NASA Technical Memorandum TM 102784

Continuous Hydroponic Wheat Production Using A Recirculating System

C. L. Mackowiak
L. P. Owens
C. R. Hinkle
The Bionetics Corporation, Kennedy Space Center, Florida

R. O. Prince
NASA Biomedical Operations and Research Office, Kennedy Space Center, Florida

September 1989

National Aeronautics and
Space Administration

John F. Kennedy Space Center

NASA

TABLE OF CONTENTS

SECTION	PAGE
TABLE OF CONTENTS	i
ABSTRACT	ii
LIST OF TABLES	iii
LIST OF FIGURES	iv
ACKNOWLEDGMENTS	v
PRODUCT DISCLAIMER	vi
I. INTRODUCTION.	1
Objectives	4
II. MATERIALS AND METHODS	4
A. Environment	4
B. Nutrient Solution Delivery System	4
C. Nutrient Solution	5
D. Solution and Air Sampling	11
E. Seed Germination	11
F. Harvests	12
G. Statistical Analyses	12
III. RESULTS	13
A. Nutrition	13
B. Microflora	28
C. Harvests	30
D. Tissue Analyses	31
IV. DISCUSSION	40
A. Nutrients	40
B. Harvest	42
V. APPENDIX	45
VI. REFERENCES	47

ABSTRACT

Continuous crop production, where plants of various ages are growing simultaneously in a single recirculating nutrient solution, is a possible alternative to batch production in a Controlled Ecological Life Support System (CELSS). A study was conducted at John F. Kennedy Space Center (KSC) where 8 trays (0.24 m^2 per tray) of Triticum aestivum L. "Yecora Rojo" were grown simultaneously in a growth chamber at 23°C, 65% relative humidity, 1000 ppm CO_2, continuous light, with a continuous flow, thin film nutrient delivery system. The same modified Hoagland nutrient solution was recirculated through the plant trays from an 80 L reservoir throughout the study. It was maintained by periodic addition of water and nutrients based on chemical analyses of the solution. The study was conducted for 216 days, during which 24 trays of wheat were consecutvely planted (one every 9 days), 16 of which were grown to maturity and harvested. The remaining 8 trays were harvested on day 216. Grain yields averaged 520 g m^{-2}, and had an average edible biomass of 32%. Consecutive yields were unaffected by nutrient solution age. It was concluded that continual wheat production will work in this system over an extended period of time. Certain micronutrient deficiencies and toxicities posed problems in this study and must be addressed in future continuous production systems.

LIST OF TABLES

TABLE		PAGE
1	Comparison of Hydroponic Solutions	3
2	Chamber and Environmental Parameters	6
3	Experimental Solution A	9
4	Solution Electrical Conductivity/Elemental Correlations	15
5	Mass Balance Budget for Entire Study	19
6	Wheat Harvest Data Summary (per tray)	32
7	Wheat Harvest Data Summary Continued	33
8	Harvest Correlations of Wheat Trays at Maturity	34
9	Growth Data From Final Harvest (multiple ages)	35
10	Total Dry Matter From Final Harvest (multiple ages)	35
11	Tissue Proximate Analyses of Mature Wheat Plants	38
12	Tissue Proximate Analyses of Immature Wheat Plants	39
13	Comparison of Theoretical and Actual Nutrient Additions	42

LIST OF FIGURES

FIGURE		PAGE
1	System Layout	7
2	Hydroponic Wheat Tray	8
3	Stand Pipe Level Indicator	10
4	Solution pH	14
5	Electrical Conductivity	14
6	Nitrate-nitrogen Concentrations	16
7	Nitrate-nitrogen Acumulations	16
8	Phosphate-phosphorous Concentrations	18
9	Phosphate-phosphorous Acumulations	18
10	Potassium Concentrations	20
11	Potassium Acumulations	20
12	Calcium Concentrations	21
13	Calcium Acumulations	21
14	Magnesium Concentrations	22
15	Magnesium Acumulations	22
16	Iron Concentrations	24
17	Iron Acumulations	24
18	Manganese Concentrations	25
19	Manganese Acumulations	25
20	Copper Concentrations	26
21	Copper Acumulations	26
22	Zinc Concentrations	27
23	Zinc Acumulations	27
24	Viable Counts of Total Microorganisms and Total Fungi in the Atmosphere of the EGC During the Continuous NFT Hydroponic Cultivation of Wheat	28
25	Viable Counts (nutrient agar) of Total Microorganisms in the NFT Nutrient Solution During the Continuous Hydroponic Cultivation of Wheat	29
26	Daily Water Usage by the System	30
27	Leaf Area Ratio (LAR) Over Time	36
28	Single Plant Leaf Area Over Time	36
29	Dry Weight Per Plant Over Time	37
30	Plant Height Over Time	37
31	Photosynthetic Energy Conversion Efficiency Over Time	37

ACKNOWLEDGMENTS

This project was conducted under the direction of Dr. William M. Knott III, Biological Sciences Officer, Life Sciences Research Office, and Dr. Albert M. Koller, Jr., Chief Programs and Planning Office, Biomedical Operations and Research Office, John F. Kennedy Space Center under NASA Contract No. NAS10-10285.

The authors gratefully acknowledge the valuble comments and suggestions of Dr. John C. Sager, NASA Biomedical Operations and Research Office, and Dr. Raymond M. Wheeler, The Bionetics Corp. We also appreciated the assistance of the following people, Dr. Richard F. Strayer for microbial monitoring, Teresa L. Englert for inorganic chemical analyses, and Peter V. Chetirkin for computer programming.

PRODUCT DISCLAIMER

This report, in whole or in part, may not be used to state or imply the endorsement by NASA employees of a commercial product, process or service, or used in any other manner that might mislead.

I. INTRODUCTION

The National Aeronautics and Space Administration (NASA) Controlled Ecological Life Support System (CELSS) Program is a long range program of research and engineering with a goal to understand how life can be maintained in autonomous systems during long duration spaceflights and extraterrestrial habitations. This program draws upon all aspects of the scientific community for information needed to accomplish a working CELSS. It includes the utilization of research data accumulated over the past twelve years by active NASA/CELSS grant research efforts and the application of previous biological and physical data collected from various projects.

MacElroy and Bredt (1984) described the components of a CELSS and discussed system control and bioregenerative life support in relation to reservoirs and buffers in a space environment. In a conceptual design option study of a CELSS, Oleson and Olson (1986) found that a volume of 56.9 m^3 per crew member will be required for growing crops, support equipment and access. Tibbitts and Alford (1982) compared the uses of various higher plants in a CELSS and developed a list of the most promising crop species.

The CELSS Kennedy Space Center Breadboard Project (Biomedical Operations and Research Office, 1986) is designed to provide containment, hardware, subsystems, designs and cultural techniques for the production of biomass and oxygen, the preparation of food and the processing of wastes in a controlled, recycling system. The project as conceived, will test and operate a "breadboard" facility to accomplish proof-of-concept evaluation. It will characterize system operations, mass budgets and energy budgets. The biomass production component is currently receiving major effort in the CELSS Breadboard Project. A large sealed biomass production chamber (BPC) has been constructed to supply information on the following factors:

- power requirements
- space (area and volume) requirements
- atmospheric environment and contaminant control
- propagation methods
- crop nutrition
- delivery and maintenance of hydroponic solutions
- root zone environment control
- crop production management systems

Many of these factors are presently under study. The components will function in an open loop at first, and in a more closed condition as knowledge is gained and funds permit.

The first crop to be grown in the BPC will be wheat. There is extensive literature on its culture and nutritional composition. According to Hoff et al. (1982), it ranks high in both nutritional and cultural criteria in comparison with other conventional crops. There has also been extensive environmental chamber work by Bugbee and Salisbury (1985a, 1985b, 1987a and 1987b) using wheat in hydroponic systems in the areas of photoperiodism, integrated photosynthetic photon flux (PPF) and temperature effects on yield.

Hydroponics is being used in the CELSS Breadboard Project to deliver nutrients to the roots of plants. Jones (1983) defines hydroponics as a nutrient solution delivery system which does not contain any organic or inorganic media for plant support. Hydroponics minimizes problems such as clogged irrigation nozzles, cleaning of culture media between crops and allows for more precise control of the root zone environment.

The breadboard project is using nutrient film technique (NFT) for distribution of the nutrients to the crop. Not only does this minimize the total weight of the hydroponic system, the rapid flow of the solution over the roots and the increased surface area also circumvent the need to aerate the hydroponic solution.

There are endless numbers of nutrient solutions and modified versions thereof, which have been published in the past 50 years. The University of California (Berkeley) agricultural experimental research station bulletin by Hoagland and Arnon (1938) is recognized as the basis for many formulations currently being used by investigators and commercial firms (Table 1). Depending on the species and environmental conditions, adjustments to the recipe are frequently made for improved growth. Fertilizer mixes, such as Peter's Hydrosol (1987) are commonly used in industry because they are ready-made. The slightly lower salt concentrations in Hydrosol also allow for nutrient manipulation as needed for the culture of a wide variety of plants. However, copper and zinc concentrations are well above the average found in many other nutrient solutions (Table 1). For reasons of quality control and the need to modify constituents, many researchers do not use commercial mixes.

Bugbee and Salisbury (1985a) modified the Hoagland/Arnon formula to grow wheat hydroponically under high irradiance and elevated CO_2 environments. The relatively low mobility of boron (Baker 1983), calcium and magnesium lead to an increasing of their concentrations in the nutrient solution (Table 1, Column 4). Lowering the phosphorous concentration allowed for an increase in iron uptake by the plants. Bugbee and Salisbury (1985a) added silica to their solution to minimize micronutrient toxicity symptoms. In addition, silica was added to their solution, in part, as a means to minimize micronutrient toxicity symptoms. Vlamis and Williams (1967) mention similar findings in work with other grasses. With these considerations, the breadboard project used a modified nutrient solution recipe following the macronutrient concentrations of Hoagland and Arnon (1938) and the micronutrient concentrations of Bugbee and Salisbury (1985a) Table 1, Column 5.

System stability and efficiency are paramount in the functioning of a CELSS system. Continuous use of a recirculating nutrient solution would be an efficient approach and would promote system stability by avoiding large swings in nutrient uptake in response to plant age. In a study using models for a lunar life support ecosystem, Rummel and Volk (1986) concluded that a large number of small batch growouts, started at timely intervals can improve nutrient reservoir stability and CO_2/water condensate efficiencies. Unfortunately, published research is scarce concerning the effects of using a single nutrient solution with plants of different ages. Prince et al. (1981) successfully grew lettuce in a controlled environment on a continuous basis. However, they replaced the solution at weekly intervals rather than using the same nutrient solution over the course of the experiments.

Table 1. Comparison of Hydroponic Solutions

Element	Hoagland #1 (mM)	Peter's Hydrosol (mM)	Salisbury Bugbee (mM)	Experimental Solution A (mM)
N	15.0	3.6	15.0	15.0
P	1.0	1.5	0.2	1.0
K	6.0	5.4	3.0	6.0
Ca	5.0	*	12.0	5.0
Mg	2.0	1.3	4.0	2.0
S	2.0	1.2	2.0	2.0
	(uM)	(uM)	(uM)	(uM)
Fe	50.0	50.0	100.0	100.0
Si	----	----	300.0	300.0
B	46.0	46.0	80.0	80.0
Mn	9.0	9.0	8.0	8.0
Zn	0.8	2.3	0.8	0.8
Cu	0.3	2.4	0.3	0.3
Mo	0.5	1.0	0.1	0.1

*Ca is added separately to desired concentration as $Ca(NO_3)_2$.

Continual reuse of the nutrient solution for cropping is an important means of conserving water in a CELSS since the treatment of spent nutrient solution would be costly in terms of equipment, energy and space. In a recirculating system, water and nutrients need to be replaced as they are removed by the crop but the reservoir volume and constituents should remain constant. As with multi-aged plant systems, there are few accounts in the literature concerning growth and yield effects of using continuously maintained nutrient solutions for successive, long-term cropping. Preliminary, unpublished Breadboard Project studies have found no significant differences in wheat yields when growing three consecutive batches on the same nutrient solution.

Many of the Breadboard Project wheat studies have used elevated atmospheric CO_2 concentrations, i.e. >350 ppm, as a means to increase biomass production. Strain (1978) reported that CO_2 enrichment tends to increase lateral branching and increase

seed yield in wheat, while Sionit et al. (1981a) reported increased total dry weight, numbers of tillers and number of heads when CO_2 was elevated from 350 ppm to 1000 ppm. In addition the weight and number of seeds grown with elevated CO_2 concentrations were significantly greater. Sionit et al. (1981b) studied the effects of elevated CO_2 at different levels of mineral nutrition. Wheat grown with 675 ppm CO_2 continued increasing in seed weight and number as the Hoagland solution concentration was increased from 1/16 to 1/2 strength. However, no gain resulted in using Hoagland solution at the full strength concentration.

In preparation for plant growth experiments inside the BPC, a study was conducted to determine if wheat could be grown hydroponically in a continuous mode of production using an elevated CO_2 environment. A recirculating system containing a constant volume of solution, which would be maintained only through replenishment of nutrients and water, was also evaluated.

The major objectives of the study were:

1. Use a hydroponic NFT system to maintain a continuous production of wheat for 216 days (16 cycles).
2. Monitor and control biological conditions in order to determine effects of nutrient solution age on successive wheat yields.
3. Create a plant growth curve and determine water and nutrient budgets associated with the system.

II. MATERIALS AND METHODS

A. Environment

A semi-dwarf cultivar of spring wheat (Triticum aestivum L.), 'Yecora Rojo', was used in the study. It is grown commercially in the San Joaquin and Imperial valleys of California and Qualset et al. (1985) mention its good protein content, good milling and excellent baking qualities. Bugbee and Salisbury (1985a, 1985b, 1987a and 1987b) used this cultivar in numerous CELSS related studies. Our study was conducted in a 1.8 m x 2.4 m walk-in growth chamber (EGC)[1]. The radiation was provided by a combination of 30 Vitalite fluorescent lamps (F96T12/Vitalite/1500)[2] and 16 standard, frosted incandescent bulbs (60 watt). The atmospheric CO_2 was monitored and controlled at 1000 $\mu mol\ mol^{-1}$ using an ANARAD (AR 500) infrared gas system[3]. Growth chamber conditions are given (Table 2).

B. Nutrient Solution Delivery System

Solution was delivered from a single reservoir utilizing two submersible, centrifugal pumps[4], one for each side of the chamber. Each pump delivered solution to four trapezoidal-shaped PVC trays (51 mm deep). Solution was pumped from the reservoir, through a 64 µM filter via 1.3 cm ID CPVC pipe, to a manifold which

[1]Environmental Growth Chambers, Chagrin Falls, OH
[2]Durotest, North Bergin, NJ
[3]ANARAD, San Diego, CA
[4]Dayton Electric Mfg. Co., Chicago, IL

distributed flow to the four trays (Fig 1). From the manifold it passed through a valve mounted at the front of each tray, then to an emitter mounted inside the back of each tray. Each emiter consisted of a 1.3 cm ID CPVC pipe with a series of 0.2 cm holes along its length and a cap at the end (Fig 2). The solution entered the tray via these holes and flowed by gravity at a rate of 1.0 L min^{-1} to a drain at the other end of the tray, exited and returned to the reservoir via a 2.5 cm ID PVC pipe. The plant support tops were constructed from extruded "tee" strips of PVC with black/white polyethylene wings (Fig 2). Cages constructed of black plastic netting stretched across a white PVC framework, provided vertical support for the growing plants (Fig 1).

C. Nutrient Solution

The experimental solution "A" used in this study was a combination of Hoagland's macronutrient concentrations and Salisbury/Bugbee micronutrient concentrations (Table 1). Nutrients were added to the reservoir every three days from stock bottles containing 1M concentrations of the various salts. The replacement of nutrients to the reservoir was based on the estimated millimoles of each nutrient depleted per liter of water used in the system over each 3-day period (Table 3). Iron chelates (Fe-HEDTA and Fe-EDDHA) and the other micronutrients were added at full strength concentrations every 14 days. The estimated daily depletion values of the nutrients were calculated from the solution chemical analysis of wheat grow-out studies done previously for the breadboard project. Concentrations of Mo, B, Si and S were not determined. Ongoing chemical analysis of the solution and general crop appearance were the basis for nutrient adjustments in this study. A chronological listing of the adjustments is given in the Appendix. Control of the solution pH (between 5.5-6.0 units) was automated using a pH controller and 10% (v/v) nitric acid. Daily monitoring of the solution's temperature and the dissolved oxygen (for the first 50 days of the experiment) presented variations of less than 10% per week. It was decided to continue recording these values at weekly intervals, rather than daily. The level of nutrient solution in the reservoir was monitored by using a stand pipe level indicator (transparent siphon tube, Fig 3). The solution volume was maintained by daily addition of deionized water to a predetermined mark on the level indicator.

