29.

113. David Vofsi, "An Agro-Industrial Complex in the Arava," *Science and Public Affairs; Bulletin of the Atomic Scientists*, October 1972, pp. 48-49. The work at Abu Dhabi is well-known.

114. "Greenhouse Survey in Kuwait," undated, 1 p. Provided by S. Almannai, Under-Secretary, Agriculture Department, Ministry of Public Works, Kuwait, March 28, 1972.

115. Based on: *Annual Report 1971-72, Environmental Research Laboratory, University/Arid Lands Research Center, Abu Dhabi*, pp. 11-17; Miguel R. Fontes, "Controlled-Environment Horticulture in the Arabian Desert at Abu Dhabi," *HortScience*, February 1973, pp. 13-16; discussions with Merle Jensen and Hamdy Eisa of the Arid Lands Research Center, Abu Dhabi, April 9, 1973. (The yield levels reported here supplant those reported by Fontes.)

116. The cool winters and wet summers of Hong Kong might well provide the base for at least some plastic houses in the future—not so much to increase the cropping intensity as to modify the cropping pattern or increase yields. (Based on: a trip through the New Lands and a conversation with Dr. C. T. Wong of the Department of Agriculture and Fisheries, April 7, 1973; Charles J. Grant, *The Soils and Agriculture of Hong Kong*, The Government Press, Hong Kong, 1960, pp. 3-5, 119, 12 fig. 1/f.

117. "Facilities of Glass and Other Houses for Horticulture" (in Japanese), Ministry of Agriculture and Forestry, Bureau of Silk and Horticulture, 1970. (Provided and translated by Yujiro Hayami of Tokyo Metropolitan University.)

118. 1970 Agricultural Census, Ministry of Agriculture and Forestry (as cited by David Hume, Agricultural Attache, American Embassy, Tokyo, March 6, 1972).

119. "Facilities of...," *op. cit.* Estimate of melon area provided by S. Sekiyn, Chief, Vegetable and Flowers Division, Ministry of Agriculture and Forestry, Tokyo, May 9, 1972.

120. Michael Rodway, "Japan's Portable Greenhouses," *World Crops* (London), December 1967, p. 28. Also see Masataka Yanagisawa, "Development of Agricultural

Plastics Applications in Japan," *4th International Colloquium on Plastics in Agriculture,* June 1970, Paris, 1971, pp. 62-65. The area under tunnels in 1968/69 was 84,000 acres (34,000 ha.) ("Facilities of. . .," *op. cit.*).

121. Rodway, *op. cit.*, p. 28.

122. *Ibid.*

123. Ichiro Kato, "Future Prospects of Equipped Horticulture," *Farming Japan,* November 1969, pp. 5-12.

124. *Ibid.*

125. Compiled by the Office of Rural Development and provided by M. H. Heu, College of Agriculture, Seoul National University. Suwon, August 2, 1972.

126. Letter from Robert B. Morrow, Agricultural Economics Advisor, US/AID, Seoul, April 26, 1972.

127. *Ibid.* 1970 data compiled by the Vegetable Section, Office of Agricultural Development, Ministry of Agriculture and Forestry, Tokyo, and provided by Morrow.

128. Morrow, *op. cit.*

129. The National Agricultural Library has a number of books on the technical aspects of greenhouses in China, but none appear to provide any statistical data. Nor do U.S. specialists on Chinese agriculture know of any such data.

130. New China News Agency, Peking, February 23, 1972. News item located and translated by L. C. Kuo of the National Agricultural Library, April 18, 1972.

131. Based on information provided by Jose R. Deanon, Division of Horticulture, Department of Agronomy, University of the Philippines, in letter and during a visit by the author to the Philippines on April 6, 1973. The only written reference is found in E. C. Quisumbing, et al., "Other Cultural Practices," in *The Philippines Recommends for Vegetables, 1972-73,* National Food and Agricultural Council.

132. Based on letters from: L. R. Kavanagh, Chief, Division of Plant Industry, Department of Agriculture, New South Wales, Sydney, June 2, 1972; D. S. Wishart, Director of Agriculture, Department of Agriculture, Melbourne, Victoria, June 2, 1972; D. M. Hunt, Acting Chief Horticulturist, Tasmanian Department of Agriculture (to L. R. Kavanagh); R. Marks, Horticultural Research Officer, Department of Agriculture, Adelaide, South Wales, October 12, 1972.

133. "Annual Statistics, Schedule No. 10, Glasshouse Crops," New Zealand Department of Agriculture, Wellington. 1971 (provided by Roland E. Anderson, Jr., Agricultural Attache, American Embassy, Wellington); letter from J. H. Watt, Advisory Services Division, New Zealand Department of Agriculture, Wellington, May 24, 1972.

