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APPLICATIONS OF CELSS TECHNOLOGY TO CONTROLLED ENVIRONMENT AGRICULTURE

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ABSTRACT

Controlled Environment Agriculture (CEA) is defined as the use of environmental manipulation for the commercial production of organisms, whether plants or animals. While many of the technologies necessary for commercial success of CEA are still in the early stages of development, investment in greenhouses and aquaculture systems in North America is nevertheless doubling approximately every five years. Economic, cultural, and environmental pressures all favor CEA over field production for many non-commodity agricultural crops. Many countries around the world are already dependent on CEA for much of their fresh food (e.g. Holland, Israel, Saudi Arabia, Japan).

Controlled Ecological Life Support Systems (CELSS), under development at NASA's Ames Research Center, Kennedy Space Center, and Johnson Space Center expand the concept of CEA to the extent that all human requirements for food, oxygen, and water will be provided regenerated by processing of waste streams to supply plant inputs. The CELSS will likely contain plants, humans, possibly other animals, microorganisms and physicaly and chemical processors In effect NASA will create engineered ecosystems.

In the process of developing the technology for CELSS, NASA will develop information and technology which will be applied to improving the efficiency, reliability, and cost effectiveness of CEA, improving its resources recycling capabilities, and lessening its environmental impact to negligible levels.

NASA - ADVANCED LIFE SUPPORT

Controlled Ecological Life Support System (CELSS)

A Controlled Ecological Life Support System (CELSS) is a regenerative system which incorporates biological, physical and chemical processes to support humans in extraterrestrial environments. The key biological processes in such a system are photosynthesis and transpiration. Green plants utilizes light energy (radiation) to produce liquid quality water, food, and oxygen while removing carbon dioxide, water, and inorganic elements for air and waste streams. Figure 1 is a diagram of the CELSS concept.

The CELSS concept involves resource recycling by regenerative systems. In an ideal CELSS all materials are cycled between crew and regenerative processors: no new mass would need to be added to the closed system. The only essential input is energy. The CELSS system results from the management of the fluxes of mass and energy while the total mass of the system remains constant.

Development of a CELSS requires identification of the critical requirements that will allow the system to operate with stability and efficiency. When this information is incorporated into electronic expert systems the whole CELSS can be operated as a life support machine, responsive to the needs and activities of the human crew. A major objective or the CELSS R&D efforts at NASA/Ames is to characterize the ability of a plant-based system to provide food, oxygen, purified water, and carbon dioxide removal from closed environment for the purpose of life support. The critical requirements of the plant-based system are genetic, environmental, and cultural. They are the conditions of light, air, and the nutrient solution which control plant growth. They are bred into the gene pool of the selected cultivar. They are the specific processes of crop management known in the past as farming.

Plant Growth Chambers

The primary tool of the plant growth researcher is the growth chamber. This is essentially a container holding a volume of air at controlled conditions of temperature, carbon dioxide concentration, and water content (humidity), a source of photosynthetically active radiation (light), and a container in which roots are bathed in nutrient solution. The light source is a combination of several electric lamps of various types. The nutrient solution consists of water, oxygen and salts of thirteen or more elements essential to plant nutrition (hydroponics). All systems are managed by controllers to maintain the desired plant growth environment. Plant growth chambers allow us to observe and measure the response of specific populations of plants to environment and cultural practice. Such systems are "leaky" - while conditions are maintained, mass flows into and out of the system, sometimes at rapid rates. Therefore the surrounding environment acts as a sink for evolved oxygen, various hydrocarbons, and transpired water. Sources of water, carbon dioxide and elemental ions must be provided continuously.

Crop Growth Research Chamber (CGRC)

In order to study the response of plants to conditions existing in a CELSS it is necessary to build a growth chamber which is closed with respect to mass; That is, no exchange of mass with the ambient environment surrounding the chamber is allowed. Gases must be carefully added and removed and internal pressures controlled.

NASA/Ames Research Center is currently constructing one of the first such chambers in the world (Figure 2). Named the Crop Growth Research Chamber it will give researchers total control of the plant environment within a volume closed with respect to mass. The CGRC is for the study of plant growth and development under stringently controlled environments isolated from the external environment and is designed for the growth of a community of crop plants. The CGRC is the individual unit where various combinations of environmental factors can be selected ant the influence on biomass, food and water production and oxygen/carbon dioxide exchange of crop plants investigated. Sever Crop Growth Research Chambers and laboratory support equipment provide the core of a closed systems plant research facility. This facility will be utilized for research, volatile gas analysis and trace gas challenge to the plants, technical studies (development and evaluation of technology), system control system modeling (development and validation), and system operation.