D. Solution and Air Sampling

Samples of the nutrient solution were collected for inorganic chemical analyses and bacterial counts. For the chemical analyses, three (125-ml) replicates of nutrient solution were removed from the reservoir prior to and following each replenishing exercise (every three days). Analytic methods were as follows:

Parameter	Method
NO_3-N, NO_2-N	Automated colorimetry
pH	Potentiometry
Conductivity	Conductimetry
P, K, Ca, Mg, Fe, Cu, B, Mn, Zn	Atomic absorption/emission spectrophotometry

Table 2. Chamber and Environmental Parameters

Chamber Parameter	Reading (range)	Monitor/Control	Frequency
PPF (umol m-2 s-1)	250	manual	monthly
Source	incandescent fluorescent	----------	---------
Photoperiod (hr)	24	automated	1· min-1
Temperature (oC)	23	automated	1· min-1
Relative humidity (%)	65	automated	1· min-1
Carbon dioxide (umol mol-1)	1000	automated	1· 4 min-1
Air velocity (m sec-1)	0.8	manual	Day 1
SOLUTION PARAMETER			
pH	5.8	automated	continuous
Temperature (oC)	23	manual	1· week-1
Conductivity (umhos cm-1)	2000	manual	1· 3 days-1
Dissolved O_2 (ppm)	6 - 8	manual	1· week-1
Flow rate (L m-2 min-1)	4.17	manual	2 · month-1

FIG 1. SYSTEM LAYOUT

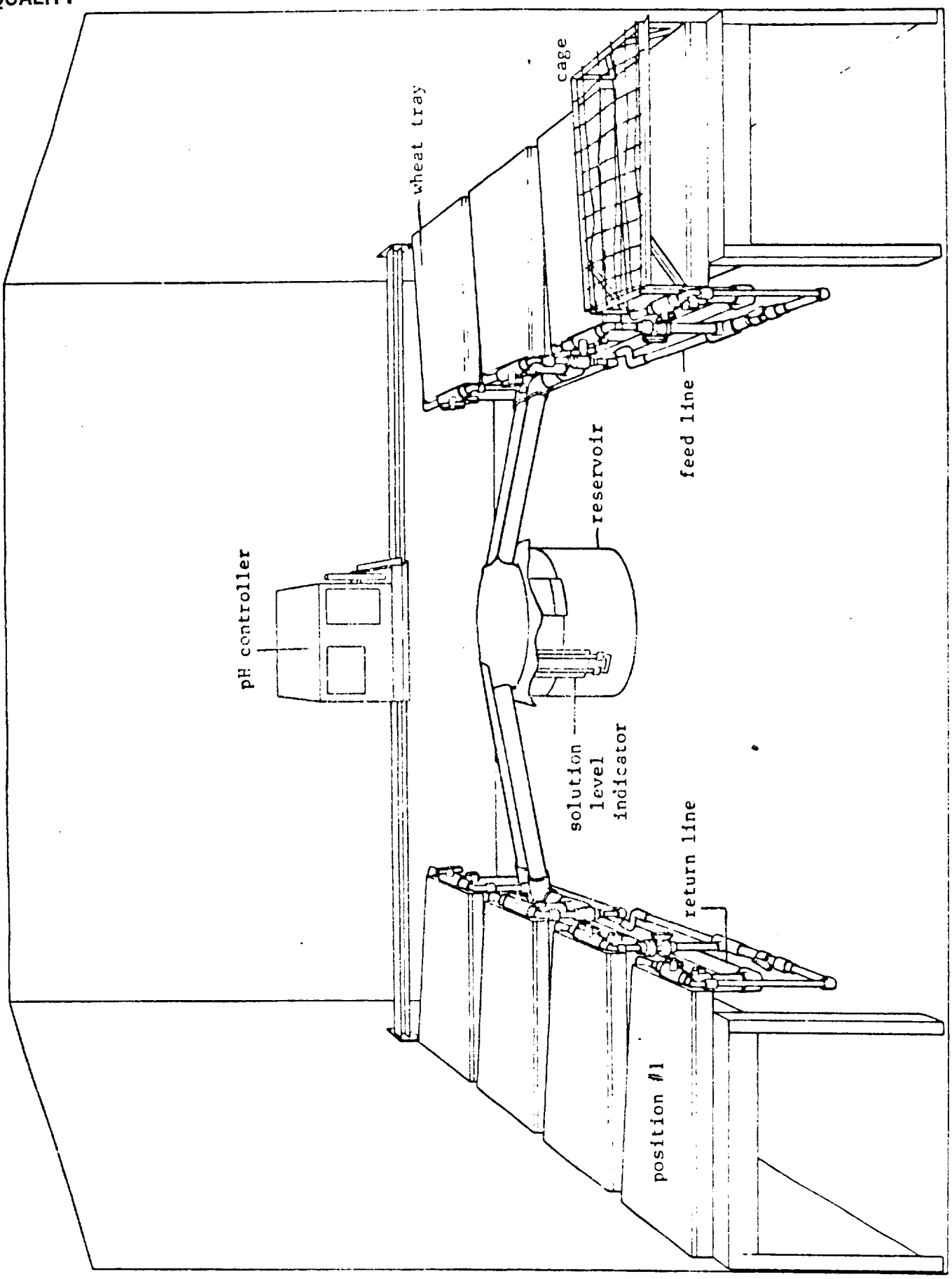


FIG 2. HYDROPONIC WHEAT TRAY

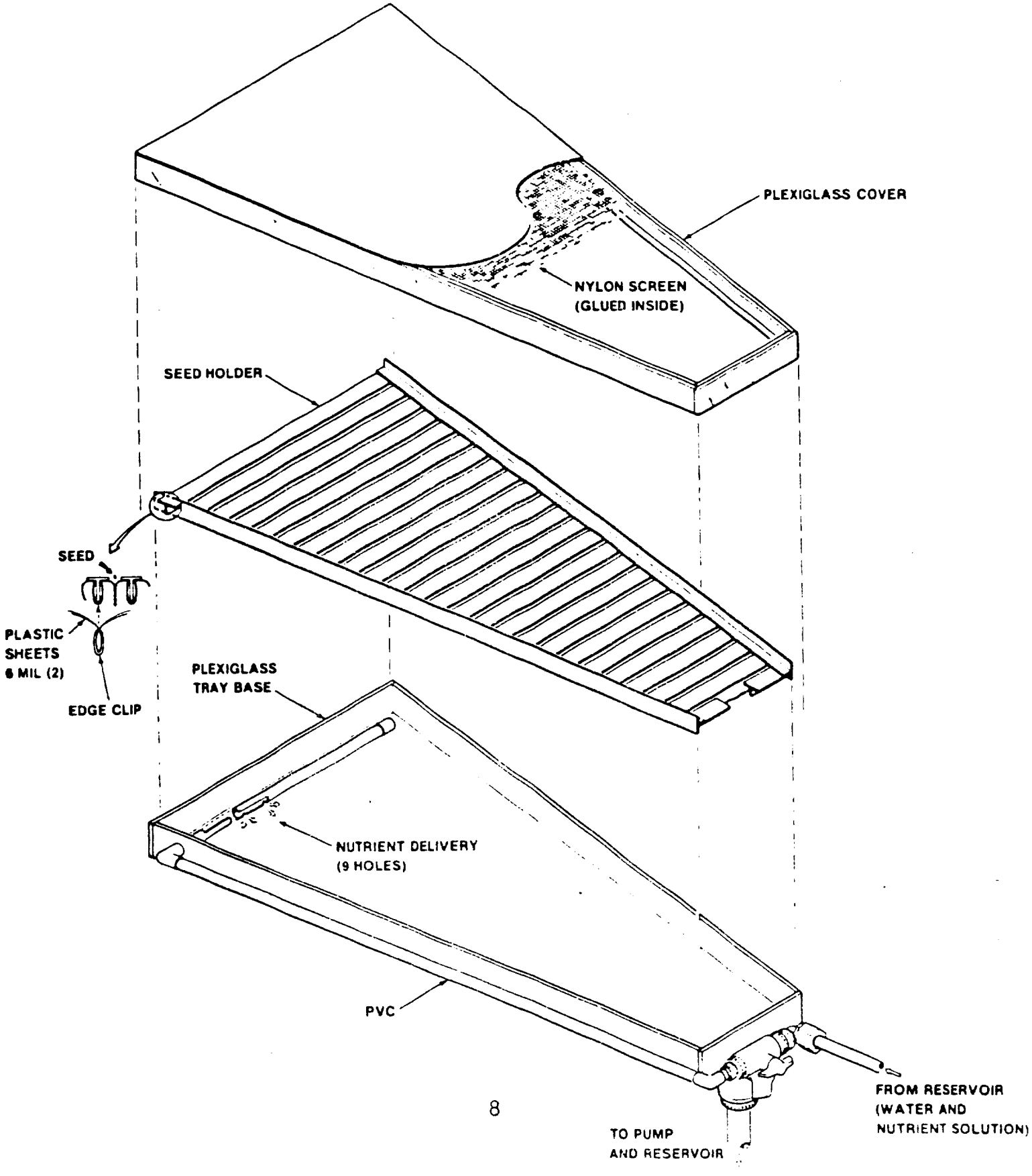
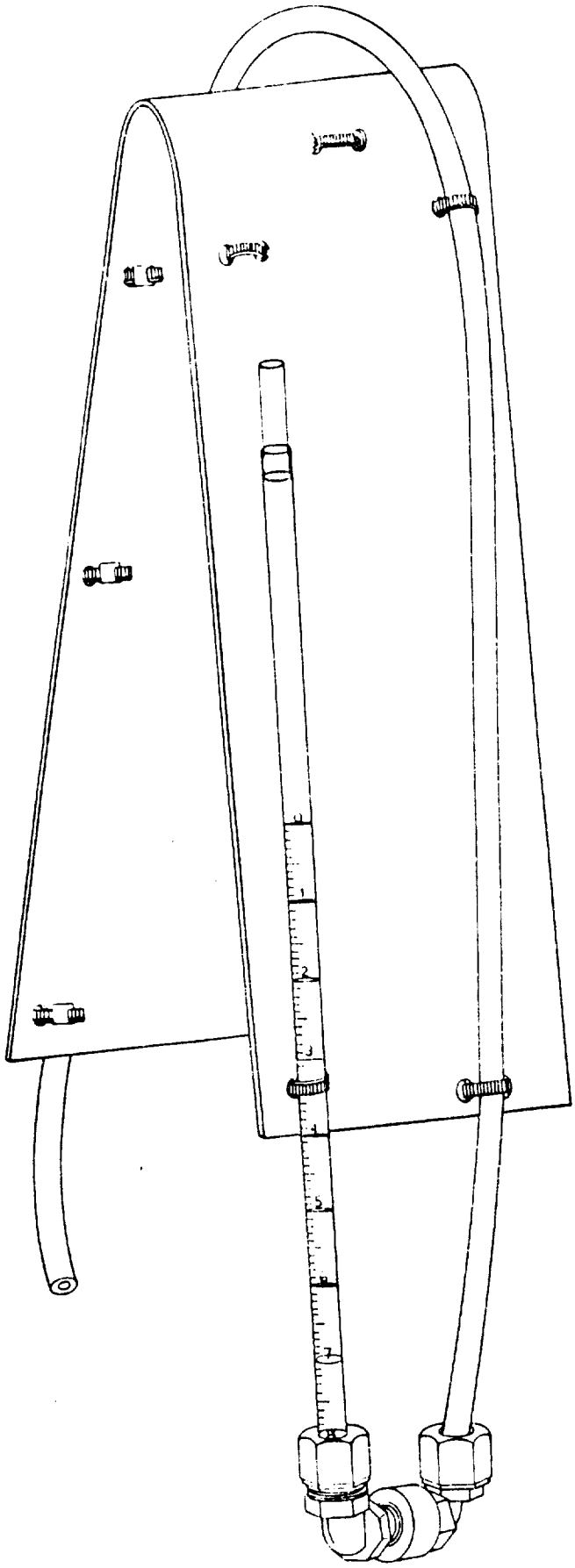


Table 3. Experimental Solution A

element	desired concentration in solution (mM)	estimated daily use (mmol/L water)
N	15.0	4.50
P	1.0	1.00
K	6.0	2.50
Ca	5.0	1.00
Mg	2.0	0.38
S	2.0	0.38
	(μM)	**(μmol/L water)**
Fe	100.0	25.00
Si	300.0	90.00
*B	80.0	5.70
*Mn	8.0	0.57
*Zn	0.8	0.06
*Cu	0.3	0.02
*Mo	0.1	0.04

* Added as full strength concentrations every 14 days.

Fig 3. STAND PIPE LEVEL INDICATOR



The nutrient delivery system's filters had mesh covered cores, which were cleaned every four weeks. The cores were rinsed with deionized water, to remove particulate matter, before being placed back into the filter bodies. For determination of total viable bacterial counts, the solution was sampled twice a week. A sterile 10 ml test tube was aseptically filled with 5 ml of nutrient solution directly from the reservoir. The sampling procedure entailed three replicates. Serial (ten-fold) dilutions were made into sterile isotonic (phosphate-buffered) saline solution. Subsamples (0.1 ml) of appropriate dilutions were spread onto nutrient agar media for enumeration. Viable counts were made after two to four days of incubation at 28°C. Counts were expressed as colony forming units (CFU) per ml. Atmospheric sampling for bacterial and fungal counts was performed twice per week. A Matson-Garvin slit-to-air (STA) sampler was used to collect air samples directly onto the surface of trypticase soy (TSA), for total viable microorganisms and inhibitory mold (IMA) for total viable fungi agar media. Flow rate of the sampling device was 1 ft^3 min^{-1}. The sampling period lasted five minutes, in which time three replicates were collected.

E. Seed Germination

Four days prior to planting, 'Yecora Rojo' wheat seed were surface sterilized for 15 minutes in a 3000 ppm formalin solution as suggested by Smilanski (1986). The seeds were then cold treated (4 days at 6°C) before planting 350 onto a tray top. The planted tray top was placed into the chamber (position #1, Fig 1) and attached to the nutrient delivery system. Two liters of solution were placed in the tray bottom, where it remained for six days. Trays were covered with germination hoods constructed of 0.25 inch white plexiglass. Each hood was 1" deep and had a lip running around the perimeter to overlap the tray bottom (Fig 2). The inside surface was covered by a layer of fiberglass screen. Both seeds and screen were sprayed with deionized water prior to placing the hood on the tray. On Day 4 the germination hood was removed and germination counts recorded. On Day 6 the recirculating solution was started through the tray at 1 L min^{-1}. A support cage was placed on the tray two weeks after planting (Fig 1). A new tray was prepared every nine days in the same manner described above until all eight positions were filled.

F. Harvests

Harvesting of a tray occurred on Day 72 and every nine days thereafter, (± 3 days). At harvest the solution flow to the tray was turned off. The tray was removed from the chamber. After measuring the canopy height, the root mat was cut off the stems and the number of plants counted. Statistically determined variance from previous `in-house' wheat studies warranted the use of 67% of the plants per tray as a representive tray sample size. The following items were determined from each harvest:

- number of primary heads
- number of nonprimary heads
- number of spikelets per head
- number of seeds per head
- seed and straw fresh weights
- seed, straw and root dry weights

Seed number and dry weights were calculated by taking two 5-gram samples, counting the number of seeds in the samples, drying them at 60°C for 48 hours and reweighing them. All other harvest data were extrapolated from the above values. Individual 100-gram (dried tissue) samples of seed, straw and roots were analyzed by a certified commercial laboratory. The laboratory has approved methods of analysis specified by agencies such as: AOAC, USDA, USP, FDA, NF, EPA, AOCS and AACC. The seeds were analyzed for K, Ca, Mg, Fe, S, P, Cu, Mn, Zn, water soluble vitamins, sugar, amino acids and fiber. Proximate analyses, which included protein, moisture, fat, ash, fiber, carbohydrate and calories were performed on the seeds, straw and roots. The straw and roots were also analyzed for the same elements. Protein was calculated as N x 6.25. Carbohydrates were figured by subtraction. On the last day of the experiment (Day 216) all of the trays were removed from the chamber. Prior to their removal, light photosynthetically activated radiation (PAR) measurments were recorded at canopy level and below the canopy of each tray. The oldest tray (63 days) was harvested in the same manner as the previous trays. In order to harvest all eight trays in a single day, 20% samples were taken rather than 67%. In addition to the aforementioned data, the immature plants had the following data collected;

- individual plant height
- number of tillers
- leaf area

G. Statistical Analysis

Descriptive statistics were calculated with the STAT80 Interactive Statistics Package[5] . A correlation analysis was performed to test for linear correlation between conductivity and nutrient concentration and Pearson product moment correlation coefficients and t-statistics calculated. A correlation analysis was also run to test for linear correlation between the various harvest parameters. Correlations between water use/conductivity and water use/nutrient use, were also analyzed, although not presented here. Linear regression analyses were run on growth data and confidence bands determined. Linear curves were plotted with Grafit/1000, a graph generation package[6] .

III. RESULTS

The results have been separated into phases. Phase I covers the experimental start-up (0-72 days), during which time the system was being filled with a seeded tray every nine days until all tray positions were filled. Phase II covers days 73-144, when continuous seeding and harvest (every nine days) occurred. Phase III (145-216 days), was when major changes occurred in the replenishment of Mn, due to the appearance of injury symptoms on the leaves. Phases II and III had some differences in the replenishment of other salts as well. Information concerning nutrient solution constituents, evapotranspiration, plant growth, harvests and tissue analyses is addressed in this section.

A. Nutrition

[5] Statware Inc. Salt Lake City, UT

[6] Graphic User System, Inc., Santa Clara, CA

analyses of the nutrient solution. The 'loss' values were calculated by subtracting the nutrient concentration just prior to replenishment from the nutrient concentration right after the previous replenishment (3 days before). The 'accumulation' values were calculated by subtracting the nutrient concentration just prior to replenishment from the nutrient concentration right after replenishment of that same day.

pH

The pH controllers kept the pH relatively uniform throughout the entire study. Values recorded daily from the pH controller were closer to the optimum (5.8) than were the values received from the chemistry support laboratory's analyses of the nutrient solution (Fig 4).

Conductivity

The nutrient solution conductivity was maintained at 2000 μmhos cm^{-1} throughout the study (Fig 5). Most of the variation was during Phase I, when the system's biomass was increasing. The conductivity correlated best with NO_3-N and Ca $(CaNO_3)_2$ concentrations (Table 4).

Nitrate-nitrogen

Nitrate-nitrogen concentrations fluctuated during Phase I, while the system was gaining biomass (Fig 6). Nitrate was added in the form of nitric acid (HNO_3) for pH maintenance, however the amount added in this manner was negligible in relation to the concentration of NO_3-N added during replenishments. Although the NO_3-N concentration was usually below the desired concentration, it was not considered to affect the plant growth. From looking at the overlapping accumulation and loss data points (Fig 7), the system removed all of the NO_3-N that was added as replenishment. A total of 129.11 g of NO_3-N was supplied during the study, with 112.39 g (87%) being removed from the system.

Phosphate-phosphorous

Beginning on Day 40, there was a rise in the PO_4-P concentration which continued through Phase II (120 mg L^{-1} by day 160). At Day 166, the PO_4-P replenishment was reduced by a third (Appendix), which reduced the solution concentration to 26 mg L^{-1} (Fig 8). As shown in Figure 10, the plants removed all of the PO_4-P available to them until Day 60 and also after Day 190. A total of 75.96 g of PO4-P was added to the nutrient solution. Cumulative loss of PO_4-P amounted to 74.12 g (98%, Table 5).