134. Kenneth Lemmon, *The Covered Garden,* Dufor, Philadelphia, 1963, p. 257.

135. Jack Hill, "The Absolute Desert—Growing Vegetables in the Antarctic," *World Crops* (London), May/June 1969, pp. 94-98.

VI. CONCLUDING REMARKS

. . .the time has come when the construction of glasshouses and the production of plants under glass are regarded much in the same light as the development of manufacturing interests in a large factory; in other words, a modern greenhouse establishment is so handled at the present time that in many respects it is a factory, utilizing nature's forces in a way to reverse the seasons for the purpose of converting into wealth the products of the soil.

B. T. Galloway, 1904[1]

Galloway's factory analogy is even more apt today. The possibilities for environmental control have indeed placed the upper levels of greenhouse food production on a par with industry. But this does not mean that the problems have been removed; far from it. While some of the uncertainties associated with weather may be lessened, they have only been replaced with the increased economic uncertainties and difficulties associated with high overhead, heavier operating costs, and a highly volatile market. The problems are no less, just slightly different.

Moreover, greenhouse production is not yet free of its links with nature. Although completely controlled environments are technically possible, they are generally not yet economically feasible. Light energy, for instance, must continue to come from the sun except for special purposes. Prevailing temperatures help determine the heating bill. Hence climate, through its effects on costs, has a pronounced effect on greenhouse operations. The result is, and will long continue to be, a compromise between farm and factory.

The compromise, however, is a unique one by the standards of traditional agriculture. And it may shed some light on the direction which agriculture could take, at least in part, in years to come. One of the largest and most progressive fruit and vegetable farming operations in the United States, for example, recently established an advanced greenhouse operation in Arizona. The president of the firm thinks that the greenhouse, which is "just like a factory," represents the "agriculture of the future." He goes on to say that "there's going to be one big greenhouse on your hundred-acre field where you control the gases, the temperature, humidity, control everything."[2]

In this concluding chapter, we shall turn to a review of the role of greenhouses and environmental control in the agricultural order. The discussion will necessarily contain fewer facts, which may be a source of some relief, and more value judgments. It is both broad summary and conclusion.

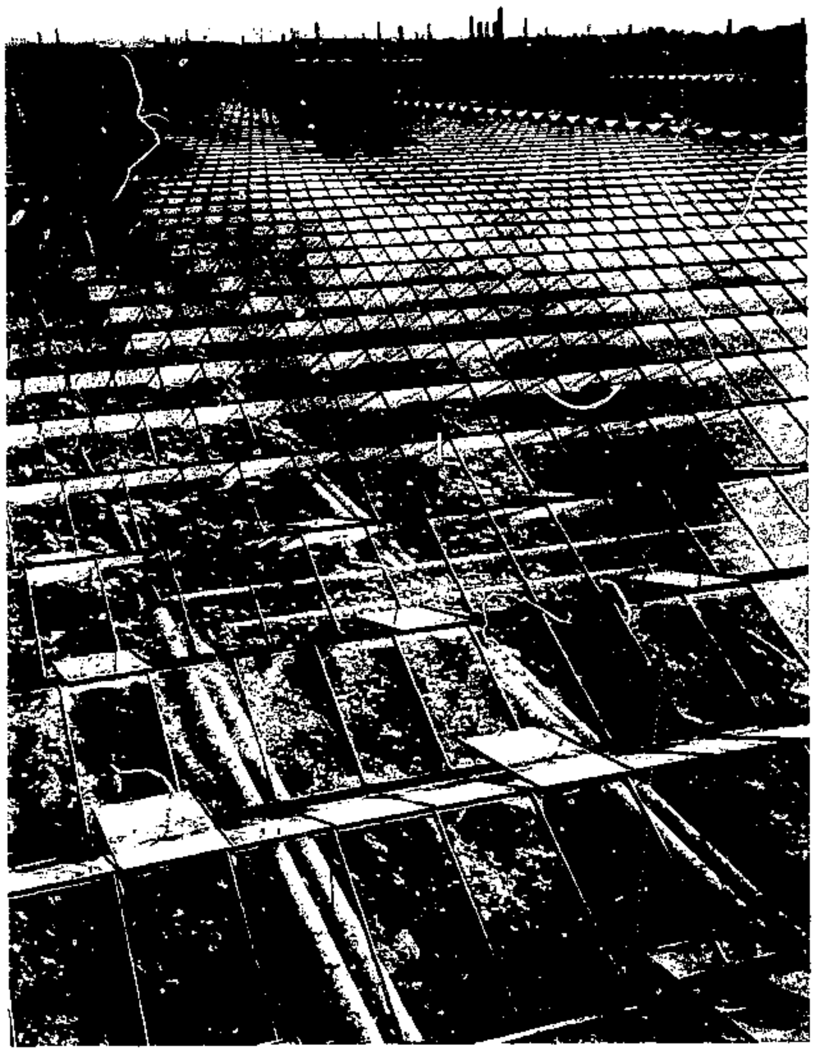

Plate 16—*Extensive greenhouse range in Holland*

ROLE OF ENVIRONMENTAL CONTROL

Environmental control is the key link between intensive agriculture and greenhouses. It makes possible an increase in the intensity of agricultural production and in turn influences the intensity of operations in greenhouses.