The advantage of the closed growth chamber is the ability through sensors and analyzers to achieve immediate feedback on the status of plant growth; That is, we can monitor crop growth and its response to environmental manipulations in real time. Having generated a response surface of crop growth to the environment we can then build and test models for management of the crop as a production system. Furthermore, the models and sensors can be incorporated into expert control systems which continually adjust environment for stage of growth, cultural practices, system perturbations, etc. Finally, a human crew can be simulated and the CGRC run as a life support system in response to the simulation. This results in a preliminary test of a CELSS-type system

CONTROLLED ENVIRONMENT AGRICULTURE

Definition

Controlled Environment Agriculture (CEA) is the commercial production of a population of genetically uniform organisms through control of the growth environment. Many kinds of organisms have been grown in CEA including: microorganisms, mushrooms, plants, fish, and other animals. We are specifically interested in food producing crop plants. By using the information gathered from growth chambers to optimize the growth of plants we have been able to generate extremely high crop yields. Table 1 shows some of the yields which have been achieved in CEA systems in comparison to field production.

Growing Organisms as a Manufacturing Process

The primary objective of CEA is to transform the production of crops into a manufacturing process having consistent and predictable output volume, cost of production, and product quality (Figure 3). As in all manufacturing systems quality and consistency of product impact on sale price, which in turn affects Return on Investment. Production efficiencies, reflected as higher yield or reduced cost to produce, also directly impact Return on Investment. Therefore CEA, unlike traditional farming, carries a lower risk of crop failure and a high degree of assurance of product quality and market timing.

In addition to economic and market considerations there are other reasons to use Controlled Environment Agriculture for crop production:

Production in Harsh or Inconsistent Environments

Good arable land with a consistent climate year around is almost nonexistent in this world. For this reason crops are only grown at certain locations in specific seasons, usually well below optimum conditions. Fresh products go in and out of season and harvest areas migrate geographically with the seasons. Deserts, cold climates, and extremely cloudy areas produce little or nothing. Droughts, storms, heat, frost, insects, and diseases kill crops and damage products. Salt buildup in some irrigated soils makes cropping impossible.

CEA cropping allows maximum productivities to be achieved on the Arabian Peninsula, in the US Desert Southwest, in Alaska, Canada, Northern Europe, and Australia. Almost anywhere in the world. Fresh products can be grown close to markets instead of being transported thousands of miles. Persons in isolated environments, e.g. Antarctica, can grow what they need. Persons in environmentally disadvantaged areas can become agricultural producers. All that is needed is a site, a well-designed CEA system, water supply adequate for plant transpiration, and a source of energy.

Land Use Competition

The world is becoming more crowded. Businesses and houses, towns and cities are encroaching on agricultural land, particularly where climates are best. In the United States large areas of agricultural land in California, Florida, and other states are being developed. Desertification in some parts of the world (Middle East, Africa) is removing land from production. Population growth requires more and more production on less and less cultivated land (China, Japan, Europe, Russia, United States). It is obvious that more intensive cropping is going to be required. Some of the world's most populous countries are already heavily committed to the development of CEA (China, Japan).

Resources Management

We have already cited arable land as a diminishing resource. CEA is conservative of land, producing up to 20 times as much product annually as traditionally cultivated land and able to equal or better that production on land where nothing would grow otherwise.

As mentioned previously, the only water needed to grow crops in CEA is that which is transpired by the plants. There is no waste due to runoff or evaporation of irrigation water. Furthermore, use of carbon dioxide supplements to enhance plant growth results in substantial reductions in water use.

CEA fertilizers consist of water soluble salts which are continually circulated to the plant roots. None are lost to runoff. The only use is that which is incorporated into plant tissue.