Fig 4. SOLUTION pH

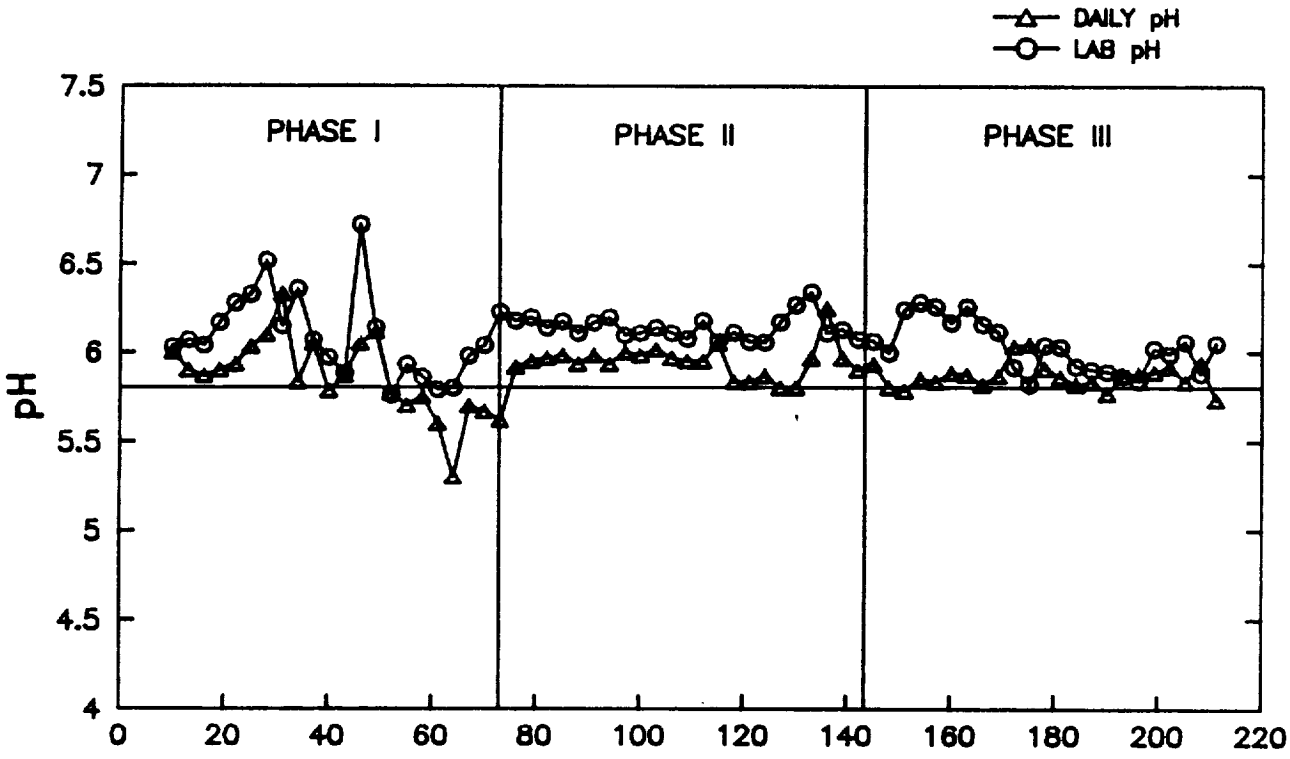


Fig 5. ELECTRICAL CONDUCTIVITY

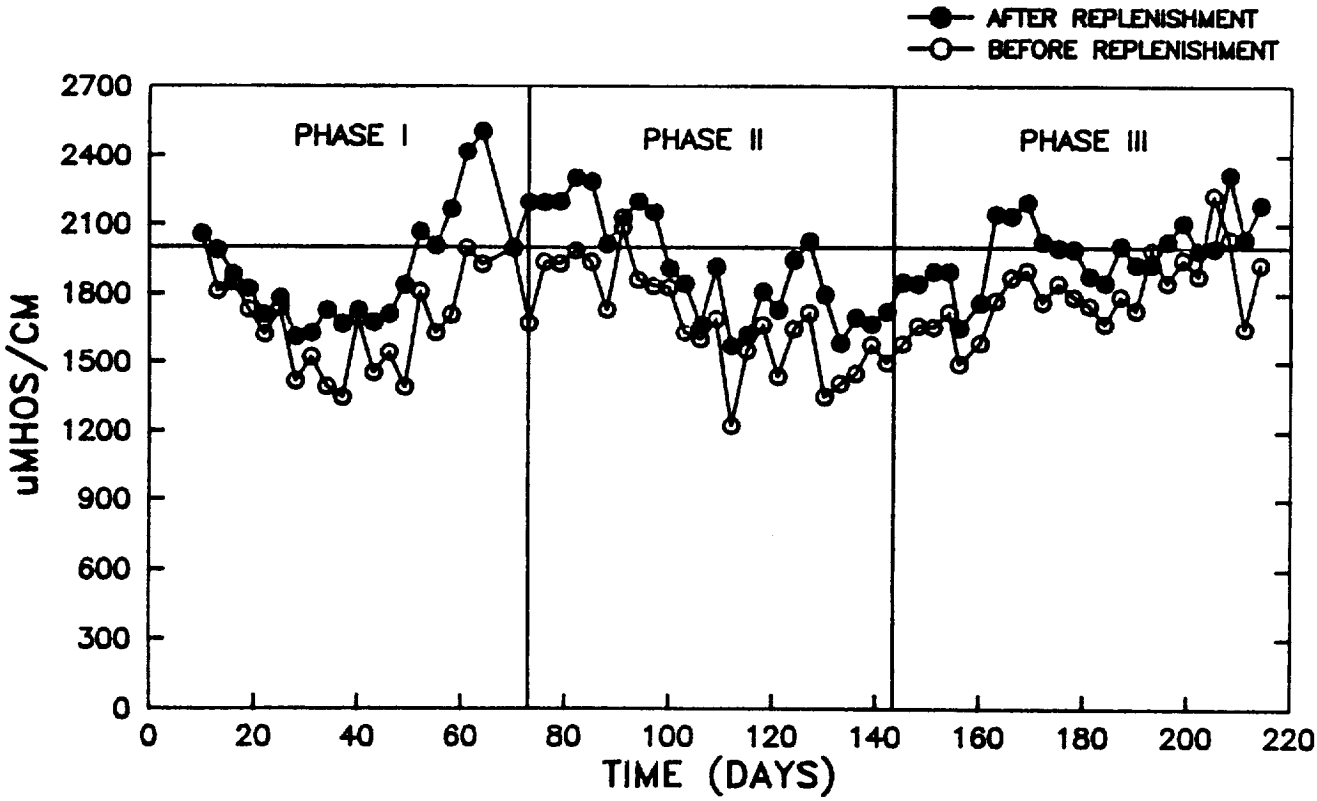


Table 4. Solution Electrical Conductivity/Elemental Correlations*

Electrical Conductivity Versus	r
NO_3-N	0.89
PO_4-P	0.32
K	0.43
Ca	0.77
Mg	0.72
Fe	0.71
Mn	0.70
Cu	0.70
Zn	0.70

*P-values (2-tailed test) were less than 0.01.

Fig 6. NITRATE-NITROGEN CONCENTRATIONS

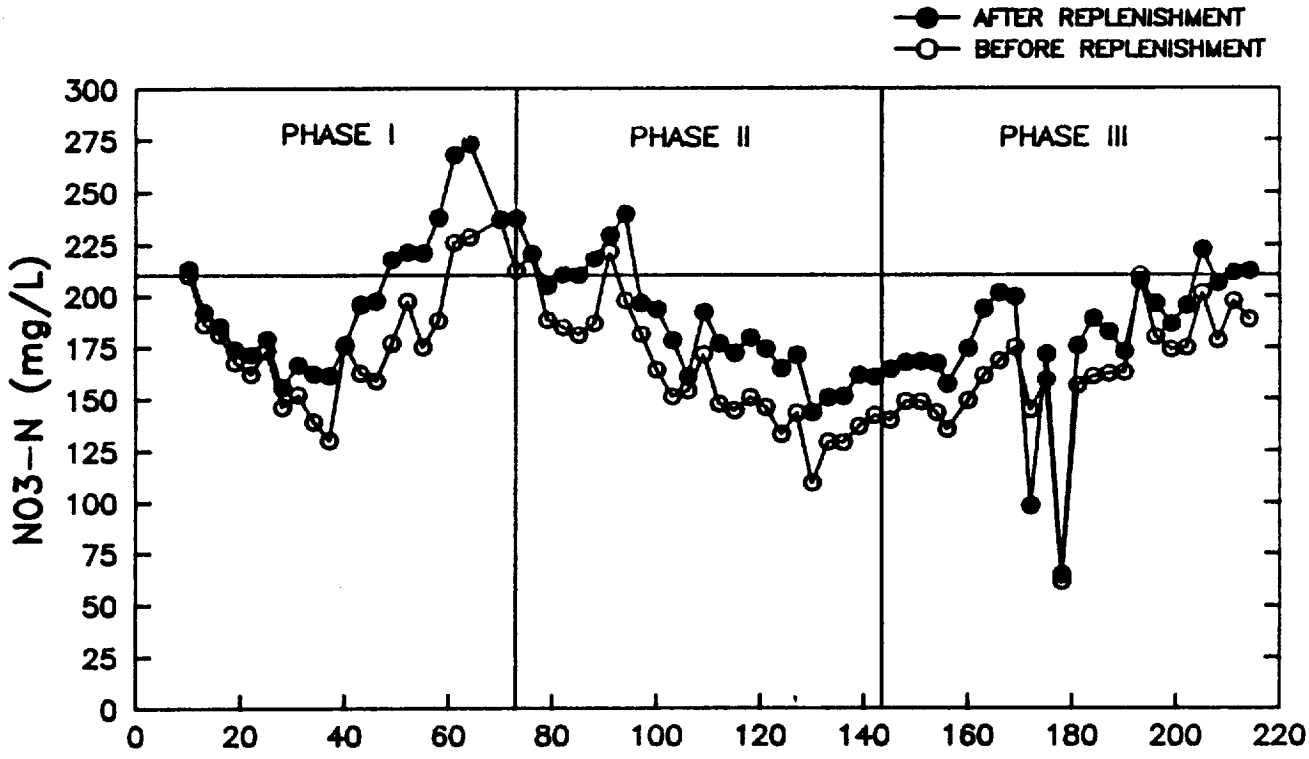
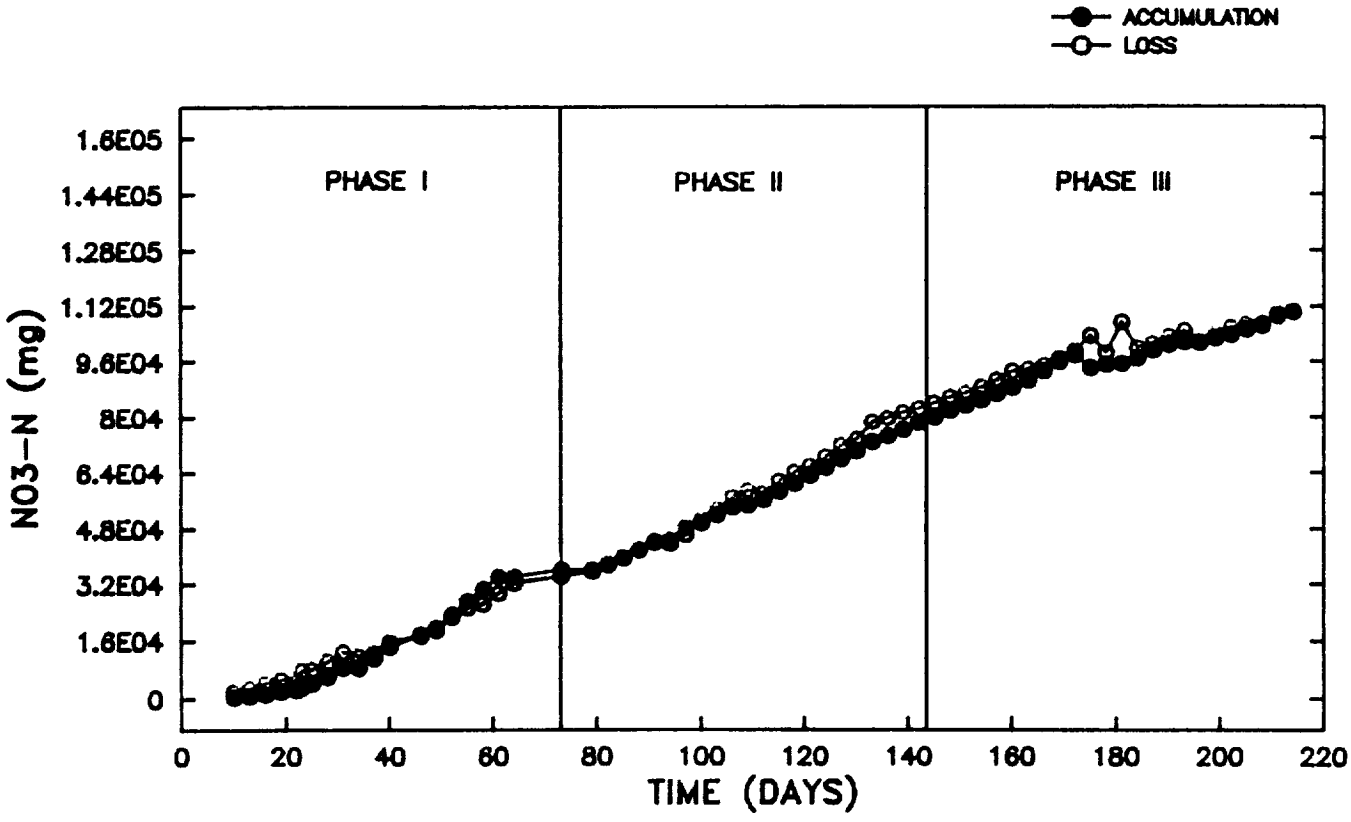


FIG 7. NITRATE-NITROGEN ACCUMULATIONS



Potassium

The preferred K concentration for this experiment was 234 mg L^{-1}. During Phase I, replenishment of K was too low and resulted in a rapid decrease in solution concentration within the first 40 days (Fig 10). On Day 49, K replenishment increased by 11% (Appendix). Peak concentrations of 319 mg L^{-1} and 292 mg L^{-1} occurred on days 64 and 151, respectively. During Phase II and the early part of Phase III large amounts of K were depleted from the solution between replenishment days. After Day 170, the concentration declined once again because of a reduction in the replenishing solution (Appendix). Throughout the entire study, 285.61 g of K were added and 273.19 g (96%) were removed (Table 5). Between Days 20 and 60 not all available K was used (Fig 11). For the remainder of the study, the loss was equal to the accumulation curve. The K concentration had a positive correlation with conductivity (Table 4).

Calcium

Beginning on Day-30, Ca increased from a baseline value of 200 mg L^{-1} to 300 mg L^{-1} by day 64 (Fig 12). The replenishment was adjusted frequently to obtain proper concentrations by day 100 (Appendix). Calcium remained near the desired concentration during Phased III (Fig 12). Looking at Figure 13, Ca depletion seemed to have been a function of how much was available, since the system never removed all that was put back by replenishment. The nutrient solution always had more Ca than was removed from the solution. A total of 105.99 g of Ca were added to the solution over time, while 89.67 g (85%) were used (Table 5). The Ca solution concentration had a positive correlation with the conductivity (Table 4).

Magnesium

The Mg concentration was to be maintained at 49 mg L^{-1}. Figure 14 shows Mg was below the desired level for most of Phase I. Beginning at Day 70, it increased to levels above the baseline during Phase II and remained between 55 and 65 mg L^{-1} for the remainder of the study. The replenishment concentration was not altered until the last 10 days of the study (Appendix). Uptake of Mg appears to be a function of availability (Fig 15). A total of 27.81 g of Mg was put in to the solution with 23.82 g (86%) being depleted (Table 5). Mg concentration had a positive correlation with the solution conductivity (Table 4).

Iron

Fe concentrations in the nutrient solution were to be kept at 5.6 mg L^{-1}. Figure 16 shows Fe starting out low and decreasing through Phase I, until Day 90. An increase in the replenisment of chelated Fe-EDDHA and Fe-HEDTA during Phases II and III (Appendix), brought levels closer to the baseline. There were excessive amounts of Fe at times during Phases II and III on days that chelators were added in place of $FeCl_3$. The accumulation and loss curves are fairly equivalent (Fig 17), which implies that the wheat used much of the Fe that was in the solution. A total of 5.75 g was put into the nutrient reservoir while 5.27 g (92%) was depleted (Table 5). The Fe concentration correlated with the solution conductivity (Table 4).

Fig 8. PHOSPHATE-PHOSPHOROUS CONCENTRATIONS

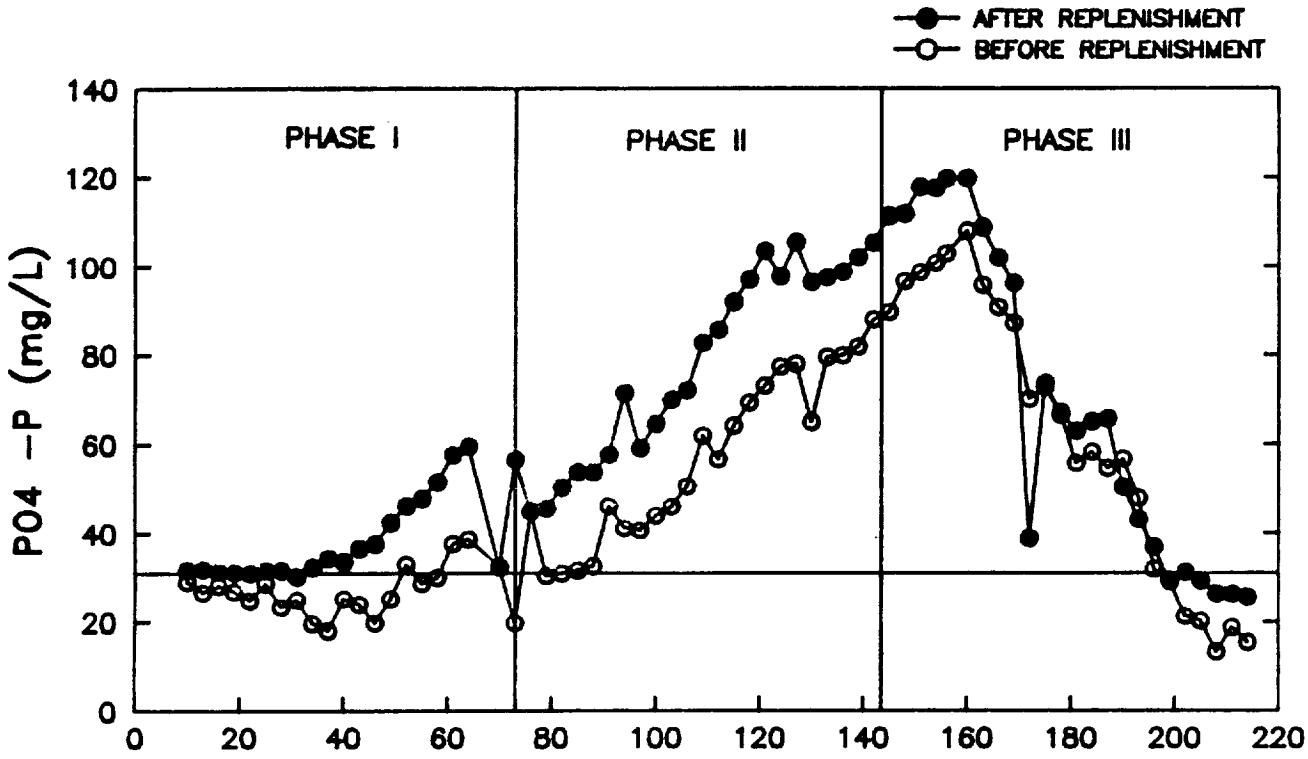


Fig 9. PHOSPHATE-PHOSPHOROUS ACCUMULATIONS

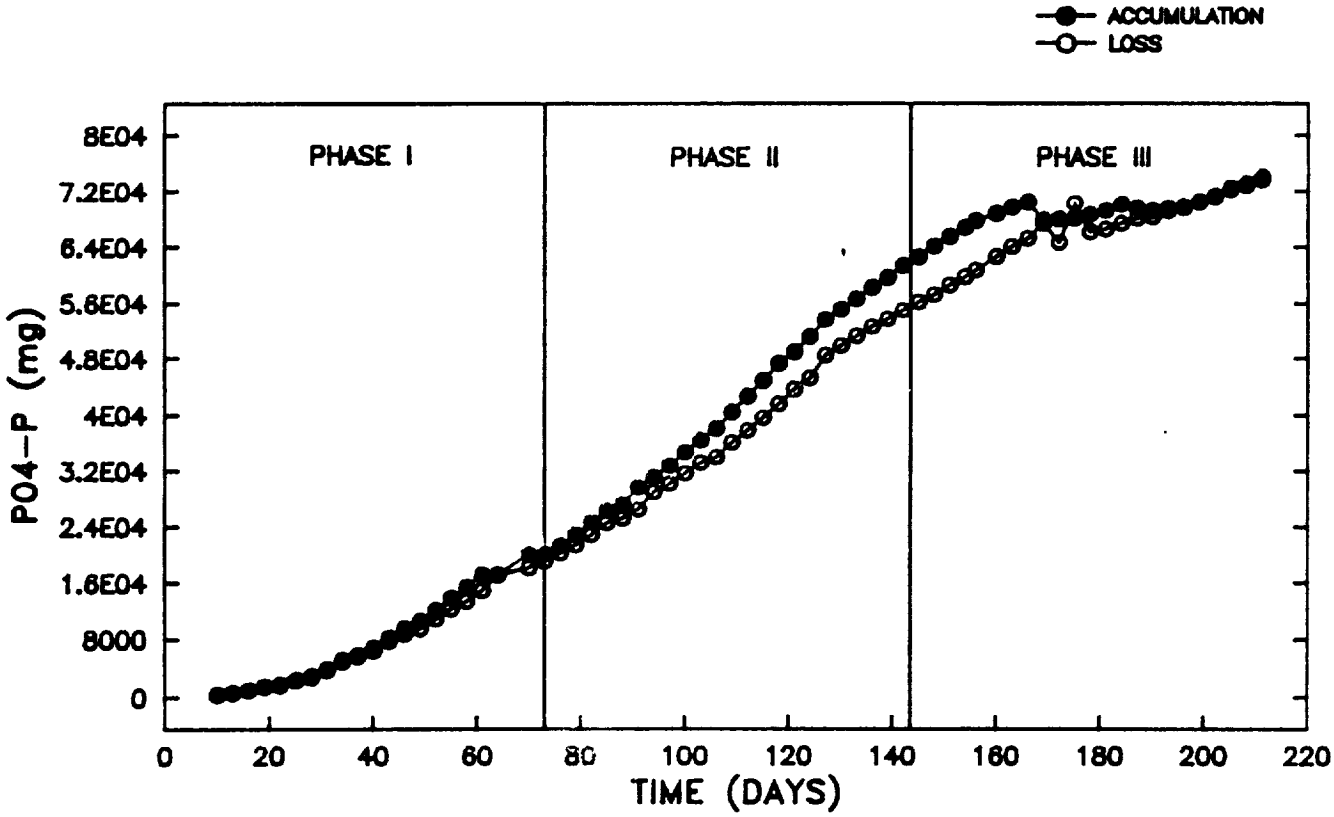


Table 5. Mass Balance Budget For Entire Study

Nutrient	Amount Added[4] (g)	Amount Removed[4] (g)	Amount in Plant Tissue[5] (g)
P	75.96	74.12	78.09
K	285.61	273.19	319.63
Ca	105.99	89.67	80.86
Mg	27.81	23.82	24.02
Fe	5.75	5.27	5.71
Mn	0.91	0.90	0.76
Cu	0.013	0.013	0.290*
Zn	0.065	0.066	0.241*

Total biomass (dry matter) produced = 8.44 kg
Total water evapotranspirated = 2430 L

*Excess in plant tissue may have been due to contamination by chamber humidifiers.