INTENSITY OF AGRICULTURAL PRODUCTION

The main thrust of modern agricultural technology has been to increase yields. Over the past century, man has been successful in this venture in what are now the developed nations. And some of the developing nations have recently begun to go through a well-known Green Revolution.

In certain regions of the world, moreover, improved technology has made it possible to add another dimension to productivity through multiple cropping—the culture of a second or a third crop a season where formerly only one grew before. In this case, the focus of emphasis shifts from (a) yield per crop to (b) total crop yield per acre (or hectare) per year. Individual crops may produce less, but output per acre is increased.

Multiple cropping, however, is not possible everywhere. It is largely confined to an area between 40° north and 20° south of the Equator. And within this zone, it is confined to well-watered areas of good soils. Climates need not permit year-round cultivation, but must allow at least a long growing season. Not many regions meet these and other qualifications.

How can the boundary of multiple cropping be extended? One way to handle the physical limitations would be through environmental modification or control. This, of course, has long been done to some extent by fertilization and water control (particularly irrigation). But such practices get at only part of the climatic limitations; they do nothing about the key problems of temperature and protection from the elements.

While methods of extensive modification of environment in field culture are difficult to conceive, greenhouses have been commercially used for this purpose for a century. The key factor is the enclosing of space in a transparent structure which allows fuller temperature control. In addition, numerous other aspects of environment can be modified.

In such a setting, the most intensive types of agriculture can be practiced in what are otherwise inhospitable environments. Yields per acre per year may not exceed those possible in the field in the most favored regions of the world—but they can allow a much larger portion of the world to move closer to those levels. And they may allow production of crops not otherwise possible.

INTENSITY OF GREENHOUSE PRODUCTION

Environmental control in greenhouses is inextricably intertwined with intensive agriculture. This is because each environmental control step has a cost attached to it. The capital investment per acre is inevitably well above that of open field culture. Operating costs are higher, in part because the greenhouse structure limits mechanization and raises labor requirements. Thus while greenhouse production makes possible large yields per given unit of land per year, it also necessitates high returns in order to pay for the higher costs. This means that the crops raised must have a very high value per unit of area.

There is, of course, a range involved: lower degrees of environmental control may be associated with less intensive forms of agriculture; high degrees of control are usually associated with more intensive forms. While there are exceptions, the link between environmental control and intensity generally remains a positive one.

Over time, greenhouse production has become more intensive as environmental control techniques have improved. This shift is not so apparent in North America as it is in Europe. One reason is that North American production has traditionally been oriented to the spring and fall months and has long involved multiple cropping; in Europe, by contrast, unheated greenhouses were initially largely used for the summer production of one crop. A second reason is that flowers have always been much more important than vegetables in U.S. greenhouses; the reverse has been true in Europe.

While the initial demand for greenhouse food in Europe could be met by unheated houses, there was a gradual growth in demand for products raised both earlier and later in the season. This meant that there was an increasing need for heated houses. (Initially these involved a substantial fixed investment in heating systems; more recently, hot air heaters have found increasing use.) With this improvement in environment, it was a relatively small step to other techniques such as semiautomatic watering (often including fertilizer in solution form), automatic ventilation, and concern with humidity control. With the increased use of heat it became increasingly expensive to ventilate with cold outside air; the use of CO_2 enrichment provided a way to keep ventilation at a minimum in the coldest months. Since light is apt to be insufficient in winter in the most northern regions, artificial illumination is used to start plants and carry them to the transplant stage.

Most of these changes have involved the extension of production of the same crops into different periods of the year. But they increase the chances of raising other—and possibly even more intensive—products. These will not always be food crops. In fact, flowers are becoming increasingly important in some traditional greenhouse areas such as Holland. They may be grown in rotation with vegetable crops, but it is more common to raise one or the other.

Concurrently with the shift to flowers, some vegetable area is being used for bedding or potted plants. These may not be more intensive than vegetables but do represent a form of diversification.