The one resource which CEA systems appear to require in substantial quantities is energy. In greenhouses this energy is used for heating and cooling(ventilation) to maintain growth environments. Energy use appears high because it is concentrated into a small area, when figured on the basis of use per pound of food produced, energy use in controlled environment agriculture systems is not excessive and is clearly economically sound. However, this too can be conserved. Waste heat from other manufacturing systems, e.g. Archer Daniels Midland's corn sweetener plant in Illinois, or from electrical power plants, e.g. Pennsylvania Power and Light's Montour station in Pennsylvania, can be recovered to heat greenhouses. Off peak energy, excess power generated during certain times of the day, can also be effectively used in CEA especially where electric lighting is used, since supplemental lighting can be done at night. Solar heat can be used both for heating at night and for daytime electricity. Burning of sawdust and wood chips, waste products from forest industries, is used to power greenhouses in Minnesota.

Pollution Control

Closed environments can effectively exclude pests and diseases they may carry. Control of environment provides a means of controlling insects and diseases. Highly oxygenated, healthy root systems and well grown plants are more resistant to diseases. Elimination of soil removes a major source and incubator of pests and diseases. Efficient sterilization of nutrient solutions, as with UV light, can be accomplished in hydroponics. Natural pest control methods, such as predatory insects, work very well in greenhouses. All of the above result in the virtual elimination of the need for chemical pesticides and thus also eliminate potential for pollution of growing systems and the general environment.

Plant nutrients in CEA are water soluble salts composed of ions of thirteen elements: nitrogen, phosphorus, potassium, calcium, magnesium, sulfur, iron, boron, copper, zinc, manganese, molybdenum, and chlorine. All are essential to plant growth. Sometimes other elements such as silicon, aluminum, sodium, cobalt, chromium, etc. are added as trace elements. Of all these ions the ones which cause the most problems when released to the environment are nitrogen (as nitrate or ammonium) and phosphorus (as phosphate) because they constitute the bulk of the salts used. Runoff from fertilized fields and leaching into water tables has been a serious concern for both farms and CEA facilities. Recirculating hydroponics used in a closed system or a well-designed CEA system does not have excess nutrient ions dumped out into the environment. Salts are added at the rate which plants extract them from solution and incorporate them into biomass.

In an ideal CELSS all solid wastes are processed back into carbon dioxide, water, and nutrient salts. Most of this can be accomplished through low technology processes such as drying (evaporation) and burning (combustion). The only problem with combustion is that the nitrogen mostly ends up in gaseous forms and some of the resulting ash is not water soluble. In CEA solid wastes have become a problem. Growing media, old plants, roots, and unsold products must be removed and disposed of. Efficient methods of composting or drying/combustion are definitely needed.

<u>Greenhouses and Plant Factories</u>

Greenhouses are those CEA facilities which use sunlight as the primary source of photosynthetic photon flux for plant growth. They consist of some transparent or translucent material (glazing) fixed into a framework. Glazing is usually glass or plastic. Many different configurations and levels of technology are being used. The advantages gained are protection from the extremes of the ambient environment, provision of a contained volume of atmosphere which can be controlled to some advantage, such as by elevation of temperature and carbon dioxide concentration, resulting in increased efficiency of use of available sunlight. Crop yield, quality, consistency, and predictability are improve as a result.

All greenhouses are driven by the availability of sunlight and require heating and cooling to maintain a good plant growth environment. When available sunlight is insufficient - winter, cloudy days - electric supplemental lighting may be employed to provide additional growth. The design and use of lighting systems has become a major area of research and development in greenhouse crop production.

Some plant growing entrepreneurs have attempted to avoid the vagaries of sunlight and environment by completely enclosing their growing systems so that total control of the environment, including light, is achieved. These "plant factories", essentially large versions of plant growth chambers, have taken a major step toward making crop production a manufacturing process. In doing so they are forced to face questions of lighting, environmental control, plant growth, and economics. Only a few commercial units are currently operating in the world and most of those grow only bedding plants.

<u>The World View</u>

The present and future of Controlled Environment Agriculture in the World is excellent. Holland has about 25,000 ha of greenhouses, 11,000 ha of which are in vegetables. Israel and Saudi Arabia produce their own supplies of fresh vegetables, nearly all from greenhouses, and export to other countries. Columbia exports huge quantities of fresh flowers grown in greenhouses, mostly to the United States. Japan and China are moving rapidly into greenhouse production. Canada, having no warm climates for winter vegetable production, has developed a successful greenhouse industry both in vegetables and flowers. In the United States the greenhouse area is doubling about every five years and is now the fastest growing segment of American agriculture.