[4] Analyzed by "in-house" laboratory, The Bionetics Corp., KSC, FL.
[5] Analyzed by Nutrition International, East Brunswick, NJ.

Fig 10. POTASSIUM CONCENTRATIONS

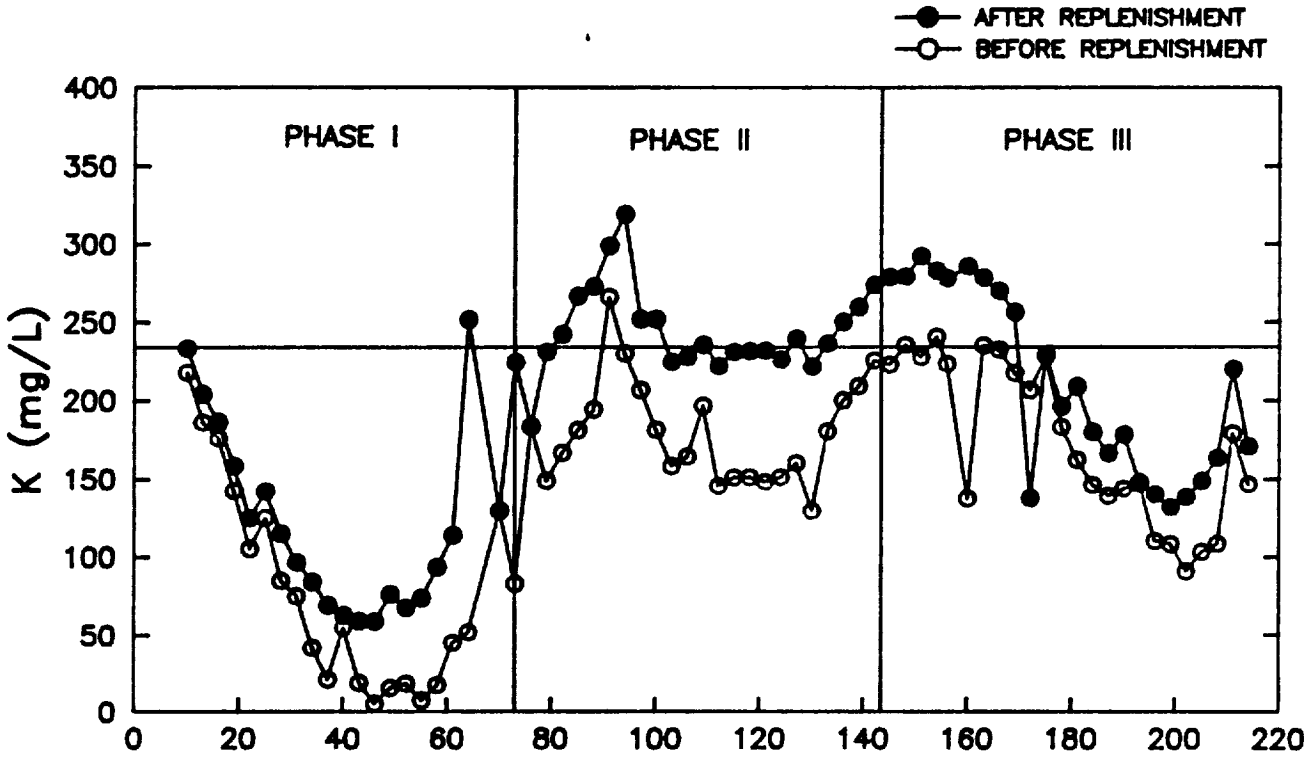


Fig 11. POTASSIUM ACCUMULATIONS

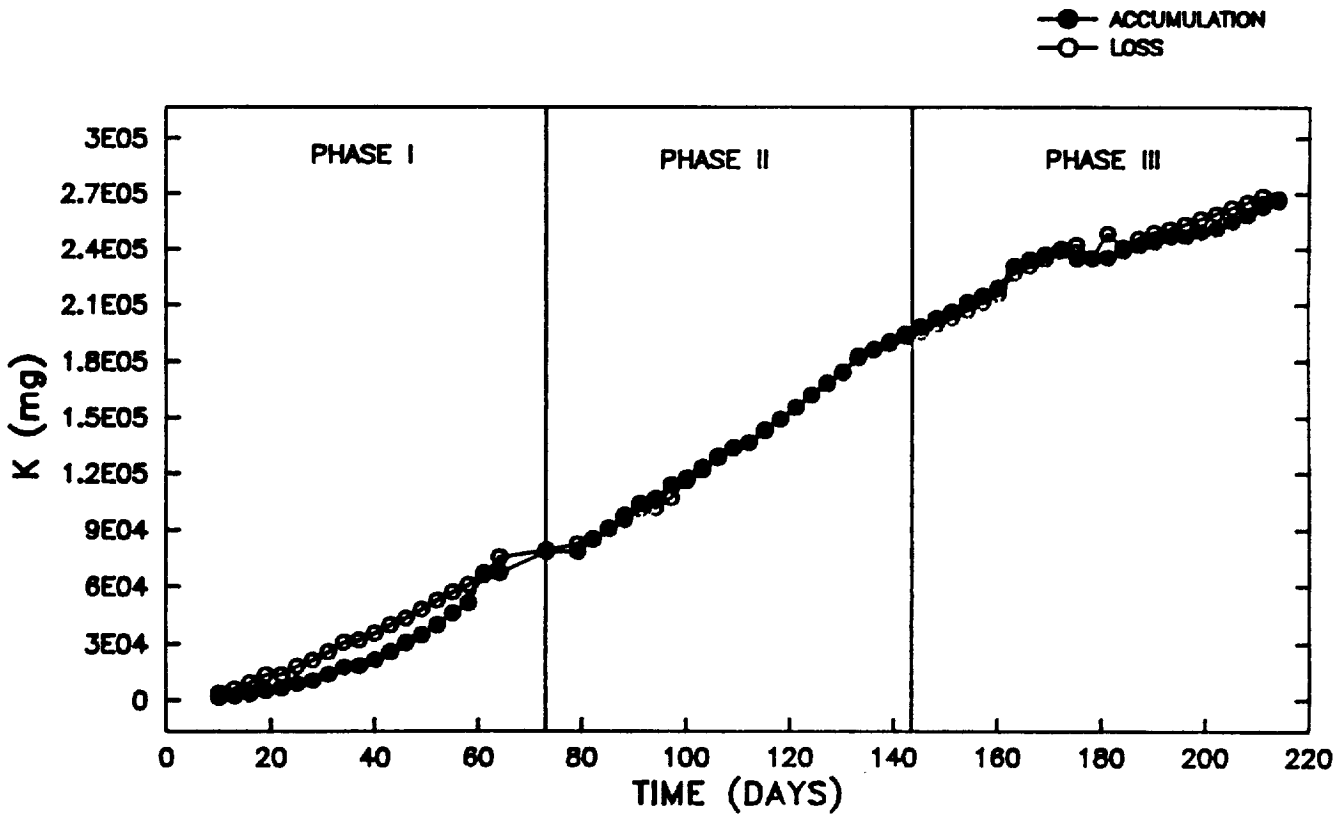


Fig. 12. CALCIUM CONCENTRATIONS

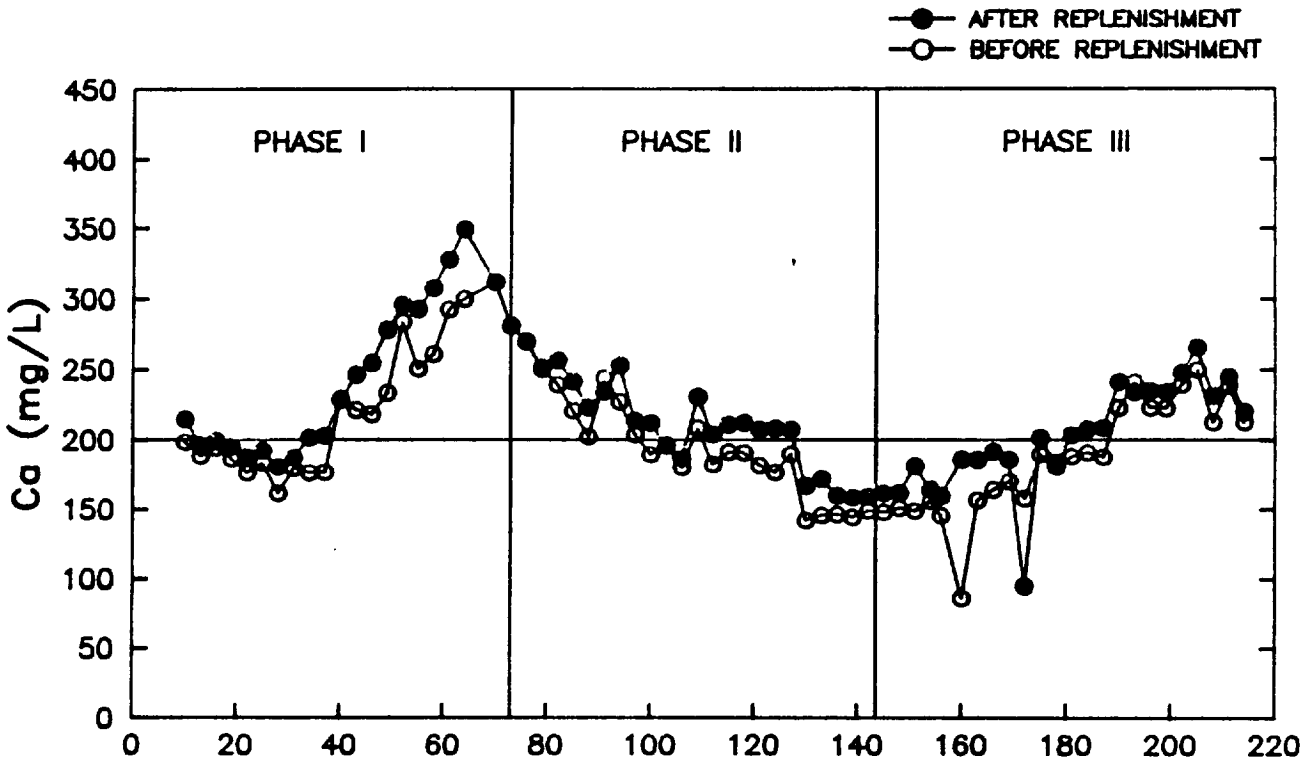


Fig 13. CALCIUM ACCUMULATIONS

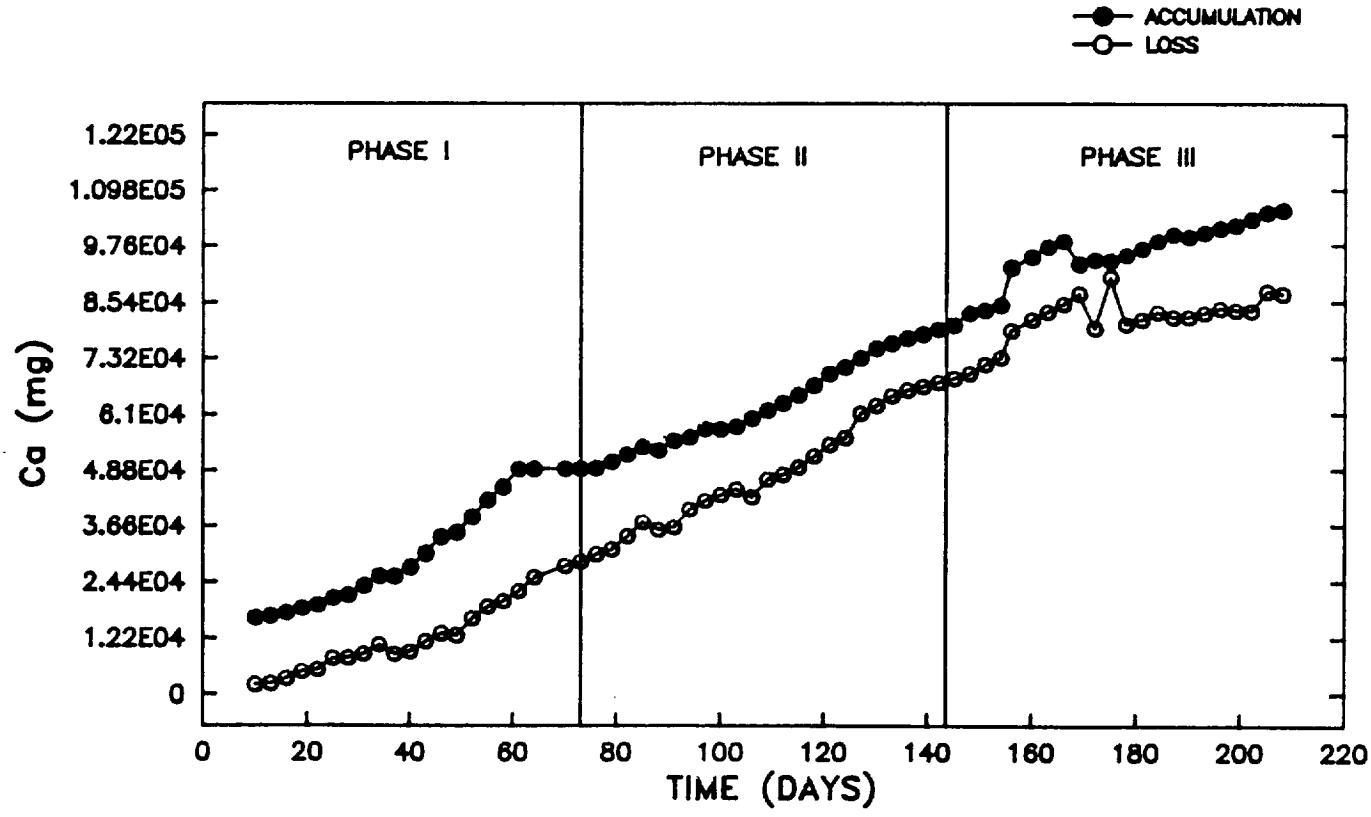


Fig 14. MAGNESIUM CONCENTRATIONS

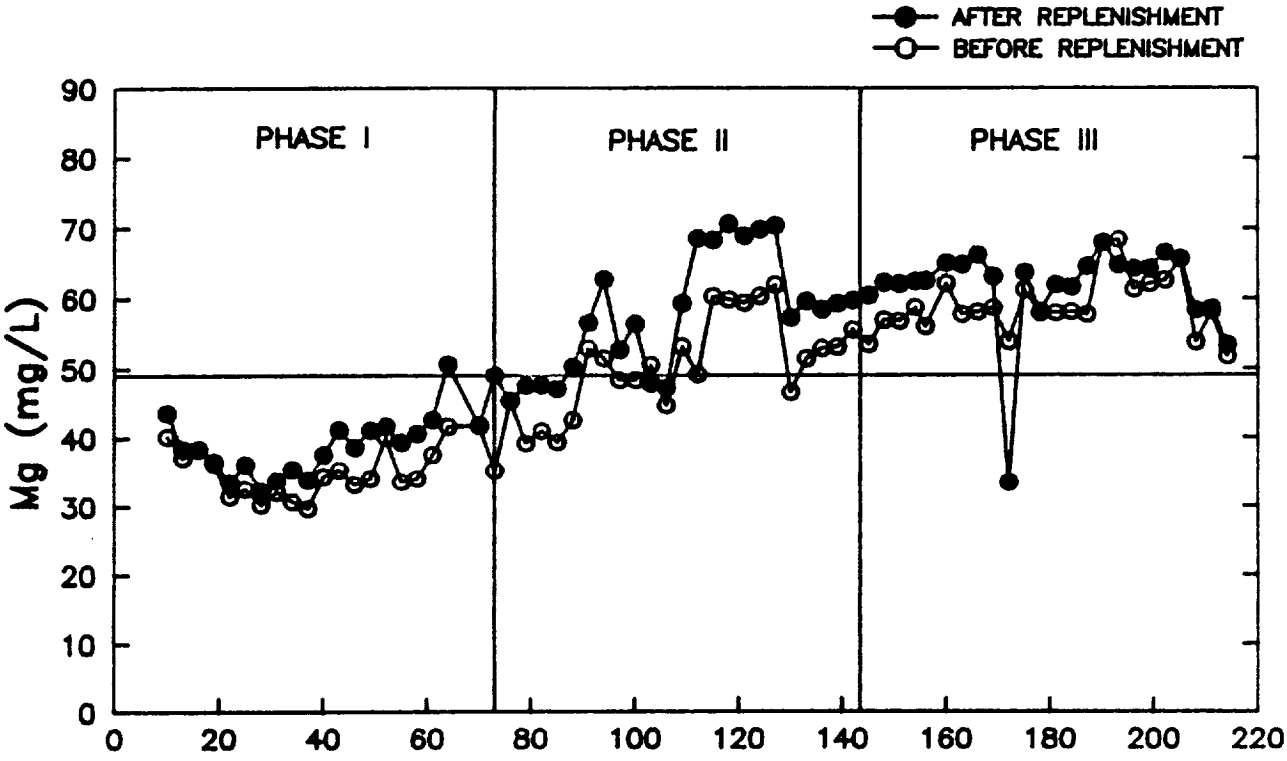
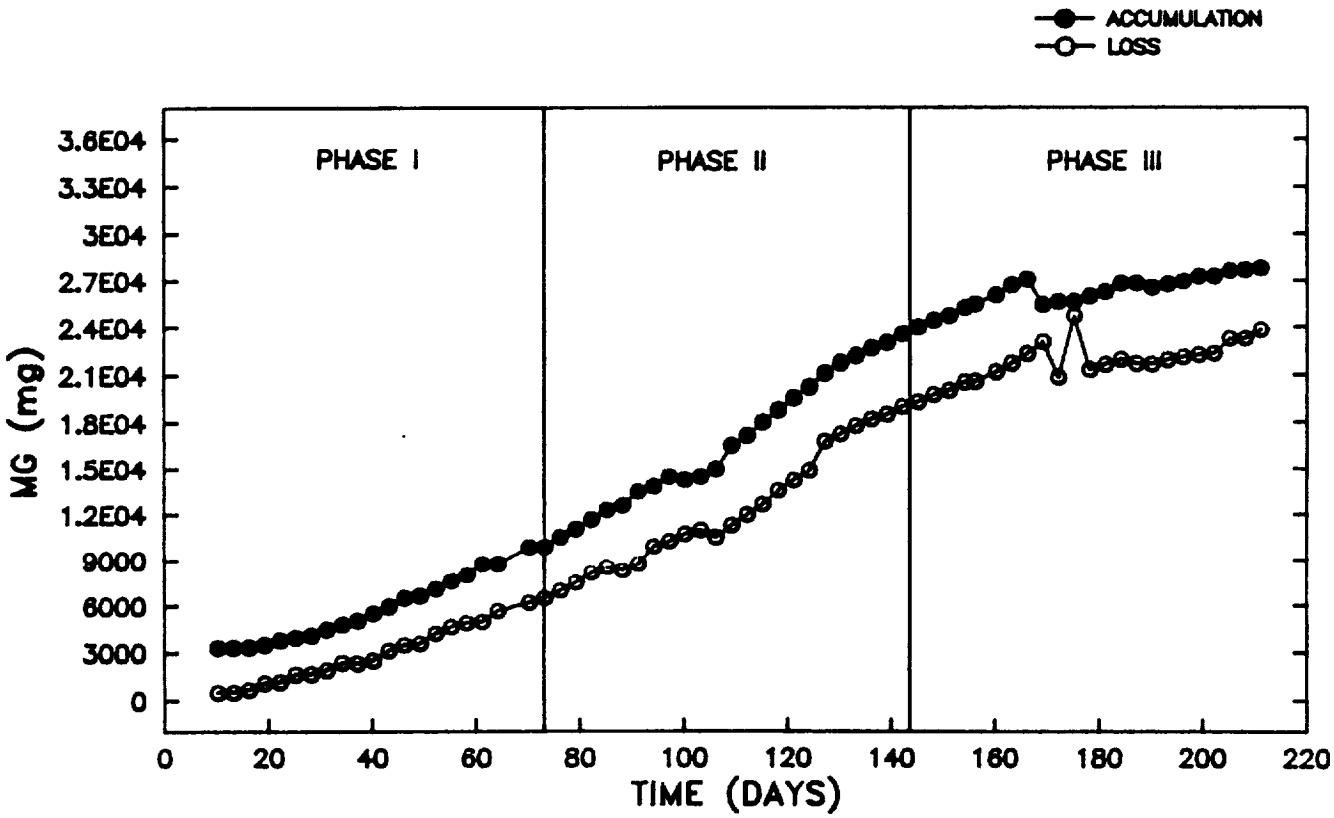


Fig 15. MAGNESIUM ACCUMULATIONS



Manganese

The Mn concentration in the nutrient solution should have remained near 0.4 mg L^{-1}. Figure 18 shows it starting out low and dropping to 0 mg L^{-1}. The Mn was brought up to 0.55 mg L^{-1} by replenishing often with $MnSO_4$ (Appendix). For the remainder of Phase II and the first half of Phase III, Mn concentrations (prior to replenishments) were below detection limits. As can be seen in Figure 19, the wheat used all of the Mn available in the solution. From a total of 0.91 g of Mn added to the solution, 0.90 g (99%) were removed (Table 5). The Mn concentration correlated with the conductivity (Table 4).

Copper

The baseline Cu concentration in the nurient solution should have been 0.02 mg L^{-1}. Cu levels started out three times higher than baseline and remained that way through most of Phase I (Fig. 20). After Day 60, Cu fluctuated near 0.02 mg L^{-1} during Phases II and III when the system's biomass remained the greatest (Fig. 21). During Phases II and III the solution lost the amounts of Cu that were added through replenishment. Approximately 0.013 g of Cu was added during the study while 0.012 g (94%) were removed (Table 5). The concentration of Cu in solution correlated with the conductivity (Table 4).

Zinc

The desired concentration of Zn in the nutrient solution was 0.05 mg L^{-1}. It began at 0.11 mg L^{-1} but declined through Phase I (Fig 22) and remained between 0.001 and 0.01 mg L^{-1} until Day 85. The Zn concentration reached baseline on Day 49 and exceeded it for about 20 days (Day 94-115), due to micronutrient replenishment (Appendix). For the remainder of the grow-out, Zn reached baseline after replenishment and rapidly dropped prior to each new replenishment. Concentrations were below the baseline during much of Phase III. According to Figure 23, the replenished Zn was completely removed from the nutrient solution. The data show that 0.065 g were added while 0.066 g (101%) were depleted (Table 5).

B. Microflora

Viable counts of airborne fungi and total microorganisms (predominantly bacteria) are shown in Fig. 24. The total microbial counts were always higher than the fungal counts, and underwent sporadic fluctuations. The range in total counts was similar to counts in EGC chambers during batch growth of wheat (unpublished data). The fungal counts appeared to increase between days 110 and ca. 145. The reason for this nearly four-fold rise or the subsequent decrease are unknown. In past EGC experiments, the growth chamber humidifier was identified as a source for total viable counts in the early stages of wheat seedling growth, before crop evapotranspiration lead to the humidity control system being dominated by dehumidification instead of humidification. This effect was not observed in this experiment, but the cause (presumably, a microbiologically clean water supply for the system humidifier) has little to do with whether the wheat was grown in batch or continuous culture.

