NASA Technical Memorandum 103496

Proximate Composition Of Seed And Biomass From Soybean Plants Grown At Different Carbon Dioxide (CO_2) Concentrations

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May 1990

National Aeronautics and
Space Administration

John F. Kennedy Space Center

NASA

TABLE OF CONTENTS

LIST OF TABLES AND FIGURES

ABSTRACT

Soybean plants [Glycine max (L.) Merr. cvs. McCall (MC) and Pixie (PX)] were grown for 90 days in controlled environment chambers at 500, 1000, 2000, and 5000 ubar (ppm) atmospheric carbon dioxide (CO_2) and compared for proximate nutritional value. The highest seed and total plant biomass yields were obtained from cv. McCall plants grown at 1000 ubar. For both cultivars, seed protein levels were highest at 1000 ubar (39.3% and 41.9% for MC and PX) and lowest at 2000 ubar (34.7% and 38.9 % for MC and PX). Seed fat (oil) levels were highest at 2000 ubar (21.2% and 20.9% for MC and PX) and lowest at 5000 ubar (13.6% and 16.6% for MC and PX). Seed carbohydrate levels were highest at 500 ubar (31.5% and 28.4% for MC and PX) and lowest at 2000 ubar (20.9% and 20.8% for MC and PX). When adjusted for total seed yield per unit growing area, the highest production of protein and carbohydrate occurred with cv. McCall at 1000 ubar CO_2, while equally high amounts of fat were produced with cv. McCall at 1000 and 2000 ubar. Aside from the proportionately higher fat levels from seed produced at 2000 ubar, no major effects of CO_2 on proximate composition of soybean seed were observed. This suggests that atmospheric CO_2 concentration can be used in space life support systems to maximize soybean seed yield with minimal effect of seed composition.

INTRODUCTION

In preparation for long-term space habitation by humans, NASA has begun studies of plant (crop) production in controlled environments. The plants would provide on-site production of food, oxygen, and pure water for human life support, thereby reducing resupply costs. These studies have been conducted under NASA's Controlled Ecological Life Support Systems, or CELSS program (MacElroy and Bredt, 1985).

Soybeans are one of several candidate crops recommended for study for CELSS because of the high protein and oil content of their seed (Tibbitts and Alford, 1982; Hoff et al., 1982). To date, CELSS studies with soybeans have focused on the nitrogen nutrition in hydroponic systems and controlled environments (see Tolley-Henry and Raper, 1986a, 1986b). In addition to the mineral nutrition, however, many other factors in the environment will affect soybean growth, including irradiance, temperature, humidity, and carbon dioxide (CO_2) concentration (Thomas and Raper, 1976; Raper and Thomas, 1978). Because the atmospheric systems within a CELSS will be tightly closed, knowing the effects of CO_2 will be particularly important. Numerous CO_2 studies with soybean have been reported, but most of these studies have focused on whole plant development and yield, with little emphasis being placed on the nutritional qualilty of the crop (see Rogers et al., 1984; Jones et al., 1985; Allen et al., 1988; Baker et al., 1989). In addition, many of these CO_2 studies have been conducted under field settings and only compared the effect of a doubling of the normal ambient concentration in the atmosphere (350 ubar versus 700 ubar). In sealed

human life support systems, however, CO_2 could reach levels much higher than either one or two times Earth-ambient, e.g. up to 6000 ubar in Skylab (Ross, 1973). Preliminary tests conducted under tight atmospheric closure in NASA's Biomass Production Chamber (see Prince et al., 1987) have shown that CO_2 levels may change as much as 1500 ubar each day from the accumulation of respired CO_2 during a daily dark period (Wheeler et al., 1990).

In this report we present proximate and caloric analysis data from soybean seed, pod, leaf, stem and root tissue taken from plants grown at four different CO_2 concentrations. Such information may prove useful to the overall management of crop production systems used for human life support in space.

MATERIALS AND METHODS

A series of four 90-day studies was carried out in walk-in plant growth chambers at the NASA Life Sciences Support Facility (Hangar L) at Kennedy Space Center. Carbon dioxide (CO_2) levels for the four studies were controlled to near 500, 1000, 2000 and 5000 ubar (ppm) (assuming 1.013 bar total atmospheric pressure), with final averages equally 506, 979, 1984, and 4986 ubar $\pm$ approximately 8% (CV) of the set point. A "low" treatment of 500 was selected instead of the normal ambient (340-350) to avoid periodic increases resulting from human activity around the chambers during the workday. For all treatments, CO_2 enrichment was provided by continuously adding a small amount of pure CO_2 to the chamber to maintain a set point. Chamber CO_2 levels were monitored with an infrared gas analyzer (ANARAD Inc., Santa Barbara, CA) and controlled with a dedicated computer system.

Calibrations and updates of the computer conversions of analyzer signals were performed automatically each day using a zero-gas (nitrogen) and span-gas near the working range for the particular CO_2 treatment.

Irradiance within the chambers was provided with 30 96-inch VHO Vita-Lite fluorescent lamps (Duro-Test Inc, North Bergen, NJ) separated from the growing area by a clear acrylic barrier. Photosynthetic photon flux (PPF) levels for all the tests averaged 294 umol m^{-2} s^{-1} $\pm$ 38 umol m^{-2} s^{-1} (s.d. between individual tests) using a 12-h light/12-h dark photoperiod. Temperatures for all the tests averaged 25.7°C $\pm$ 0.3°C in the light and 20.0°C + 0.2°C in the dark. Relative humidities were held constant during the light and dark and averaged 63% $\pm$ 3%.