A large part of the technology for this growth comes from Europe, especially Holland and Denmark. However, it is a young industry and its commercial development, and that of the more sophisticated plant factories, will require a great deal more understanding of the control of environment, the growth of plants, and the engineering and manufacture of efficient systems for both.

CONTRIBUTIONS OF NASA CELSS RESEARCH AND DEVELOPMENT

<u>Exploring the Limits of Plant Productivity</u>

In our quest to determine the potential of plant crops in life support we will push them to their productive limits. Defining those limits and the environmental parameters with which they are associated are keys to achieving crop production potential.

<u>Environmental Response Surfaces for Specific Cultivars</u>

We already know that each genetically different plant population has its own characteristic responses to environment. It is necessary to learn how that particular population will interact with environment if it is to be incorporated in a life support system. This set or responses is called the environmental response surface for the crop. The methods for determining response surfaces for specific plant cultivars and the descriptions of such surfaces are valuable elements in improving the operating efficiency of CEA.

Models for Management of Controlled Environment Cropping Systems.

Response surfaces and other information about the growing system and plant environment are incorporated into models which allow both predictability and control of crop growth. Development and testing of such models will be a major CELSS activity. The application of the resulting models to CEA will be a substantial new business.

Methods of Mass and Energy Management.

In addition to plant growth models other models will be required to describe the movement of mass and energy through a CELSS. The availability of both is going to be severely limited in space and efficiency of management is essential. As part of the CELSS development we will be learning how to monitor and efficiently control mass and energy fluxes. The resulting models, methods, and systems should be very useful in building better plant factories.

Plant Growth Lighting

One of the energy-based systems mentioned above is plant growth lighting. In a CELSS we need to get the most out of the energy input to plant lighting. This will require both improved engineering of lighting hardware and improved utilization of the light delivered to plants. As an example, light utilization efficiency has been increased by four times in many crops. The lighting systems, cultural methods, and models which describe their interaction will all be of great use to CEA.

Specific Ion Monitoring

In the area of mass balance there is a specific need for sensors/analyzers which can reliably monitor the concentrations of nutrient ions in solution over extended periods of time. In order to maintain plant growth rates the essential ions must be balanced. None should be excessive and potentially toxic or deficient. Differential rates of uptake can upset this balance. Development of hardware and methods for ion control will be useful for all users of recirculating hydroponic culture.

Expert Systems.

In order to incorporate all of the information about systems, plant populations, response surfaces, and mass and energy management, expert systems will be developed. Such systems could monitor environment, systems operations, and plant responses. From these inputs it could make decisions for control and issue advisories to crew for cultural needs. Expert systems could also provide a means for troubleshooting problems and issuing instructions for repairs. Such systems will be essential in plant factories and extremely useful in greenhouses, particularly those operated without resident experts.

Methods for Waste Recycling.

CELSS requires recycling of severely limited resources. While not so severely restricted, CEA production systems will face increasing pressures to conserve and recycle resources and to reduce solid wastes. Holland already restricts the disposal of growth media, inedible crop material, and nutrient salts. In other countries disposal is expensive. Methods for efficiently regenerating such wastes will be very important to the future of Controlled Environment Agriculture.

SUMMARY

Regenerative Life Support and Controlled Environment Agriculture require the same technologies for crop production. They differ only in their objectives and the constraints imposed on them by their applications. CEA is profit motivated - yield, quality, price, and costs of products are its primary concerns. Its constraints are light, climate, markets, cost-to-grow, and investment. Regenerative Life Support is concentrated on the safety and well-being of a human crew in an extraterrestrial environment. Regeneration of air and water are comparable in importance with food production. Reliability and controllability are critical. Constraints are light, environment, volume, mass, and power. The technologies developed for use in a CELSS will be immediately useful to Controlled Environment Agriculture. In fact, new products for plant production will likely result. However, as explained above, it is not new technology which drives the development of CEA. It is consumer demand in the marketplace for consistently high-quality plant products and it is the pressures of population growth and cultural change in the world. The technologies developed by NASA for CELSS will help to make it possible to market fresh plant products at reasonable prices to consumers and profit to growers, to grow fresh produce in places where nothing currently grows, and to minimize the impact of growing on the land, on resources, and on the environment.