Fig 16. IRON CONCENTRATIONS

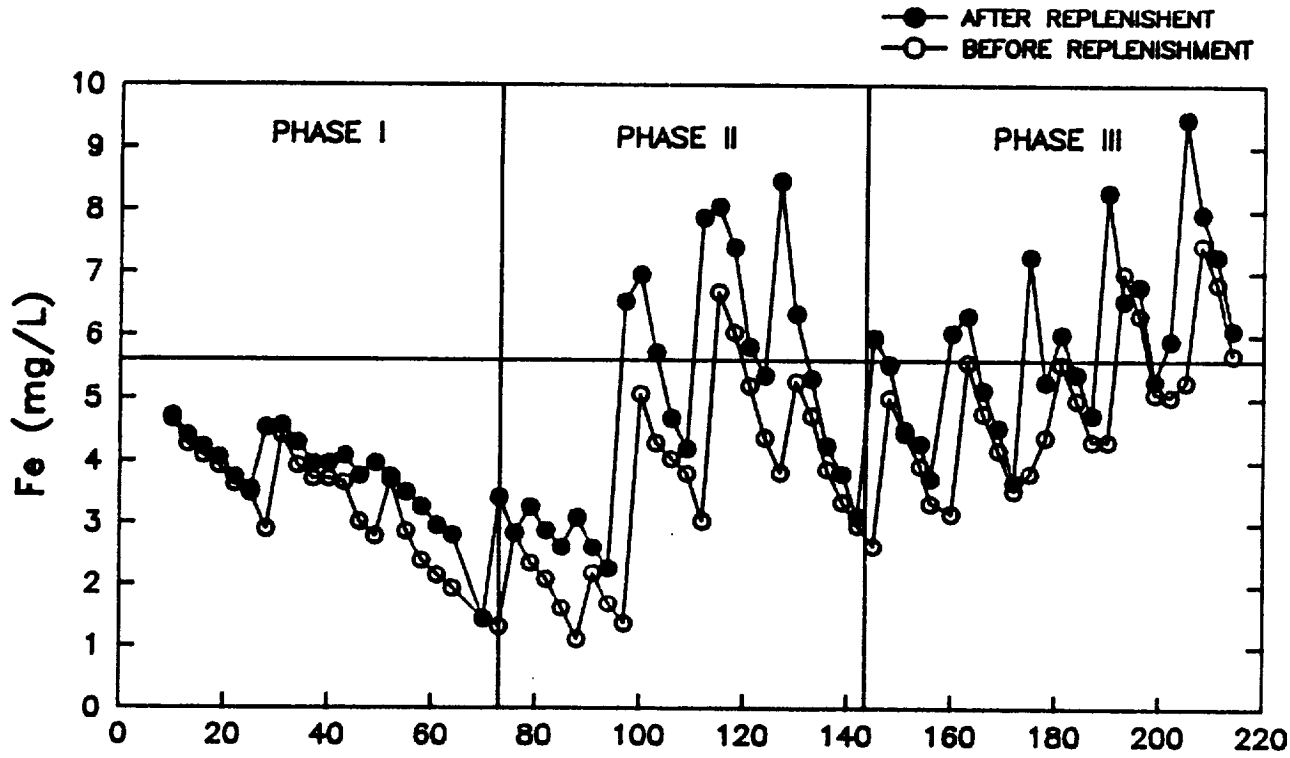


Fig 17. IRON ACCUMULATIONS

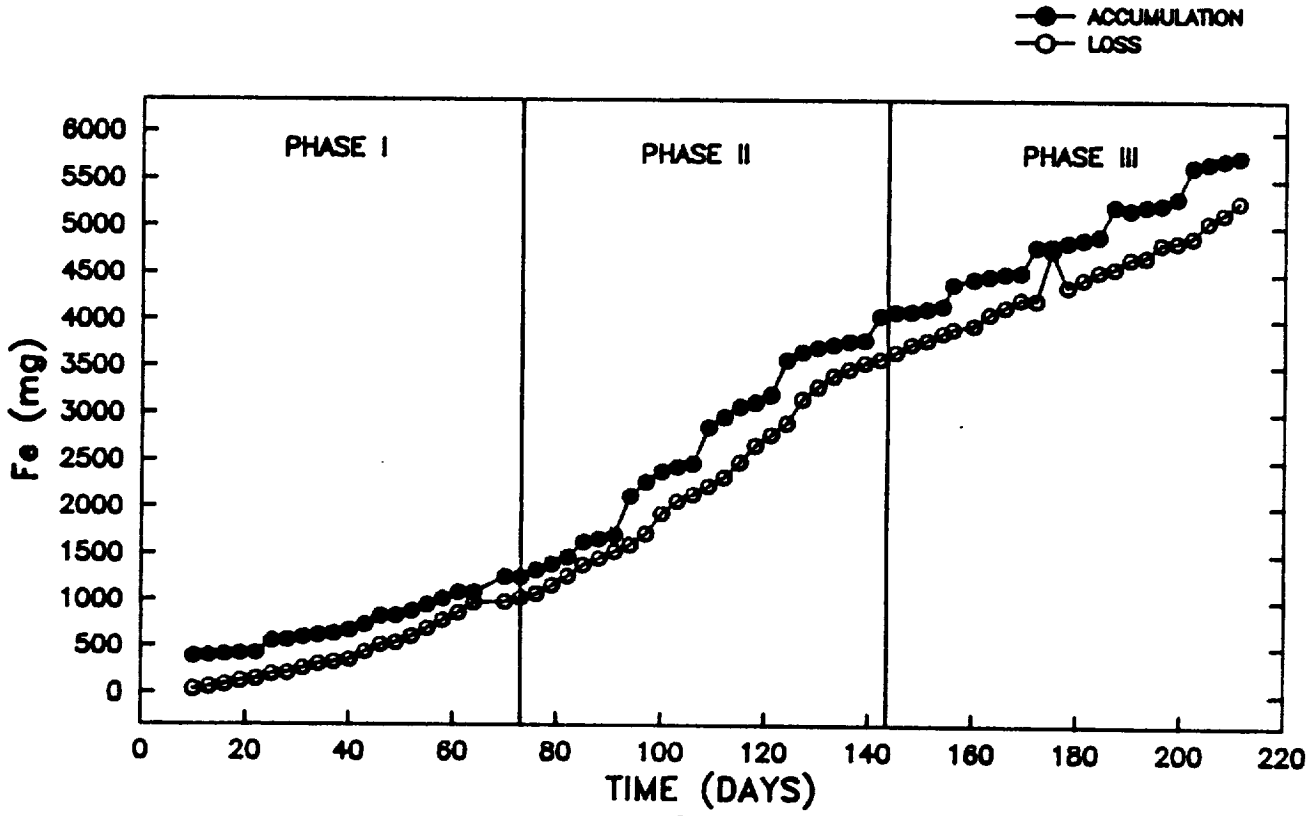


Fig 18. MANGANESE CONCENTRATIONS

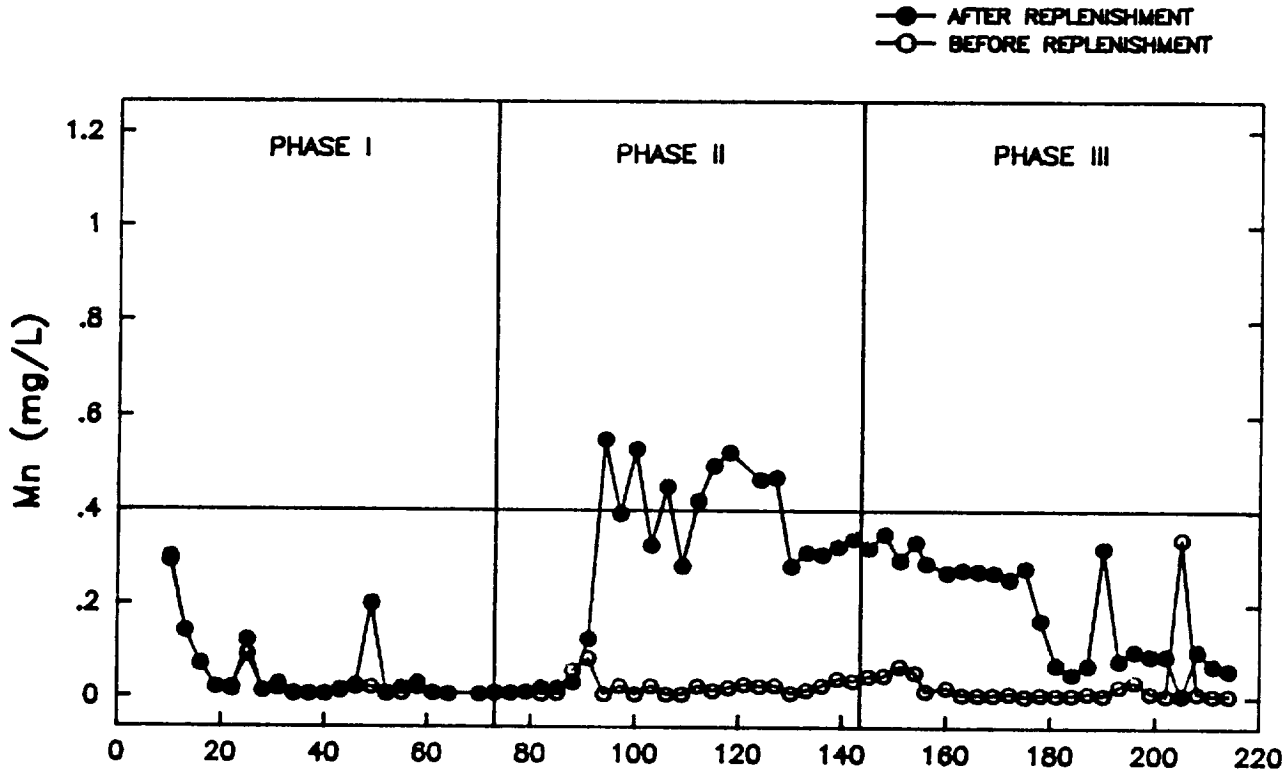


Fig 19. MANGANESE ACCUMULATIONS

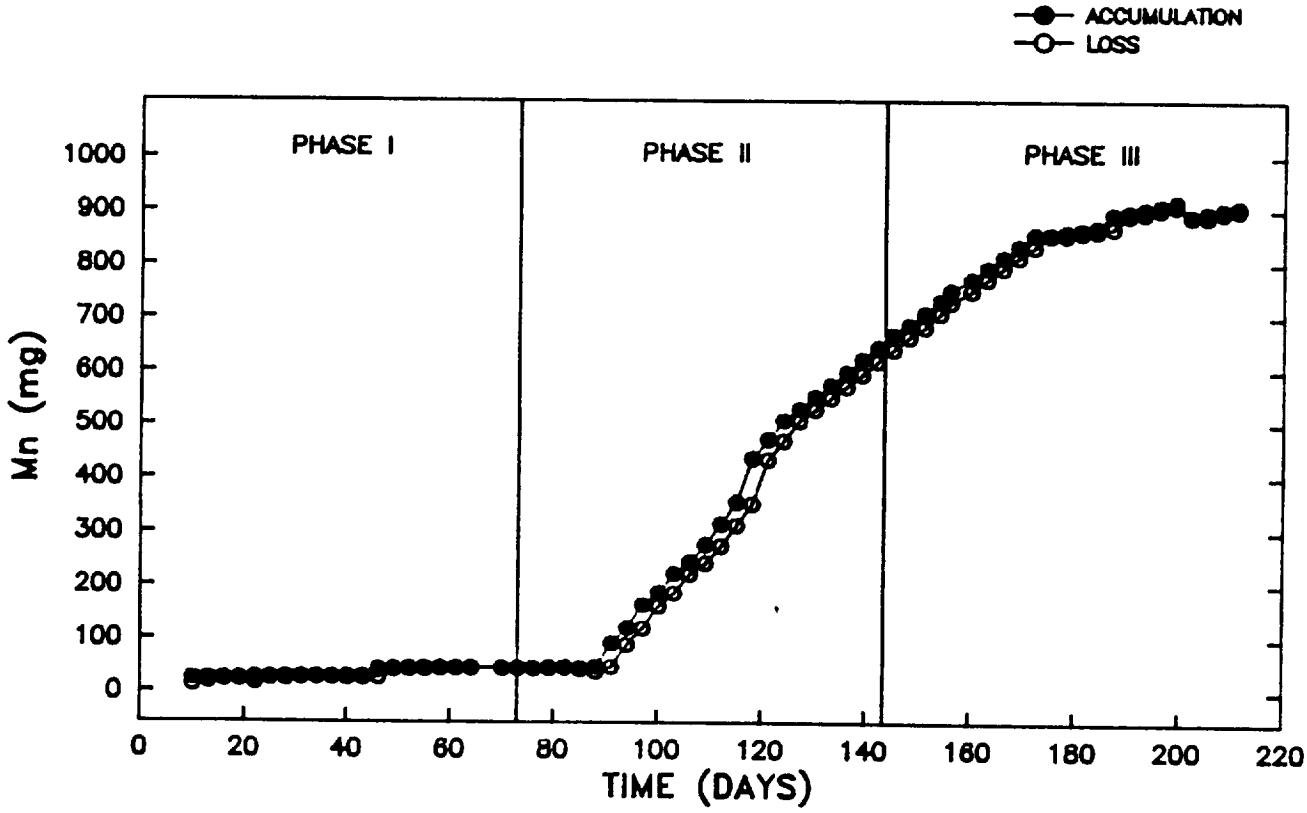


Fig 20. COPPER CONCENTRATIONS

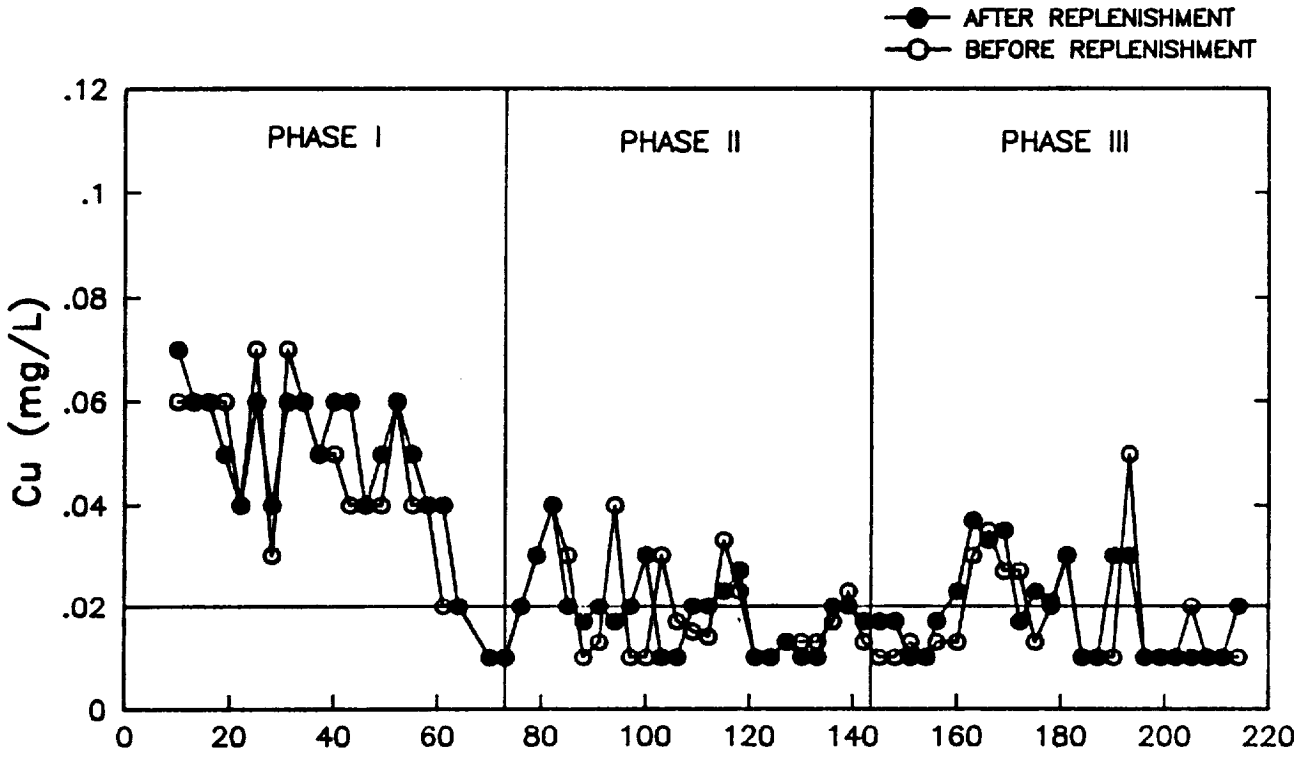


Fig 21. COPPER ACCUMULATIONS

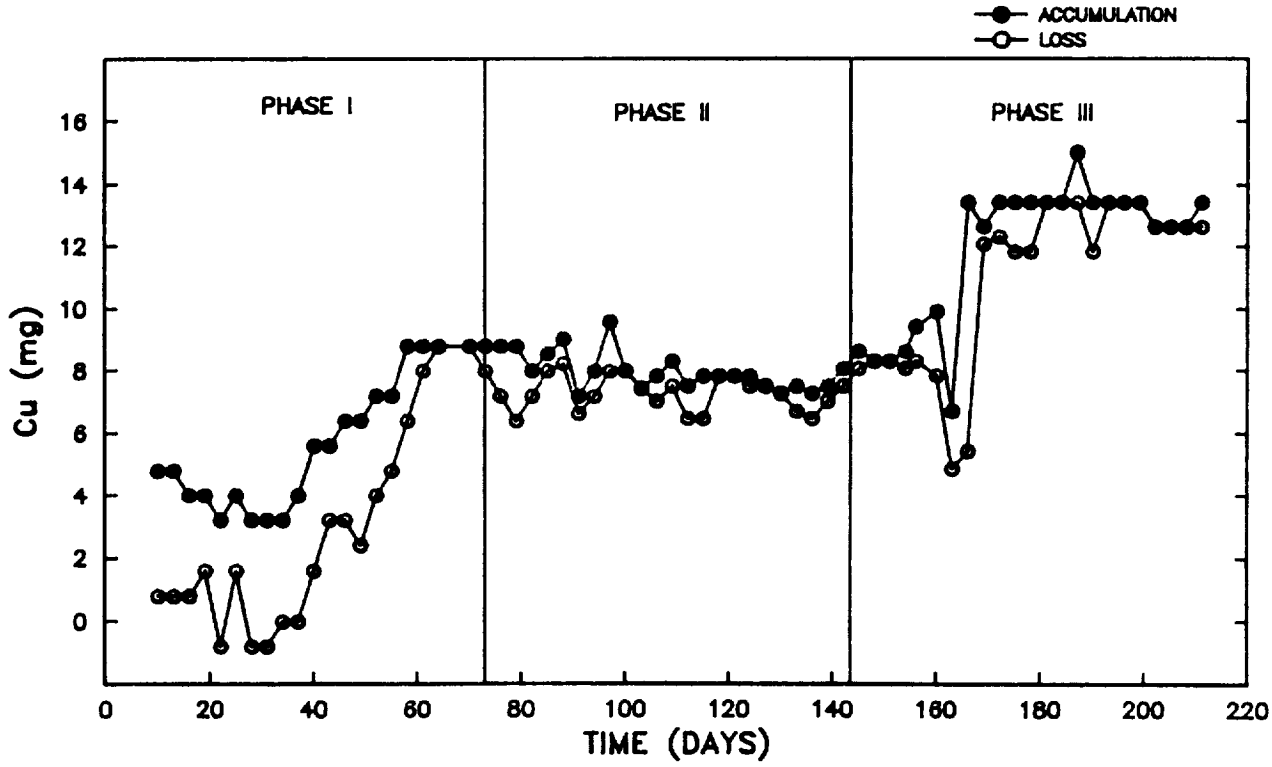


Fig 22. ZINC CONCENTRATIONS

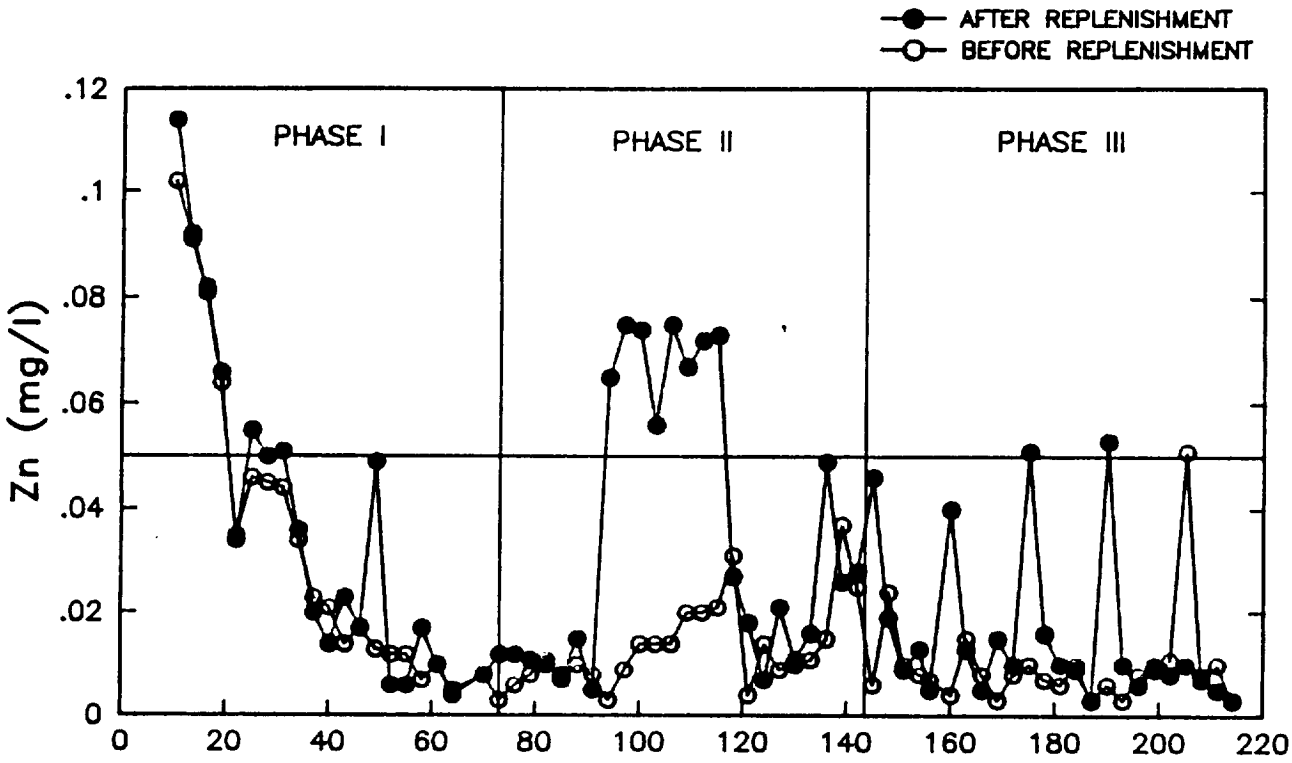


Fig 23. ZINC ACCUMULATIONS

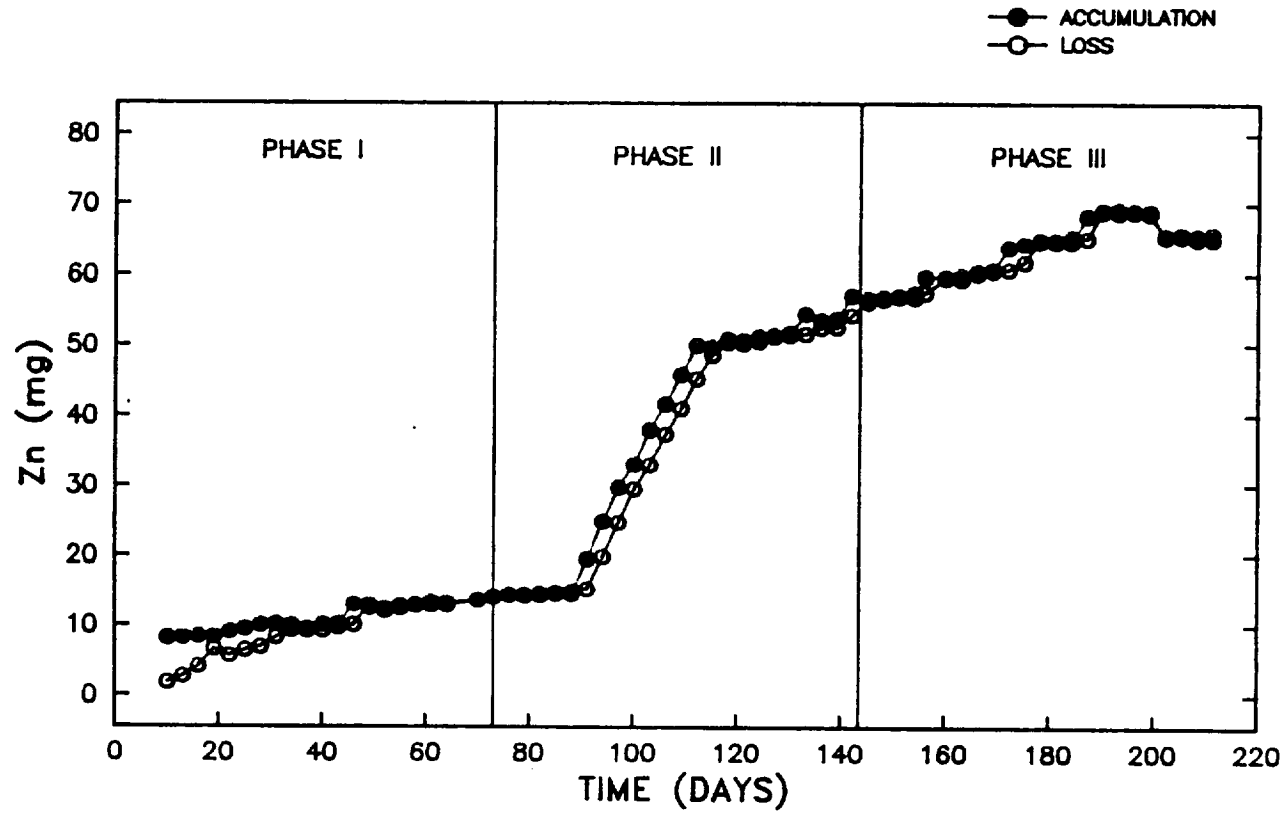
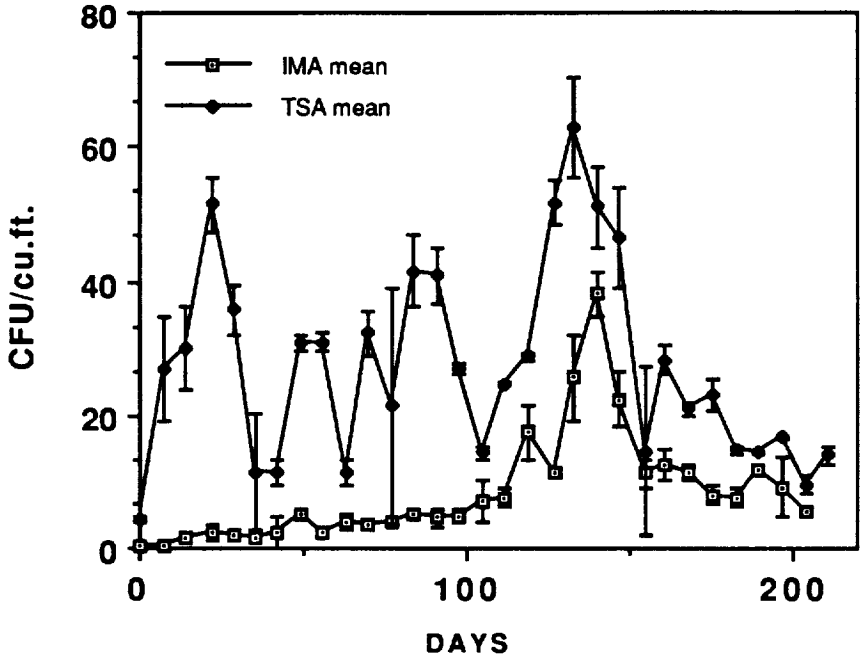


Figure 24. Viable counts of total microorganisms (TSA mean) and total fungi (IMA mean) in the atmosphere of the EGC during the continuous NFT hydroponic cultivation of wheat (Triticum aestivum cv Yecora rojo).



The viable counts of total microorganisms in the nutrient solution are presented in Fig 25. Both the low numbers (2×10^4 to 2×10^5 per mL) and the fluctuations in counts also were observed in other experiments when wheat was grown in batch culture. The enumeration of microorganisms during hydroponic growth of wheat in either batch or coninuous culture has not appeared in the literature, thus comparisons cannot be made. The low values for total counts (ca 10^5 per mL) indicates the relative unimportance of the solution microbial community in relation to key ecological functions. In general, at least 10^6 per mL would be needed