An unsettled question in all of this is the role of plastic greenhouses. Most of the changes discussed have to date involved glasshouses where there was a high fixed investment. While plastic houses can be constructed which are every bit as sophisticated in their environmental control systems as glasshouses, this is not usually the case. On a global basis, the plastic houses are normally either put up where extensive environmental control is not needed for the present crop or where it is necessary to keep capital costs down: in the latter instance, other environmental control techniques may also be minimized. Thus there is a question as to how readily some plastic houses might be shifted to more intensive practices. The problem may be negligible in some of the relatively advanced plastic structures put up in the northern United States but could be severe in some crude unheated structures built in the United States and elsewhere. On the other hand, the investment in most plastic houses is so minimal that the best thing would probably be to build an entirely new structure should environmental control increase. In sum, intensification in plastic houses may follow a different route.

The overall path, in any case, is for environmental control to make shifts to more intensive agriculture possible. In turn, improvements in environmental control can further increase the intensity of production in greenhouses.

GREENHOUSES AND SOCIETY

What benefits have greenhouses provided to society to date? What promise do they offer? Since greenhouse food production has not yet been evenly spread around the world, or even within most nations, the answers must be divided along rough geographic lines.

OUTSIDE THE TEMPERATE REGIONS

Although very little food is produced in greenhouses outside of the temperate regions at present, this does not mean that environmental protection will be of no concern. There are at least two basic reasons for interest.

First, some of the environmental control concepts or techniques could be applicable. For example, numerous countries suffer from too much or too little rainfall.

– In some tropical and semitropical regions, summer vegetable production is difficult because of intense rains. A relatively inexpensive type of structure could provide shelter. This procedure has, in fact, been followed in the Philippines.

– In desert regions, the use of greenhouse type structures could reduce water loss to the point where it might be possible to utilize desalinized water long before it is economical for field cultivation. Greenhouse operations utilizing desalted water are in use in Kuwait and Abu Dhabi. Evaporative cooling could make summer vegetable production possible in arid areas where temperatures are presently too high.

Second, several nations in this belt, especially in Central America and in northern South America, are considering stepping up winter exports of vegetables and flowers to northern markets where they will often compete with greenhouse produce. These nations need to know more about their competition.

The combination of inexpensive structures and increased interest in northern markets could well lead to further use of greenhouses in tropical and semitropical nations.

WITHIN THE TEMPERATE REGIONS

Within many countries in the temperate regions, greenhouse food production has been of influence to both society as a whole and to the individual.

Benefits to Society

The main returns to society have been in economic terms. Greenhouse food production has been a source of both export earnings and import substitution.

The majority of greenhouse production in Holland, for example, is exported to nearby European nations; the prospect of export earnings was probably the basic reason for the expansion of the greenhouse industry in Bulgaria and Rumania. Alternatively, domestic greenhouse production may substitute for imports and reduce foreign exchange costs.

In other cases, domestic greenhouse production may provide a response to the desire for an improved standard of living which cannot be economically met by field production or imports. The Soviet Union probably falls in this class; climate limits the outdoor production of salad crops, and the internal transportation system for bringing fresh produce to cities from distant production points is not very good. Hence the most economical initial course of action may have been to locate greenhouses near large cities as it has done. Another side of this issue which could have been a factor is that greenhouse produce, because of the demand for it and its high prices, offers a way of soaking up excess purchasing power.

Greenhouses, because of their high labor requirements per unit of land, provide an excellent source of employment in rural areas. There is much talk these days of bringing factories into the countryside to provide job opportunities. Greenhouses do just that. And since greenhouses can be operated where other forms of agriculture are not possible, they may provide income to a wide range of areas. The high labor requirements have usually meant that greenhouses are family operations.

Benefits to the Individual

The two main groups of individuals concerned are producers and consumers.

At the farm level, the story has been mixed. While greenhouse food operations have been typically concentrated in the hands of family farm units in the middle income level, it is questionable whether greenhouses in long-established areas have been any more profitable than other forms of horticulture requiring similar levels of capital investment and management skill.[3] In newer areas, especially where it has been possible for lower income farmers to use lower cost structures, the returns may well have been above those in other enterprises. In either case, the greenhouses may at least be a source of employment for others.

At the consumer level, the benefits have long fallen to the higher income groups. The form of benefit is simply the availability of a high-quality fresh product over a longer period of the year. The consumer must pay for this, and the product probably contributes little to his nutritional level since that is probably more than adequate anyway. But as the price of greenhouse produce drops and it is purchased by a wider sector, it offers promise of meeting demands for improved standards of living and may make a contribution to improved nutrition during winter periods when fresh produce is in less abundant supply. Yet it is hard to see costs ever getting low enough to benefit the poorest people.