REGENERATIVE LIFE SUPPORT SYSTEM

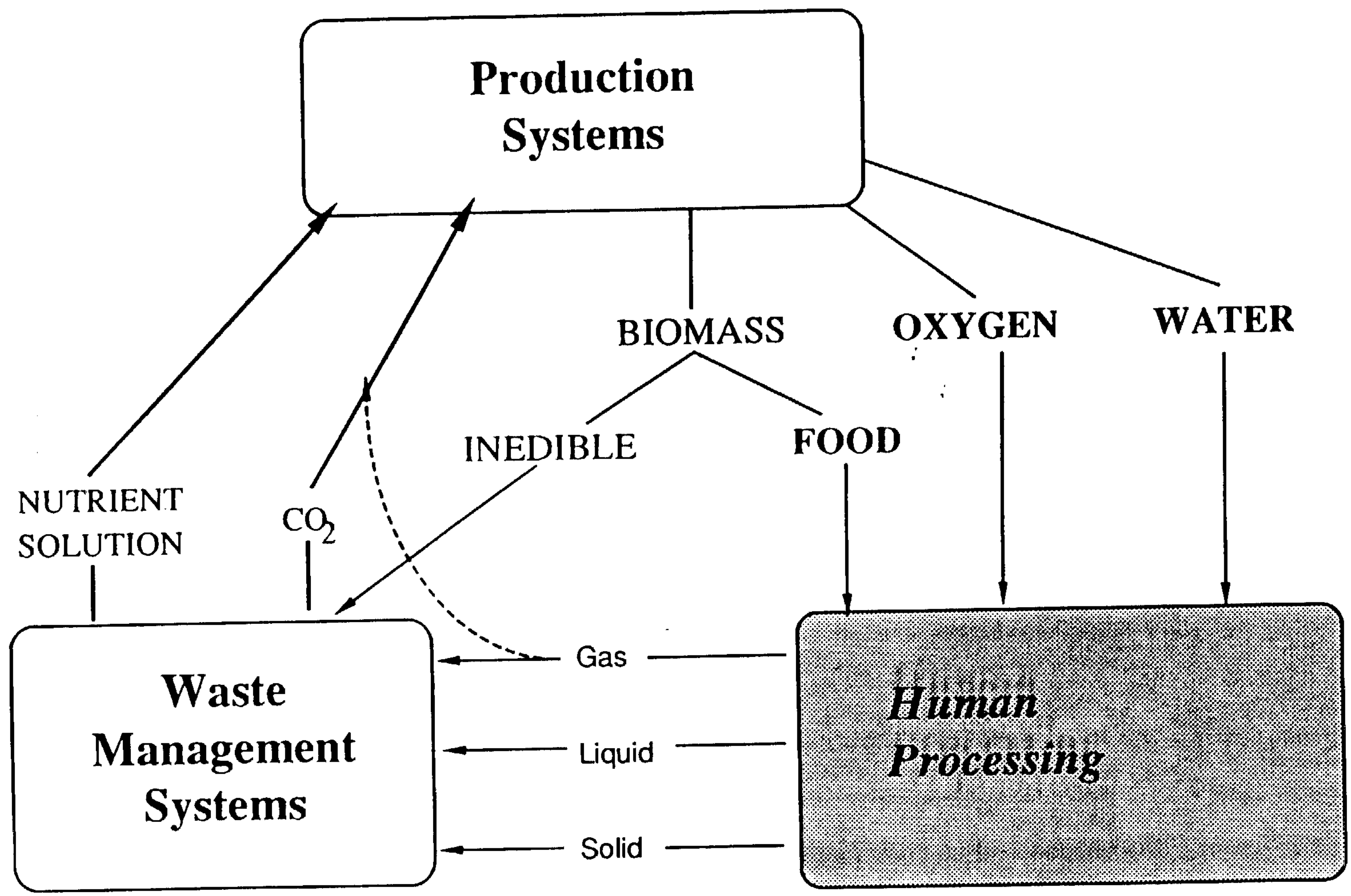

Figure 1. Diagram of the Regenerative Life Support System concept

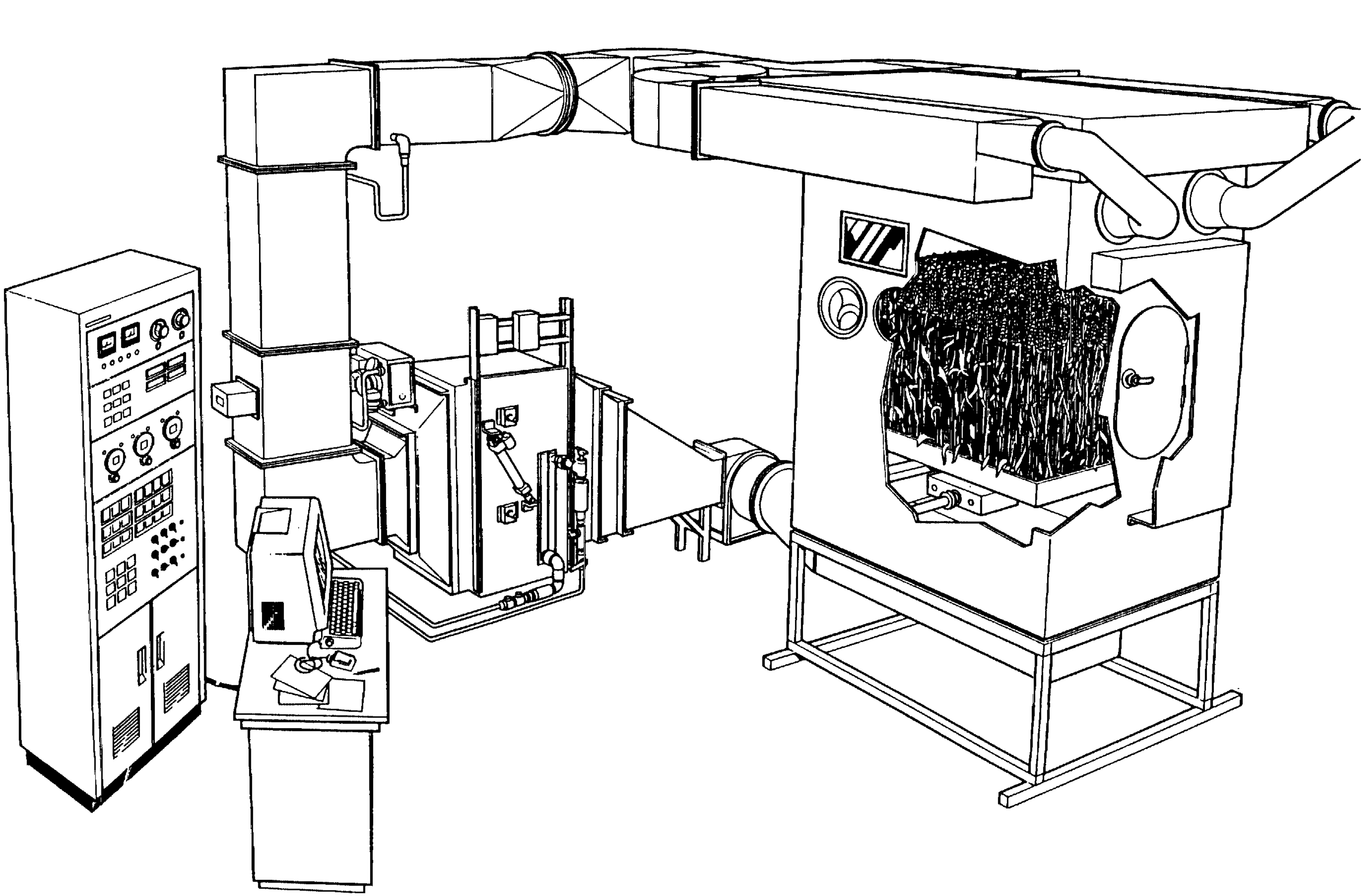

Figure 2. The Crop Growth Research Chamber is a unique tool for studying the growth of crops in controlled environments and determining their environmental response surfaces.