for any individual microbial species to have a significant impact on functions such as the carbon and nitrogen cycles in solution. The relative constancy of microbial numbers over such a long time is surprising, and suggests that the sources--i.e., root sloughing hardware biofilm sloughing, filter sloughing, and growth--and sinks--i.e., removal by root mats and filters, attachment to inert surfaces, and death--for the solution microbial community are in equilibrium. A complication to this interpretation is that root mats, containing roughly 2×10^{10} per mL bacteria, were removed from the system at each tray harvest, about every nine days.

Figure 25. Viable counts (nutrient agar) of total microorganisms in the NFT nutrient solution during the continuous hydroponic cultivation of wheat (Triticum aestivum cv Yecora rojo).

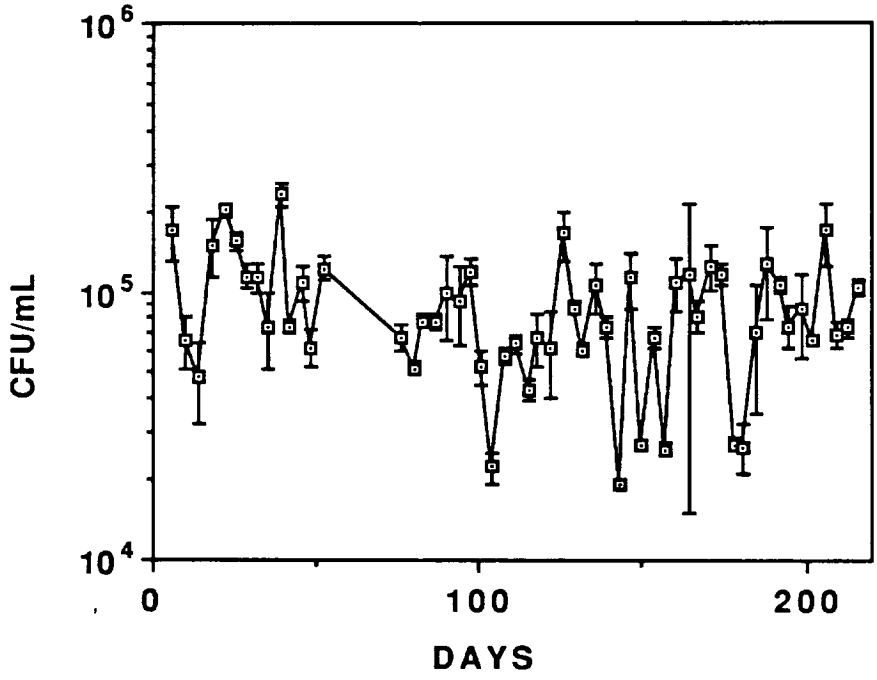
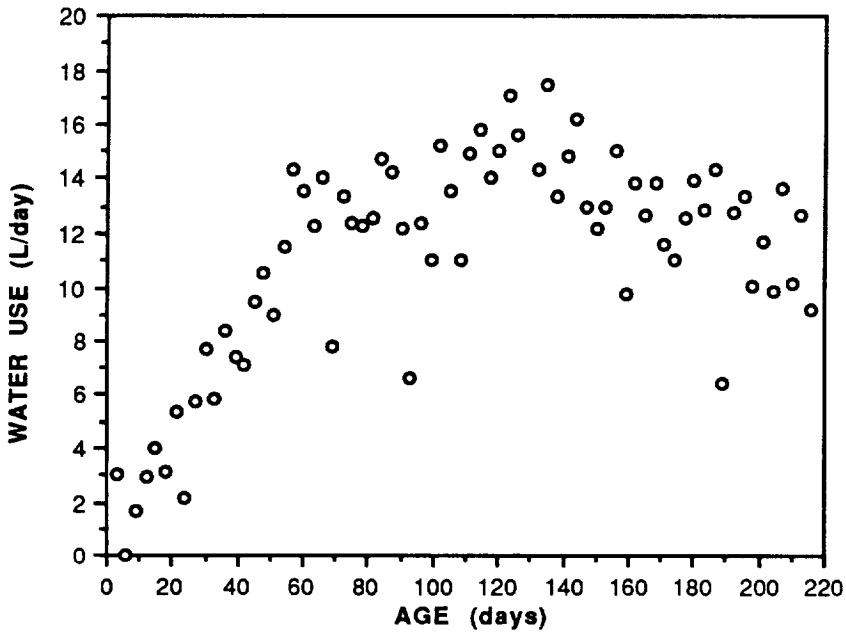


Fig 26. DAILY WATER USAGE BY THE SYSTEM



Mass Balance Budget

Table 5 summarizes quantities of nutrient elements added to and removed from the solution, and those found in the plant tissue. Nitrogen is not included because it was analyzed for as NO_3-N in the solution and TKN in the plant tissue. High values for Cu and Zn in the plant tissue are shown. Other discrepancies concerning the quantities of nutrients found in plant tissue and amounts removed from solution are within the range of experimental and analytical error (approximately 15%).