Potential Future Benefits

In the future, greenhouses may make even more significant contributions. With increasing population and dwindling land reserves, the environmental control possible in greenhouses can lead to both increased yields of individual crops as well as additional crops. Year-round farming is technically possible in many cases where it is now difficult to grow even one crop. In fact, greenhouse food production is possible anywhere sunlight, water, a fuel source, and capital are available (poor natural light can be augmented with artificial light; salt water can be desalinized; CO_2 can be added). Further, any crop can be raised. Economics, however, presently dictate far more circumscribed locations and crop selections.

LIMITS TO GREENHOUSE GROWTH

The limits to growth of controlled environment agriculture are tied up with economics and resource availability. These will, as in the past, lead to the rise and fall of various greenhouse areas.

ECONOMIC CONSTRAINTS

Capital may provide a restraint to individual operators but is seldom an industry-wide problem where production is profitable. Profitability in turn is related to supply and demand. The production of food in controlled environments simply costs more under current conditions than field culture. The higher costs of greenhouse operation, particularly the high fixed costs, mean that high-value crops must be raised. To be high in value per acre a crop must have high yields and/or high prices. This pretty much restricts the selection to horticultural and floricultural crops. But their high prices restrict their purchase, especially when lower cost versions are available from other sources. As greenhouse costs are reduced, and prices lowered, more will be purchased, but the cost structure places limits on how far this can go.

As a result of these supply and demand factors, greenhouse food production presently is largely limited to a few fresh products for salads which tend to be purchased by the wealthier members of society. Future technological developments may reduce greenhouse costs, but other innovations may also lessen the production or transportation cost of field products. Increases in purchases of greenhouse products will, therefore, also be dependent on their superior quality, unique availability out of season, and increases in income. Neither cost reduction nor income increase will normally happen very quickly.

Other restraints may be imposed by trade policies and developments in transportation. Should free trade exist, then trade patterns will be influenced by comparative advantage in production and transport costs. Changes in transportation technology have been important in the past and could be more so in the future. Increasing use, for instance, is being made of air transport to fly strawberries from California to Europe or flowers from Latin America to North America. The major greenhouse crops could ultimately be influenced by the expansion of such factors. Should barriers to trade—such as tariffs and quotas—continue to exist or be established, then future growth may be more influenced by other factors. One must also allow for possible shifts in tastes and preferences which might not favor greenhouse crops.

Thus, the future for greenhouse food production is not without severe potential constraints. For this reason, flowers and other nonfood crops may continue to be an important complement to food crops.

RESOURCE RESTRAINTS

Two main types of resources are involved in greenhouse production: human and technical. Scarcity of either category could limit the expansion of environmental control, either directly through its absence or more likely indirectly through the effect on price. In either case, they may be reflected in capital requirements.

Greenhouses, as we have noted, are an anomaly in a day of mechanized agriculture; except for a few highly mechanized units, they are basically a handicraft industry. Hence labor is easily the major cost. Securing labor does not seem to have been a critical problem in the past, in part because of the family nature of business and the relatively pleasant working conditions. But this could change. Sharp increases in wages could upset a delicate cost situation. And as field producers are able to mechanize, greenhouse operators could be at an increasing cost disadvantage. In such cases, a premium will be placed on mechanization within the greenhouse.

The second resource category primarily concerns the natural resources—fuel and water. The most immediate problem may be fuel. Fuel is the second major variable cost in greenhouse operations; if reduced supplies sharply raise its cost, the effects on the greenhouse industry could be severe. Already natural gas, which is used in many installations, is becoming a scarce good in the United States (and in Utah, for instance, has been a limiting factor on greenhouse expansion).[4] Fuel oil, the other major source of heat, may also become more limited in supply. There are not many alternatives aside from a return to coal: electricity normally is far too expensive and hot water from springs or industrial plants carries with it severe restraints on location. Resource shortages have been aggravated by a gradual cooling of the earth since 1940.[5] Hence there may need to be further efforts to reduce heat loss (as through the use of insulation or double glazing)[6] or to improve the absorption of solar radiation (possibly solar heaters will be further developed).

The second natural resource problem could be water. As we have noted, greenhouses by their basic nature require irrigation. A great deal of water is needed per acre, although not necessarily per unit of product. Amassing a sufficient supply of water is not an easy task in some regions. Since water is usually not a major cost, this prospect is not as severe as the fuel question. Moreover, growers could take to collecting run-off water from the greenhouse roof or to developing irrigation systems which minimize use. In the long run there is always the possibility that the cost of desalinized water could be reduced to the point where it could be more widely used in coastal areas.

Other inputs, such as electricity and construction materials, could also become scarcer and hence more expensive, but this point is probably so far off as to be beyond the concern of this report.

THE RISE AND FALL OF GREENHOUSE AREAS

The economic and resource restraints just noted will, along with other factors, have an impact on the life cycle in the greenhouse industry. Obviously, areas where there is a strong demand and where costs are low will be at an increasing advantage. Older areas may be at an increasing disadvantage.