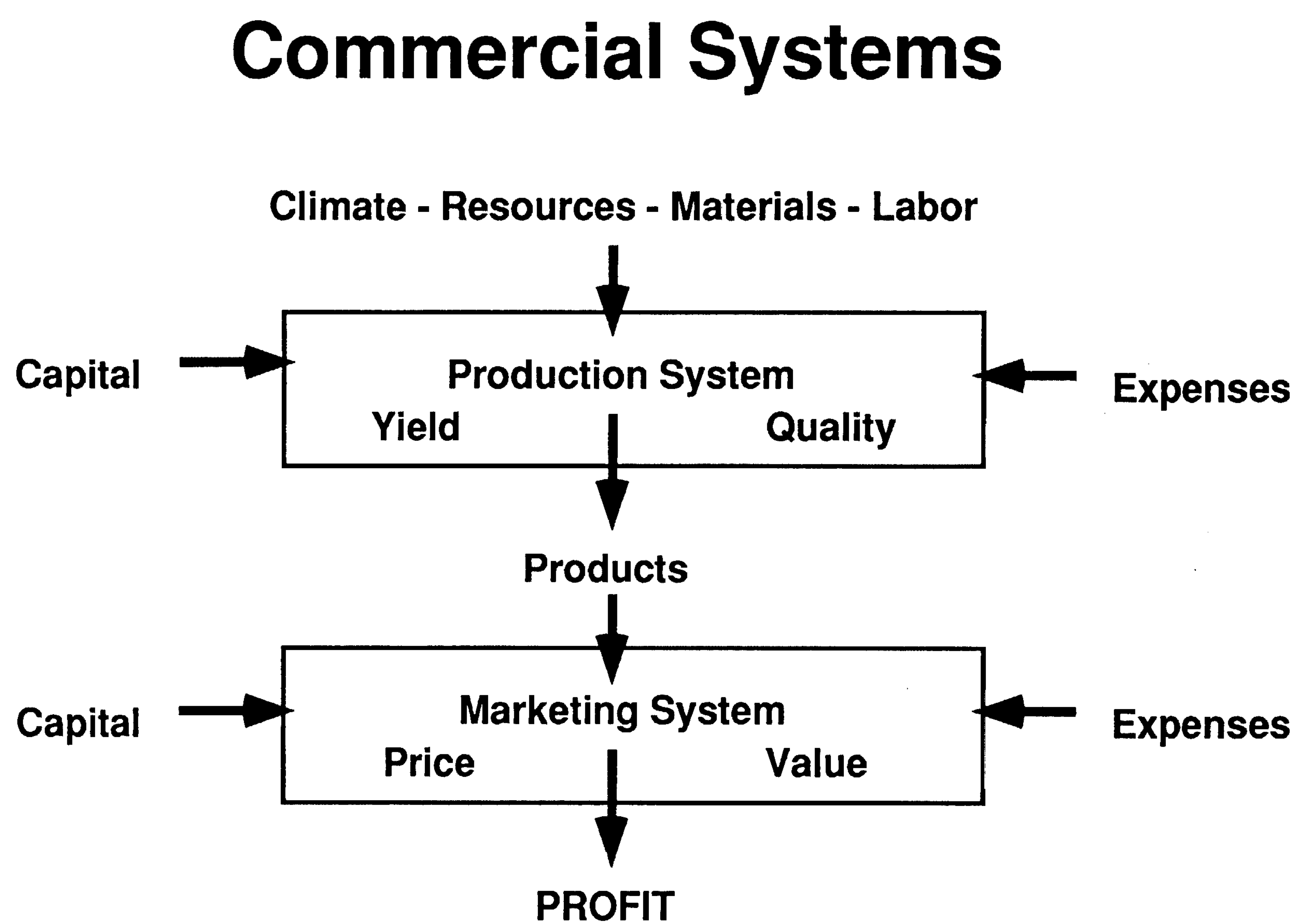

Figure 3. Diagram of commercial system. Controlled Environment Agriculture attempts to minimize effect of climate and the input of resources while maximizing yield and quality of the products grown.

	LETTUCE	TOMATOES	CUCUMBERS
FIELD CROPPING	0.5 - 3.0	0.5 - 3.0	1 - 5
GREENHOUSE	4 - 10	4 - 11	5 - 19
ABU DHABI (CEA Greenhouse)			
ACHIEVED	10.2	8.1	19.0
ESTIMATED POTENTIAL	13.8	9.0	20.7
G.E. GENIPONICS (Plant Factory)			
ACHIEVED	40.0	21.1	34.1
ESTIMATED POTENTIAL	65.0	48.0	50.0
PHYTOFARMS (Plant Factory)			
ACHIEVED	55.0		
ESTIMATED POTENTIAL	75.0		

Table 1. Yields (pounds per square foot per year) of three vegetable crops grown in various cropping systems.