C. Harvests

Harvest data are summarized in Tables 6 and 7. The edible biomass index (EBI), was calculated as seed dry weight/total biomass dry weight. The volume calculations were based on a tray area of 0.24 m^2 and a mean plant height of 0.514 m. The trays were variable in number of plants, yield and the EBI. Average yields for trays 1 through 16 (throughout the study) were 520 g m^{-2} of seed (dry matter), 1546 g m^{-2} total plant dry matter and an edible index of 32.4% (Table 6 and 7). Heights averaged 514 mm and plants averaged 1.6 heads per plant with 14 spiklets and 9 seeds per head (Table 6). Non-primary heads were included in the spikelet and seed values. Correlation analyses performed on the harvest data are summarized in Table 8. There were positive correlations in all categories except mass per seed versus total heads and the ratio of non-primary/primary heads versus mass per seed and total seed number. There were also negative correlations between percent root dry matter (DM) with various above-ground parameters (Table 8). The last day harvest data are presented in Tables 9 and 10. No seed yield data were collected on the last day harvest since the wheat heads were not mature. Data collected from immature plants showed less

percent root (DM) once tillers and heads began appearing (Table 9). Total dry weight increased substantially during this time (Table 10). Growth curves were developed from the dry weight, plant height and leaf area data that were collected from the harvest of seven trays of wheat at the conclusion of the experiment (Figs 27-31). Each tray was a different age. Figure 27 shows the relationship between plant age and leaf area ratio (LAR). The LAR was calculated with the following equation: LA/total DM , where LA = leaf area. A polynomial equation was used to describe the relationship between age and leaf area (Fig 28). Linear regression equations were developed for the growth curves using dry weight (Fig 29) and plant height (Fig 30) data. These curves were graphed with a 95% confidence interval. The photosynthetic energy conversion efficiency is depicted graphically over time (Fig 31) from the following equation: energy in the total biomass (KJ m^{-2} d^{-1}) divided by energy in the PPF (KJ m^{-2} d^{-1}).

D Tissue Analyses

The results from the nutritional proximate and mineral analyses performed on the mature wheat tissue (trays 1-16) are given in Table 11. Samples from several trays were combined for analyses. Proximate analyses were also performed on immature wheat plants (Table 12). Plants in trays 17 through 21 ranged in age from 37 to 63 days at time of harvest, while plants in trays 22 through 24 were between 9 and 27 days old. Percent protein was calculated as N x 6.25. The highest protein values were in the roots of all ages and in the straw of plants younger than 28 days. The highest carbohydrate levels were obtained from the seeds of mature plants, 63.1% by weight (Table 11 and 12). Fat levels were generally low in all tissues (less than 5%), while crude fiber was highest in the straw component.

Table 6. Wheat Harvest Data Summary (per tray)

Tray (#)	Age (days)	Height (mm)	Total Plants	Total Heads	Total Spikelets	Total Seeds	Total Seed Mass (g)	Total Biomass (g)
1*	75	521	226	402	5591	3819	138.68	414
2*	73	521	260	394	5970	5486	192.41	467
3	72	559	300	436	6906	6731	236.59	623
4*^	71	560	258	359	4452	3044	103.48	298
5^	71	508	290	403	5538	4524	144.49	442
6^	72	406	296	615	7868	2782	49.55	289
7^	72	451	299	561	6797	1226	35.86	451
8*^	72	508	278	480	5494	4114	136.09	344
9	73	559	216	372	5329	4632	111.16	330
10	72	559	261	397	6055	5481	169.81	419
11	72	508	281	391	6455	5030	146.65	380
12	71	533	299	383	6193	3827	121.17	366
13	72	483	230	488	4907	3151	94.82	260
14	72	510	265	358	5605	2968	99.20	421
15	72	510	287	400	5871	3530	122.80	354
16	73	530	282	340	3398	2538	78.46	298
average	72	514	271	424	5777	3930	123.83	371
STD	1	41	27	76	1033	1362	50.46	96

*Water stress
^Micronutrient stress (particularly Mn)

Table 7. Wheat Harvest Data Summary Continued

Tray (#)	Nonprimary + Primary Heads * (#)	Seeds per Plant (g)	Mass per Seed (g)	Seed Mass per Plant (g)	Seed Mass per m^2 (g)	Seed Mass per m^3 (g)	Root Total (% dwt)	EBI (%)^
1	0.78	16.9	0.036	0.61	583	1107	12	34
2	0.52	21.1	0.035	0.74	808	1535	8	41
3	0.45	22.6	0.035	0.79	994	1888	6	38
4	0.39	11.8	0.034	0.40	435	826	9	35
5	0.39	15.6	0.032	0.50	607	1153	9	33
6	1.08	9.4	0.018	0.17	208	395	10	17
7	0.88	4.1	0.029	0.12	151	286	11	16
8	0.73	14.8	0.033	0.49	572	1086	8	40
9	0.72	14.2	0.024	0.34	467	887	8	34
10	0.52	21.0	0.031	0.65	713	1355	7	41
11	0.39	17.9	0.029	0.52	616	1170	6	37
12	0.28	12.8	0.032	0.41	509	967	8	33
13	1.12	13.7	0.030	0.41	398	757	9	36
14	0.35	11.2	0.033	0.37	417	792	11	23
15	0.39	12.3	0.035	0.43	516	980	9	35
16	0.21	9.0	0.031	0.28	330	626	8	26
average	0.58	14.3	0.031	0.45	532	988	9	32

*Total number of nonprimary heads ÷ by the total number of primary heads
^Edible biomass index (seed dry matter ÷ by the total dry matter)

Table 8. Harvest Correlations of Wheat Trays at Maturity

VARIABLE PAIRS		Df	Correlation Coefficient (r)	P-value
mass/seed vs				
	head #	14	-0.57	0.02
	plant height	14	0.55	0.03
plant height vs				
	seed #	14	0.58	0.02
	seed mass	14	0.63	0.01
	seed #/plt	14	0.63	0.01
	seed mass/plt	14	0.60	0.01
	EBI	14	0.69	0.00
primary head seed # vs				
	height	14	0.79	0.00
	total biomass	14	0.78	0.00
	seed mass	14	0.90	0.00
	1o spikelet #	14	0.20	0.46
EBI vs				
	total biomass/m2	14	0.79	0.00
% root vs				
	seed #	14	-0.70	0.01
	seed #/plt	14	-0.58	0.02
	seed mass	14	-0.60	0.01
	total biomass/m2	14	-0.53	0.03

Table 9. Growth Data From Final Harvest (Multiple Ages)

Tray (#)	Age (days)	Plant (#)	Height (mm)	Tiller (#)	Leaf area (cm^2)	Root dwt (g)	% root*
17	63	273	494	36	0.37	19.78	6.8
19	54	297	523	58	0.46	22.93	7.3
20	46	237	512	54	0.52	21.33	8.9
21	37	256	473	53	0.75	21.86	8.7
22	27	291	317	--	0.45	13.63	16.0
23	18	294	259	--	0.39	12.98	23.0
24	9	306	154	--	0.08	4.82	22.0

*%root = $\frac{\text{root (dw)}}{\text{total (dw)}}$

Table 10. Total Dry Matter From Final Harvest (Multiple Ages)

Tray (#)	Age (days)	DW per tray (g)	DW per plant (g)	DW per m^2 (g)	DW per m^3 (g)
17	63	288	1.06	1211	3149
19	54	315	1.06	1325	3444
20	46	240	1.01	1008	2621
21	37	250	0.98	1052	2735
22	27	84	0.29	357	927
23	18	56	0.19	235	609
24	9	21	0.07	86	224

Fig 27. LEAF AREA RATIO (LAR) OVER TIME

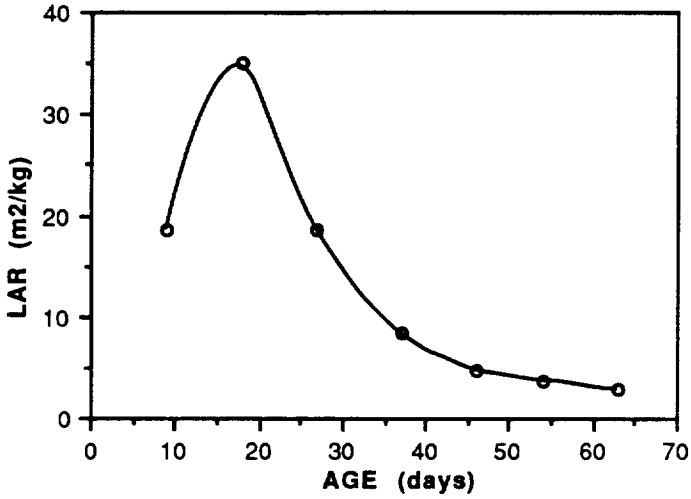


Fig 28. SINGLE PLANT LEAF AREA OVER TIME

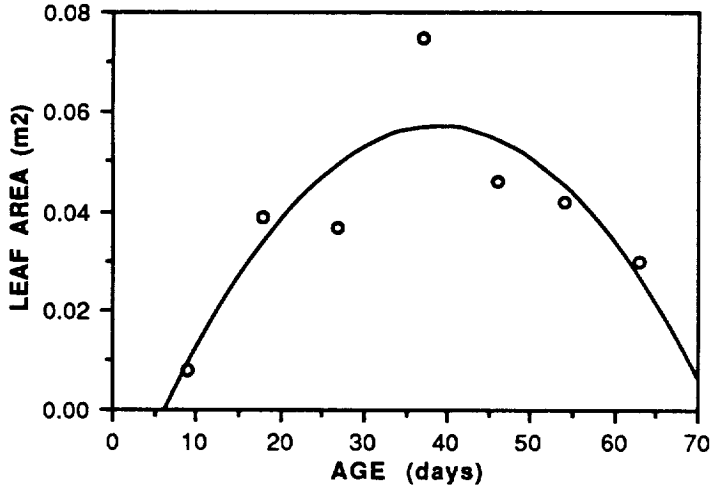


Fig 29. DRY WEIGHT PER PLANT OVER TIME

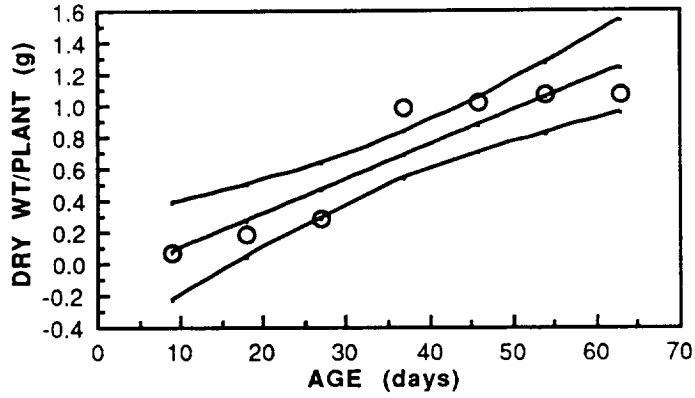


Fig 30. RELATIONSHIP BETWEEN PLANT HEIGHT AND DRY WEIGHT

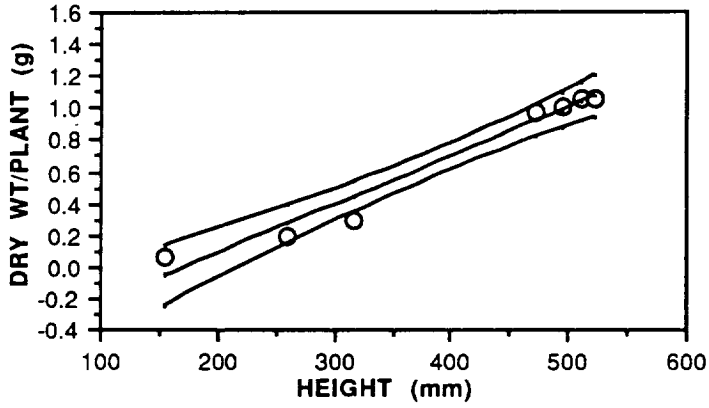


Fig 31. PHOTOSYNTHETIC ENERGY CONVERSION EFFICIENCY OVER TIME

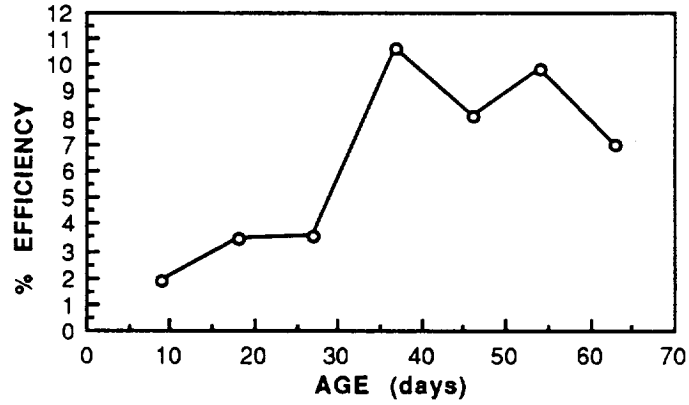


Table 11. Tissue Proximate Analyses of Mature Wheat Plants

Constituent ($\mu g\ g^{-1}$)	Seeds (n = 5)	Straw (n = 4)	Roots (n = 1)
P	5190	10720	9050
K	4710	50460	43570
Ca	460	14400	5830
Mg	1490	3680	740
S	1590	6340	3590
Fe	51	213	5875
Mn	65	776**	143
Cu	0.54	47	58
Zn	27	27	26
Mo	0.35	0.65	2.69
protein (%)*	18.3	15.4	27.4
fat (%)	1.2	1.6	1.3
ash (%)	2.2	15.7	11.8
crude fiber (%)	1.9	22.1	13.0
carbohydrate (%)	63.1	34.0	30.1
calories (cal/100g)	336	213	242

*N x 6.25

**Sample from trays 8 and 9 contained 286 $\mu g\ g^{-1}$ Mn, without those trays the mean = 8.14 $\mu g\ g^{-1}$.

Table 12. Tissue Proximate Analyses of Immature Wheat Plants

	Tissue Age (37-63 days)*			Tissue Age (9-27 days)	
Constituent ($\mu g\ g^{-1}$)	Heads (n = 3)	Straw (n = 4)	Roots (n = 1)	Straw (n = 1)	Roots (n = 1)
P	6070	11710	10730	14120	7430
K	9470	51890	52970	52400	52130
Ca	1680	11830	6610	6940	6040
Mg	2013	3842	1324	2250	2178
S	1604	4338	3367	2740	3594
Fe	65	287	8517	147	1624
Mn	117	178	143	108	58
Cu	8	12	28	10	13
Zn	27	16	20	16	16
Mo	0.55	0.73	0.53	0.77	0.89
protein (%)	13.9	18.8	25.1	26.5	20.5
fat (%)	3.0	4.9	2.7	6.9	3.4
ash (%)	3.7	15.7	15.7	14.4	14.2
crude fiber (%)	16.4	21.4	18.8	17.5	24.8
carbohydrate (%)	51.4	28.0	28.0	22.7	28.8
calories (cal/100g)	289	231	237	259	228

*The 46 Day tray (#18) was not included in the analyses._

IV. DISCUSSION

A. Nutrients

The pH, which was recorded daily from the pH controller, had consistantly lower readings than the values measured in samples delivered to the laboratory for nutrient analyses (Fig 5). Wheat grown in past studies at KSC has not shown a sensitivity to pH in the range of 5.0-7.0, so variation was not a serious concern. There are many causes for variations in pH readings (e.g. faulty equipment, dirty probes, sample storage time).

There were high concentrations of PO_4-P, K, Mn, Cu and Mo in the wheat straw. The nutrient solution's PO_4-P concentration increased to 70% more than the desired concentration during the study (Fig 8). Phosphorous was being added to the solution as KH_2PO_4. Decreasing the KH_2PO_4 replenishment would have reduced the K concentration, unless another K source was substituted, such as KSO_4. It was decided to lower the KH_2PO_4 replenishment by 0.5 mmol L^{-1} water evapotranspirated on Day 166, without supplementing with another K source (Appendix). Even though the K concentration in the solution was often at or below the desired concentration (Fig. 10), the straw contained quantities five times greater than concentrations reported for wheat by Duke and Atchley (1986). Maintenance of the K concentration in the nutrient solution at 6 mmol L^{-1} water evapotranspirated was apparently too high, as measured by the amount accumulated in the straw.

The plants appeared to be deficient in Fe and it was hypothesized that wheat may require large nutrient solution concentrations (100-200 μm) to prevent deficiency symptoms. Thus the concentration of Fe in the solution was allowed to increase up to 180 μM without concern. The wheat straw had concentrations of Fe in excess (Tables 11 and 12) when compared to Duke and Atchley (1986). Even so, Jones (1983) states that it is common to measure tissue Fe in excess of hundreds of parts per million. 'Yecora rojo' wheat appears to be a cultivar which can tolerate a large tissue concentration of Fe.

Manganese in the solution was often below the desired concentration, but analyses of the straw tissue revealed high concentrations (Tables 11 and 12). Williams and Vlamis (1957) showed that barley produced Mn toxicity symptoms when grown in a full strength Hoagland's solution (9 μM). When comparing different concentrations of Hoagland's solution and keeping the Mn concentration constant, the severity of the symptoms increased in relation to an increase of the Hoagland's solution concentration. The concentration of Mn in their nutrient solution, which is similar to our concentration, produced moderate to heavy rust-colored spotting in the barley leaves. This is similar to what was seen on the wheat leaves. Williams and Vlamis (1957) suggest a nutrient solution concentration of 0.46 μM as good for barley growth, which is 94% less than what was used in this wheat study.