Since the demand and supply characteristics are dynamic, new areas will appear and others will decline in importance. Inexpensive plastic houses can come and go rather quickly, but more elaborate structures—because of their more permanent structure and the investment they represent—just do not disappear; instead they often decline rather gracelessly. They can become fixed liabilities under changing economic conditions.

In some of the northern areas of the United States, for instance, a number of glasshouses built early in the century still limp along in use. They were not initially constructed in the most favorable areas and have not improved with age. They are farmed only because they were inherited and are fully depreciated. But as one State marketing agent put it, "Most of the greenhouse operators are along in years and there is little if any young blood interested in greenhouse operation." Similar stories can be found in other States and in older greenhouse areas in other countries. Such is the price of economic efficiency.

The rather volatile economics and changing technologies of the greenhouse food industry tend to argue against the construction of very expensive fixed structures which will last half a century or more. Rather they might suggest the minimum investment in a fixed structure and perhaps a relatively greater investment in environmental control equipment which could be moved from one house to another or sold. This point needs further study.

BEYOND GREENHOUSES

As indicated in the introduction, the underlying concern of this report has been with environmental control rather than greenhouses. It just happens that the kinds of environmental control which have been discussed are only possible in greenhouses. Because of the high cost of greenhouse structures and the fact that they reduce light intensity, it would be better if we could get along without them. But it is currently difficult to see how environmental control could be economically carried out without some kind of cover.

The arrival of clear plastic films has at least made it possible to reduce the cost of the structure. It has also made possible expanded use of traditional structures such as row covers[7] and new structures such as air-inflated domes.

Under present technology, however, row covers offer only limited opportunity for climate control, while the potential advantages of the domes have not yet been fully exploited. Still, plastic has provided the basis for a break from traditional glass structure; future technology may offer additional possibilities for reducing costs.

There are also possibilities for developments in the opposite direction—involving more complex units. The growth chamber or room, long a tool for research, is receiving increasing attention as a commercial method for raising plants to the transplant stage in the winter. The extremely high yields possible in such units could conceivably lay the basis for their eventual use as a way of raising plants to the harvest stage—particularly in northern areas with unfavorable winter weather.

It is, of course, possible that technological developments in other fields could alter the presently perceived role for environmental control. Three possibilities which might limit the need for environmental control come to mind:

– First, further breeding may produce plants which are better suited to existing environmental conditions—plants which are, for example, more drought or cold resistant. But it is difficult to see how this could do much more than stretch existing boundaries of production.

– Second, as suggested earlier, striking improvements in the production and transportation of field crops could make shipped-in produce much less expensive and/or widely available out of season. This happened in the past and certainly cannot be overlooked in a discussion of the future, though cost and quality will remain severe constraints.

– Third, inexpensive forms of climate modification—such as the wide and increasing use of plastic row covers in southern Europe—could increasingly provide competition with the more expensive forms of environmental control elsewhere.

These and other unforeseen developments could well have an effect on the place of environmental control in the years to come.

The future course of environmental control could also be eventually influenced by developments in space. The U.S. Air Force for a number of years sponsored studies on the culture of plants as a source of food and oxygen for prolonged space and extraterrestrial bases.[8] Subsequently, scientists of the National Aeronautics and Space Administration initiated studies of plant growth under low pressure situations such as those found on the moon.[9] And even more recently, NASA and the U.S. Department of Agriculture have started development of a hydroponics system for possible use on spacecraft.[10] Although these efforts are modest in size and long range in nature, it is quite likely that they will suggest ideas for intensive culture and recycling of resources which could some day be used on earth.

Controlled environment crop production has come a long way since the Roman Emperor Tiberius used transparent stone to have cucumbers available the year round. But there is no reason to think that the technical limit has at all been reached. Revolutionary developments are literally on the horizon. The direction, pace, and extent of controlled environment agriculture will, however, continue to be strongly modified by economic forces.

REFERENCES AND NOTES

1. "Growing Crops Under Glass," *Yearbook of the Department of Agriculture, 1904,* Washington, D.C., 1905, p. 163.

2. Dick Hubert and Peter Hauck, "How Fred Andrew Tills the Soil With a Computer," *Saturday Review of Society,* March 1973, p. 58.

3. The evidence on this point is confined to England and is not entirely consistent. Data noted in table 5 of the text suggested that to achieve a given income level, the capital investment for greenhouses was about twice as high as for open production of vegetables when land values were excluded and about the same when they were included. Recent national data comparing glasshouse and market garden operations for 1970/71 showed about the same average net return as a proportion of tenants' average valuation (J. A. F. Dench, *Financial Results of Horticultural Holdings; Average Results for the Crops Years 1968-70*, University of Reading, Department of Agricultural Economics and Farm Management, January 1972, p. 10; compiled from National Farm Management Survey data). The situation for individual units, however, may vary widely (see the data for specialized glasshouses in the Lea Valley reported in W. L. Hinton and W. C. Housden, *Economic Results from Horticulture, 1970 Harvest Year,* University of Cambridge, Department of Land Economy, Agricultural Economics Unit, April 1972, tables 2 to 4).

4. Klaus-Dieter Gurgel, "Survey of Utah's Tomato Industry: With Special Reference to Hydroponics," University of Utah, Department of Geography, MA thesis, August 1972, pp.26-27.

5. James D. Hays, "The Ice Age Cometh," *Saturday Review of Science.* April 1973, pp. 29-32; Bryan Silcock, "Ice Age to Come?" *The Sunday Times* (London), April 15, 1973, p. 17.

6. The technical potentials for reducing heat loss are suggested by 2 small experimental insulated greenhouses - 1 as noted in ch. V in Antarctica and the other in Yonkers, N.Y. The latter unit was constructed in the 1930's at the Boyce Thompson Institute. Heating was by lights which were turned on for an average of 3.4 hours, usually at night. On bright days in mid-winter, it was necessary to open 1 of the windows to prevent overheating. The average electrical cost for 152 square foot unit during mid-winter was about 36¢ per day. The house was sealed so tightly, however, that supplementary CO_2 was needed. With night lighting, plant growth was equivalent to that in ordinary greenhouses in March and April (J. M. Arthur and L. C. Porter, "A New Type of Insulated Greenhouse Heated and Lighted by Mazda Lamps," *Contributions from Boyce Thompson Institute for Plant Research*, July-September 1935, pp. 131-147. Summarized in William Crocker, *Growth of Plants: Twenty Years Research at Boyce Thompson Institute*, Reinhold, New York, 1948, pp. 304-305.)

7. We have noted in chapter II that paper-covered frames served as row covers in England in the early 1700's. Paper hot caps have been used for early production for many years in the United States. With the appearance of plastic, however, there has been a sharp growth in use of row covers (for further current details, see: references 104 and 105 in ch. III; *Plasticulture* (Paris), quarterly; Norman Smith, "The Sky's the Limit for Plastic in Agriculture," *American Vegetable Grower*, April 1972, p. 16; B. J. Hall and S. T. Besemer, "Agricultural Plastics in California," *HortScience*, August 1972, pp. 373-378).

8. The work, which included other potential food sources, was first done under contract with the Space Bio Medicine Department at Boeing Aircraft in Seattle and then subsequently at the School of Aero-Space Medicine at Brooks Air Force Base in San Antonio. It was very long-term in nature (1985 and thereafter) and in 1969 was a victim of tightened budgets. Study was also given to the use of activated sludge from human waste as a nutrient source.(Telephone conversations with: Arthur J. Pilgrim, formerly with the Department at Boeing; and Billy Richardson, School of Aero-Space Medicine, San Antonio, August 21, 1972.)

9. Charles H. Walkinshaw, "Lunar Horticulture," *HortScience*, December 1971, p.

518 (also in same issue: Walkinshaw and Pratt H. Johnson, "Analysis of Vegetable Seedlings Grown in Contact with Apollo 14 Lunar Surface Finds." pp. 532-535); telephone discussions with Walkinshaw and Wayland E. Hull of the Life Sciences Directorate, Manned Spacecraft Center, Houston, Texas, August 21 and 22, 1972. Should a scientific colony eventually be established on the moon, it is anticipated that plants could utilize lunar soil, human waste, and CO_2 collected from lunar base personnel. Ample sunlight will be available during lunar days.

10. Richard Dedoleh and Jacob Shapira, "The Development and Testing of an Intensive Plant Cultural System for Space Application," paper delivered at the 69th Annual Meeting of the American Society for Horticultural Science, August 27, 1972; Charles A. Berry, "The Life Sciences Program," *Hearings Before the Subcommittee on Manned Space Flight of the Committee on Science and Astronautics*, U.S. House of Representatives, February 24, 1972, pp. 197, 217. Dedoleh is at the Western Regional Laboratory of USDA in Albany, California while Shapira is at the NASA Ames Research Center, Moffett Field, California. Their system involves growing plants' outward from a rotating cylinder rooting media. While designed to operate under artificial light in space, the units could also be used in natural light in greenhouses. (I am indebted to Carrie E. Karegeannes of the NASA Historical Office for bringing the preceding references and individuals to my attention.)