Boron was not measured in the solution nor in the wheat leaves for this study, but Williams and Vlamis (1957) found problems with B toxicity using the Hoagland's concentration. It was suspected that B may have been in excess along with Mn. They suggested using boron nutrient solution concentrations of 2.26 uM for barley, 97% less

than what was used in the wheat study. In their barley, B deficiency symptoms never developed, even when it was excluded from the solution. They hypothesized that contamination from unknown sources prevented deficiencies. Although Mo content was high in the straw and roots of both mature and immature plants (Tables 11 and 12), it was normal in the seed. The same was true of Cu.

Besides having concern for the nutritional health of the plant, insight into the accumulation of metals in nonedible portions of the plant is very important for a CELSS. These portions normally considered inedible (e.g. leaves, stems and roots) may be processed for consumption by people or other animal systems in CELSS. Micronutrient contamination is a common occurrence in hydroponic systems, especially the metals Cu and Zn. Based on nutrient depletion calculations from our system, 96% of the Cu and 73% of the Zn from the total plant tissue may have come from an outside source (Table 5). The most probable source of the contaminants were brass lined humidifiers, used to humidify the growth chamber air. These humidifiers are commonly used in research facilities. The humidifiers used in this study have since been replaced with plastic fixtures but these still contain some brass components. Tissue analyses indicated that the Zn was equally distributed within the seed, straw and root tissues, whereas the Cu contaminant may have adsorbed to the plant surfaces, rather than enter the tissues. The most obvious example of adsorption to plant tissue was with Fe, which adsorbed readily to the roots (Tables 11 and 12). This was easily seen because the chelator Fe-EDDHA used in the study is dark red, giving the roots a red to red-brown appearance. Many investigators maintain the nutrient concentrations in hydroponic solutions by adjusting the electrical conductivity. Winsor et al. (1979) and Steiner (1980) suggest this method for recirculating systems, while Neilsen (1984) recommends solution maintenance via the conductivity/pH interaction. In this study we monitored both pH and conductivity but relied heavily on the chemical analyses for adjusting the replenishment of the solution (Appendix). Ben-Yaakov and Ben-Asher (1983) found good correlations between the conductivity reading and the concentrations of $K+$ and NO_3- in the solution and were able to determine the uptake rates of those ions by monitoring the conductivity. Correlation of conductivity with ($N-NO_3$) was good in our study ($r = 0.89$) but there was a poor correlation with the K concentration ($r = 0.43$). The high correlations between the divalent cations Ca^{++} and Mg^{++} with conductivity were expected but the correlations with the micronutrients were probably coincidental (Table 4).

The concentrations of nutrients were determined by measuring ppm in the solution samples. The accumulation curves (Figs 7, 9, 11, 13, 15, 17, 19, 21 and 23) were based on the assumption that 80 L of solution was in the reservoir at the time of sampling. This assumption did not take into account water retained by the roots in each tray. As the plants grew and the root mass expanded, more water was retained. For instance, by Day 80 there may have been 80 L of solution in the reservoir but another 20 L in the trays (100 L total). This discrepancy may explain some of the variations between what was assumed to be added to the solution and what was measured (Table 13).

Table 13. Comparison of Theoretical and Actual Nutrient Additions

Nutrient	Theoretical* Total (g)	Measured** Total (g)
NO_3-N	158.82	129.11
P	91.01	75.96
K	295.94	285.61
Ca	120.85	105.99
Mg	35.68	27.81

*Values were computed from the amounts of stock solutions which were added to the reservoir.

** Values were computed from the chemistry analyses which were performed on the solution in the reservoir, following replenishments.

The solution analyses were performed by a different laboratory than were the tissue analyses. In a study by Sterrett et al. (1987) using six reference plant species for tissue sampling of nutrients, 22 different commercial and university laboratories were compared. Agreement was good for N, P and Mg, where 70-80% of the laboratories had values within ± 5% of the mean and Mn and Zn were within ±10% of the mean. However, K, S, Fe, Cu and B were much lower, 30-48% of the laboratories were within either 5 or 10% of the mean, depending on the element. In our study, the variations between the tissue concentrations and estimated removal from solution were much lower for P and Mg than for the other nutrients (Table 5).

B. Harvest

The number of seed per primary head correlated closely with the total seed mass ($r = 0.90$). This relationship could be used for estimating yields on a per tray basis. However, the number of seed per primary head did not correlate well with spikelet number ($r=0.20$, Table 10). If there was a high correlation, then it could be hypothesized that the number of spikelets per head was a limiting factor for our wheat yields. Since the correlation is low, something other than spikelet number affected the number of seed produced per primary head (i.e. fertilization).

The number of seeds per primary head correlated with plant height and total biomass (Table 8). Peterson (1965) mentions that the same wheat variety can vary from 30-90 cm in height, depending upon whether water stress was a factor in its growth. Meyer

and Green (1981) documented that water stress reduced stem and leaf extension in wheat and soybeans. White (1987) found that spring wheat 'Olaf", produced less straw and grain when roots were constricted or were given a low soil water potential (0.6 MPa). In our study, there were four trays which had particularly low yields (4, 6, 7 and 16). Tray 4 had severe water stress inadvertantly placed on it at day 12 (Tables 6 and 7). Other factors probably contributed to the stress of the plants in this study. Trays 6 and 7 had coinciding leaks in their tray bottoms (30-day-old and 20-day-old, respectively). The leaks were mended with PVC cement, which may have been toxic enough to reduce the wheat yields.

The low yield of tray 16 may have been due to nutritional imbalances. Beginning with Day 118, 8 umol of $MnSO_4$ was added to the reservoir every three days. The decision to add Mn was based on the rapid depletion of Mn from the nutrient solution and the appearance of leaf symptoms similar to Mn defficiency (Appendix). As mentioned earlier, Williams and Vlamis (1957), concluded that both Mn and B produce leaf spotting symptoms and reduce yields of barley when supplied at the concentrations of a full strength Hoagland's solution. They found very little spotting when these micronutrients were maintained at 1/20 of the Hoagland's concentration. The wheat in our study had spotting of the leaves which appeared similar to Mn toxicity. The maintained concentration of Mn was usually lower than Hoagland's solution (Fig 18). Referring to the harvest results (Tables 6 and 7), it appears that the last few trays of the study had lower yields than some of the earlier harvested trays. Increasing the Mn addition may have had an influence on the yields. Since shoot tips must be analyzed to accurately characterize Mn in the plant, and tissue analyses were not done on shoot tips, it can not be concluded that Mn toxicity actually occurred in this study. Williams and Vlamis (1957) also deduced that symptoms of these toxicities were reduced when the plants were given a photoperiod, i.e. a dark cycle. The wheat in our study were grown under continuous light, so symptoms may have been reduced if a photoperiod was used. Continuous light in combination with warm temperatures (27°C) hastens the life cycle of wheat, but also reduces yields (Bugbee and Salisbury, 1987a). Thorne and Wood (1987) found warmer temperatures decreased grain number and concluded that the cause was fertilization of fewer florets. These factors may have decreased our overall yields during this study.

The PPF exerts a direct influence on wheat growth and yield. Thorne and Wood (1987) found a doubling of radiation increased total dry weight by 80%. Polonskii and Lisovskii (1980) obtained a linear type of relationship between radiation and biomass production for wheat. In addition to high radiation levels, the plant density in their study was quite high (2000 plants m^{-2}), to maximize space by the vertically positioned leaves which intercept light. Polonskii and Lisovskii (1980) had an approximate crop growth rate (CGR) of 123 g m^{-2} day^{-1} at a PPF of 1200 μmol m^{-2} sec^{-1}. Bugbee and Salisbury (1987b) in an similar studies with wheat at high irradiance levels, obtained yields of approximately 95 g m^{-2} day^{-1} at the same PPF. The CGR in this study averaged 21 g m^{-2} day^{-1} which is similar to results obtained by Bugbee and Salisbury (1987a) of 23 g m^{-2} day^{-1} at equivalent PPF. Our energy conversion efficiency averaged 7.3%, which is lower than Bugbee and Salisbury's value of approximately 10%. However, their estimated efficiency was based on an extrapolated portion of their efficiency curve which did not contain data. Using a higher plant density in our study (2000 versus 1000 plants m^{-2}) could have increased both CGR and the energy conversion efficiency, since these values are calculated on an area basis. However, it

is likely that the greatest influence on total biomass production, in this study, was the relatively low PPF in the growth chamber, where this in combination with a relatively warm temperature (23°C) produced suboptimal seed yields.

Appendix. Nutrient Solution Maintenance Revisions

	Days into Experiment (mmol/L water)							
Element	**31**	**49**	**64**	**69**	**82**	**91**	**94**	**97**
N	7.5	8.0	8.0	3.0	5.0	2.0	4.0	4.0
P	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5
K	4.0	4.5	10.5	4.5	4.5	3.5	3.5	3.5
Ca	2.5	2.5	2.5	0.0	1.0	0.0	1.0	1.0
Mg	0.68	0.68	0.68	0.68	0.68	0.68	0.68	0.68
S	0.68	0.68	3.68	0.68	0.68	0.68	0.68	0.68
Fe	43.75	50.00**^	43.75	50.00**^	43.75	43.75	43.75	50.00**^
Si	150.00	150.00	150.00	150.00	150.00	150.00	150.00	150.00
B	-----	80.00*^	-----	-----	-----	-----	80.00^	80.00*^
Mn	-----	8.00*^	-----	-----	-----	-----	8.00^	8.00^
Zn	-----	0.80*^	-----	-----	-----	-----	0.80^	-----
Cu	-----	0.30*^	-----	-----	-----	-----	0.30^	-----
Mo	-----	0.10*^	-----	-----	-----	-----	0.10^	0.10*^

*Concentrations were added only on the specified days.
**Fe was added as chelated Fe-EDDHA and Fe-HEDTA instead of $FeCl_3$. $FeCl_3$ was used on subsequent replenishments.
^Concentrations are given as if they were being added for 80 L of H_2O.

Appendix. Nutrient Solution Maintenance Revisions

	Days into Experiment (mmol/ L water)					
Element	**115**	**160**	**166**	**172**	**190**	**205**
N	4.0	6.0	5.0	4.5	4.5	5.0
P	1.5	1.5	1.0	1.0	0.0	1.0
K	3.5	3.5	3.0	2.5	1.5	4.0
Ca	1.0	2.0	1.5	1.5	1.5	1.0
Mg	0.68	0.68	0.68	0.68	0.68	0.25
S	0.68	0.68	3.68	0.68	0.68	0.25
Fe	37.50	50.00**^	37.50	37.50	50.00**^	50.00**^
Si	-----	-----	-----	-----	-----	-----
B	80.00*^	80.00*^	-----	-----	80.00*^	80.00*^
Mn	8.00^	8.00^	8.00^	8.00^	8.00^	8.00^
Zn	-----	0.80*^	-----	-----	0.80*^	0.80*^
Cu	-----	0.30*^	-----	-----	0.30*^	0.30*^
Mo	0.10*^	0.10*^	-----	-----	0.10*^	0.10*^

*Concentrations were added only on the specified days.

**Fe was added as chelated Fe-EDDHA and Fe-HEDTA instead of $FeCl_3$. $FeCl_3$ was used on subsequent replenishments.

^Concentrations are given as if they were being added for 80 L of H_2O.

VI. REFERENCES

Baker, D. A. 1983. Uptake of cations and their transport within the plant, pp. 13-15. In: D.A. Robb and W. S. Pierpoint (eds.). Metals and Micronutrients Uptake and Utilization by Plants. Academic Press, New York.

Ben-Yaakov, S. and Ben-Asher, J. 1983. A method for estimating K+ and NO_3+ uptake rate in hydroponics by a four-electrode conductivity sensor. Scientia Hort. 21:113-122.

Biomedical Operations and Research Office. 1986. CELSS "Breadboard" Facility Project Plan. NASA John F. Kennedy Space Center. FL.

Bugbee, B. and F. B. Salisbury. 1985a. Personal communication. Plant Science Dept. Utah State University, Logan UT.

Bugbee, B. and F. B. Salisbury. 1985b. Wheat production in the Controlled Environments of Space. Utah Science. Winter:145-151.

Bugbee, B. and F. Salisbury. 1987a. Studies on the maximum yield of wheat for the controlled environments of space. NASA Technical Memorandum # NCC2-139. Moffett Field CA.

Bugbee, B. and F. Salisbury. 1987b. Physiological and genetic studies on wheat for the controlled environments of space. OSSA: Space Life Sciences Symposium. 246-248 (abstr).

Duke, J. A. and A. A. Atchley. 1986. Table 3 data converted to a zero-moisture basis, p376. In: J. A. Duke and A. A. Atchley (eds.). Handbook of Proximate Analysis Tables of Higher Plants. CRC Press, Boca Raton, FL.

Hoagland, D. R. and D. I. Arnon. 1938. The water-culture method for growing plants without soil. Univ. Cal., Col. of Agri. Exper. Sta., Berkeley, CA. pp. 1-38.

Hoff, J. E., J. M. Howe and C. A. Mitchell. 1982. Nutritional and cultural aspects of plant species selection for a controlled ecological life support system. NASA Contractor Report # 166324. Purdue University, Purdue IN.

Jones, J. B. 1983. Soil and hydroponics, p.13-14. In: A Guide for the Hydroponic and Soiless Culture Grower. Timber Press, Portland, Oregon.

MacElroy, R. D. and J. Bredt. 1984. Current concepts and future direction in CELSS. In NASA Conf. Pub. 2378. Life Support Systems in Space Travel.

Meyer, W. S. and G. C. Green. 1981. Plant indicators of wheat and soybean crop stress. Irrig. Sci. 2:167-176.

Nielsen, N. E. 1984. Crop production in recirculating nutrient solution according to the principle of Regeneration. ISOSC Proceedings:421-446.

Oleson, M. and R. L. Olson. 1986. Controlled Ecological Life Support Systems (CELSS) Conceptual Design Option Study. NASA Contractor Report #177421.

Peter's Fertilizer Products. 1987. Personal communication. Fogelsville, PA.

Peterson, R. F. 1965. The wheat plant and its morphological development, p. 26. In: N. Polunin (ed). Wheat--Botany Cultivation and Utilization. Interscience Pub. Inc., New York.

Polinskii, V. I. and G. M. Lisovskii. 1980. Net production of wheat crop under high PhAR irradiance with artificial light. Photosynthetica. 14(2):177-181.

Prince, R. P., J. W. Bartok and D. W. Protheroe. 1981. Lettuce production in a controlled environment plant growth unit. Transactions of the ASAE. 24 (3):725-730

Qualset, C. O., H. E. Vogt, and N. E. Borlaug. 1985. Registration of `Yecora Rojo' wheat. Crop Sci. 25:1130.

Rummel, J. D. and T. Volk. 1986. A modular BLSS simulation model. COSPAR paper 11.2.2. NASA-Ames Research Center and Dept. of App. Sci., New York Univ. pp. 1-9.

Sionit, N., B. R. Strain and H. Hellmers. 1981a. Effects of different concentrations of atmospheric CO_2 on growth and yield components of wheat. J. Agric. Sci. Comb. 79:335-339.

Sionit, N., D. A. Mortensen, B. R. Strain and H. Hellmers. 1981b. Growth response of wheat to CO_2 enrichment and different levels of mineral nutrition. Ag. J. 37:1023-1027.

Smilanski, 1986. Personal communication. USDA Agricultural Research Center, Utah State University, Logan UT.

Steiner, A. A. 1980. The selective capacity of plants for ions and its importance for the composition and treatment of the nutrient solution. SOSC Proceedings:83-95.

Sterrett, S. B., C. B. Smith, M. P. Mascianica and K. T. Demchak. 1987. Comparison of analytical results from plant analysis laboratories. Commun. In Soil Sci. Plant Anal. 18 (3):287-299.

Strain, B. R., ed. 1978. Report of the workshop on anticipated plant responses to global carbon dioxide enrichment. Duke Environmental Center, Duke University, Durham, NC.

Thorne, G. N. and D. W. Wood. 1987. Effects of radiation and temperature on tiller survival, grain number and grain yield in winter wheat. Ann. Bot. 59:413-426.

Tibbitts, T. W. and D. K. Alford. 1982. Controlled Ecological Life Support System, Use of Higher Plants. NASA Conf. Pub. 2231.

Vlamis, J. and D. E. Williams. 1967. Manganese and silicon interaction in the Gramineae. Plant and Soil 27,(1):131-139.

White, E. M. 1987. Spring wheat growth at high and low soil water with constricted upper roots. Soil Sci. 143, (1):44-49.

Williams, D. E. and J. Vlamis. 1957. Manganese toxicity in standard culture solutions. Plant and Soil. 8, (3):183-193.

Winsor, G. W., R. G. Hurd and D. Price. 1979. Nutrient film technique. Grower's Bulletin No. 5. Glasshouse Crops Research Institute. Littlehampton, West Sussex, England.

NASA

Report Documentation Page

1. Report No.	2. Government Accession No.	3. Recipient's Catalog No.
TM 102784		

4. Title and Subtitle	5. Report Date
Continuous Hydroponic Wheat Production Using a Recirculating System	September 1989
	6. Performing Organization Code

7. Author(s)	8. Performing Organization Report No.
[1]Mackowiak, C.L. [1]Owens Hall, L.P. [1]Hinkle, C.R. [2]Prince, R.P.	
	10. Work Unit No.

9. Performing Organization Name and Address	11. Contract or Grant No.
[1,2]The Bionetics Corporation, Mail Code: BIO-3 [2]NASA Biomedical Operations and Research Office John F. Kennedy Space Center, FL 32899	NAS10-10285
	13. Type of Report and Period Covered

12. Sponsoring Agency Name and Address	14. Sponsoring Agency Code
NASA/John F. Kennedy Space Center, FL 32899	

15. Supplementary Notes

16. Abstract

Continuous crop production, where plants of various ages are growing simultaneously in a single recirculating nutrient solution, is a possible alternative to batch production in a Controlled Ecological Life Support System (CELSS). A study was conducted at John F. Kennedy Space Center (KSC) where 8 trays (0.24 m^2 per tray) of Triticum aestivum L. "Yecora Rojo" were grown simultaneously in a growth chamber at 23°C, 65% relative humidity, 1000 ppm CO_2, continuous light, with a continuous flow, thin film nutrient delivery system. The same modified Hoagland nutrient solution was recirculated through the plant trays from an 80 L reservoir throughout the study. It was maintained by periodic addition of water and nutrients based on chemical analyses of the solution. The study was conducted for 216 days, during which 24 trays of wheat were consecutively planted (one every 9 days), 16 of which were grown to maturity and harvested. The remaining 8 trays were harvested on day 216. Grain yields averaged 520 g m^{-2}, and had an average edible biomass of 32%. Consecutive yields were unaffected by nutrient solution age. It was concluded that continual wheat production will work in this system over an extended period of time. Certain micronutrient deficiencies and toxicities posed problems in this study and must be addressed in future continuous production systems.

17. Key Words (Suggested by Author(s))	18. Distribution Statement
Hydroponics, recirculating, wheat, production, nutrient film technique (NFT)	Unlimited

19. Security Classif. (of this report)	20. Security Classif. (of this page)	21. No. of pages	22. Price
Unclassified	Unclassified	56	