VII. APPENDIX

IMPLICATIONS FOR STATISTICAL REPORTING

There is no one regular central source of global statistics on greenhouse area. Some scientists in England and Holland maintain a personal compilation of estimates for Europe, but these are not published regularly. Data for several European Community countries are reported regularly in *Statistique Agricole*, but that is about it. FAO maintains no figures.

There would be several problems involved in maintaining a central set of data. The first would be the definition of greenhouses. Second is the problem of the wide variation in the frequency of data collection from individual countries: (1) some have no regular system; (2) some, like the United States, collect official data only once every 10 years (though there is hope that from now on they will be picked up every 5 years); (3) others collect data once a year; and (4) in one instance, England, they are collected twice a year.

Where any degree of multiple cropping is involved, the data need to be collected twice a year. Even this may not be fully adequate in some cases—particularly where the multiple cropping indexes are very high. Then, too, several types of statistics need to be collected. The area actually cropped in all of the multiple cropping rotations is most needed. It would also be useful to have an estimate of the amount of greenhouse area actually physically allocated to food production. This, however, may be difficult to pin down where (1) nonfood crops are grown in rotation, and (2) where temporary greenhouses are used only part of the year or for parts of two crops.

In addition to area figures, it would be desirable to have regular data, as is gathered in some European countries, on the extent of use of environmental control devices such as heating, centrally controlled water supply, automatic ventilation, and CO_2 fortification.

IMPLICATIONS FOR LANDSCAPE BEAUTY

It may seem strange to raise the matter of esthetics, but one would be remiss to talk about environmental control without considering the effect of the process on the visual side of the environment. Liberty Hyde Bailey acknowledged in 1895 that:

> In the forcing house, all architectural ambition is sacrificed to the one desire to create a commercial garden in the frosty months.[1]

The situation is little better today; if anything, the advent of plastic may have worsened it.

It is, of course, a personal value judgment as to whether greenhouses have a positive or negative influence on the landscape. My own view is that a well-maintained house, while seldom a thing of beauty, presents no great problem. However, a badly maintained glasshouse, or a torn and ripped plastic house at the end of the season, can be a real eyesore.

What does it matter? Probably very little to the individual farmer. But it may be of more concern to those concerned with rural beauty, and of major concern to countries or regions with a heavy dependence on tourist trade.

IMPLICATIONS FOR WASTE RECYCLING

Animal manure was important early in greenhouse food production. It was virtually an all-purpose input, providing heat, nutrients, carbon dioxide, and ammonia; it also helped build soil structure. With the advent of other more convenient and precise sources, and its own decreasing availability, the use of manure has steadily declined.

One wonders if in the future human waste may not provide a partial substitute. Human manure has been used for centuries in China as a fertilizer. The solid waste accumulated from municipal sewage systems has long been recognized as a potential source of fertilizer,[2] and some is sold for this purpose.[3] Such a product, however, could perhaps more readily be applied to field than to greenhouse agriculture (much greenhouse fertilization being applied in solution form through the irrigation system).[4] The liquid effluent is presently not used. An FAO team has recently suggested that the liquid waste, with further purification, eventually provides a source of water for hydroponic agriculture in water-short Singapore.[5] And any application of hydroponics in space would probably involve the recycling of human body waste.

The recycling of waste in these ways in greenhouses is undoubtedly a long way off, if indeed it materializes at all. Certainly it is a prospect that few find appealing. But it is a possibility that may one day have practical use in some situations.

REFERENCES AND NOTES

1. L. H. Bailey, "Sketch of a Century of American Horticulture," *The Florists Exchange*, March 30, 1895.

2. When Chicago was considering alternatives for sewage disposal in 1855, one possibility involved drainage into artificial reservoirs whence in turn it would be pumped and sold as fertilizer. It was not adopted because of economic uncertainties and concern with an odor problem. (Louis P. Cain, "Raising and Watering a City," *Technology and Culture*, July 1972, pp. 358-359.)

3. In addition, in Holland, municipal rubbish is transformed into a compost which is widely sold. When mixed with peat, it is suitable for greenhouse use. (Based on information provided by NV Vuilafvoer Maatschappij VAM, Amsterdam.)

4. The idea of applying animal manure in liquid form to open fields through sprinklers has existed since the turn of the century in Europe and recently has been practiced on a number of livestock farms. An expanded version has been suggested for municipal sewage

in the United States (for example, Thomas Grubisich, "Old Disposal Method Is Being Tried Again," *Washington Post*, March 22, 1973, p. E1). In either case, the process probably offers little promise for greenhouse operations unless economical ways can be found to treat the liquid.

5. "Report to the Government of Signapore on Production and Marketing of Vegetables, Orchids and Other Flowers, Including Hydroponics," FAO (UNDP), TA 2997, 1971, p. 17.

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