Soybean [Glycine max (L.) Merr. cvs McCall and Pixie] seeds were soaked in deionized water for 24 h prior to planting to hydronponic growing trays as described by Mackowiak et al. (1989). Eight trays, four of each cultivar, were placed in the chamber for each 90-day study. At about 12 days after planting (DAP), plants were thinned to either three or six plants per tray. At about 30 DAP, each tray was enclosed with a 60-cm high white, vinyl-coated fencing (5 cm x 6.2 cm holes) to confine shoot growth to the 0.25 m^2 area.

A complete nutrient solution using only nitrate-nitrogen was recirculated continuously from a common reservoir to each of the trays (Mackowiak et al., 1989). Solution pH was controlled automatically to 5.8 using dilute (0.39 M) nitric acid. Water was manually added to the reservoir each day to maintain a constant volume, and solution nutrients were replenished twice each

week to maintain solution electrical conductivity. Solution nutrient levels were monitored weekly using an atomic absorption or ICP spectroscopic techniques.

At 90 DAP all plants were harvested, seeds were removed from the pods, and all materials were oven-dried for a least 48 h at 70°C to determine dry weights. Following weighing, plant materials were separated by cultivar and plant part, i.e., seeds, pods, leaves, stems, and roots and ground through a 2-mm mesh (Thomas-Wiley mill #4). The ground tissue samples (approximately 100 g each) were sealed in plastic bags and shipped for total proximate nutritional analysis (Nutrition International Inc., East Brunswick, NJ). Proximate analyses followed standard AOAC procedures (1984). Analyses included the following: moisture by vacuum oven (AOAC paragraph 7.003); ash by muffle furnace (AOAC paragraph 7.009), protein by Kjeldahl nitrogen (AOAC paragraphs 2.056-2.058); fiber by digestion and gravimetric technique (AOAC paragraphs 7.061-7.065); fat by ether extraction or acid hydrolysis (AOAC paragraphs 7.055-7.060); and carbohydrate by difference. Dietary energy equivalents were calculated by assigning 4 kcal per g carbohydrate, 4 kcal per g protein, and 9 kcal per g fat. Total energy values were determined by bomb calorimetry. All data presented have been normalized for zero moisture content.

Because most of the available tissue was required for the complete set of analyses, no replicate samples could be taken and no statistic comparisons between treatments were made. Although apparent differences are discussed below, the reader is cautioned that these differences are not necessarily statistically signifi-

cant. On one occasion, sufficient seed tissue was available from a previous treatment and was analyzed along with another treatment's samples. Results showed that protein levels were within 1% of the previous sample, carbohydrate within 7%, and fat levels within about 15%. The discrepancies could have been caused by several factors, including analysis repeatability, differences in sample homogeneity, or changes in composition of the samples over time.

RESULTS AND DISCUSSION

Yield data (expressed as grams dry weight per unit area) for the four trays of each cultivar at the different CO_2 levels are shown in Table 1. The highest yield of seeds for cv. McCall plants occurred at 1000 ubar, while the highest yield for cv. Pixie occurred at 500 ubar. The lowest seed yield for both cultivars occurred at 2000 ubar. Regardless of CO_2 level, McCall plants always produced more seed than Pixie. With the exception of cv. Pixie at 5000 ubar, harvest index (ratio of seed to total biomass) decreased with increasing CO_2 (Table 1).

The increase in seed yield and total growth by increasing the CO_2 from 500 to 1000 ubar is not surprising for a C_3 species as soybean, where CO_2 enrichment typically results in increased photosynthetic rates and increased total plant growth (Acock and Allen, 1985). The slight decrease in yield as CO_2 was increased above 1000 ubar suggests that the higher levels (i.e., 2000 and 5000 ubar) were supraoptimal, but not particularly toxic or injurious to the plants (Kramer, 1981).

Proximate Analyses

Proximate analysis data are presented according to the different parts of the plant in Tables 2 - 6. The same data are shown again in Figs. 1 - 3, but broken out by protein, fat, and carbohydrate for ease of comparison. It is important to note that the most of the leaves, stems, and pods were senescent by 90 days and thus will likely differ significantly from healthy, actively growing tissue. However, for the purpose of CELSS, these analyses should provide an indication of what constituents can be recovered from inedible plant structures when soybeans are grown to a mature stage for seed production.

Protein. Because protein levels were determined from elemental nitrogen concentration (N x 6.25), any residual nitrate in tissues (e.g. leaves) or clinging to the surface (e.g. roots) would subsequently be interpreted as protein and could have introduced some error (Krober and Gibbons, 1962; Pace et al., 1982). This may be particularly important with plants grown in hydroponic culture with high nutrient availability. However, with the exception of some leafy vegetables, e.g. lettuce and spinach, leaf nitrate levels of most plants are commonly assumed to be low (C.A. Mitchell, personal communication). In addition, Krober and Gibbons (1962) have shown that protein accounts for 95% to 96% of the total protein in mature soybean seed.

Seeds from the various treatments ranged from about 35 to 42% protein, with the highest levels occurring at 1000 ubar CO_2 and the lowest at 2000 ubar for both cultivars (Table 2 and Fig. 1). Seed from cv. Pixie plants consistently had higher protein levels (39% to 42%) than seed from cv. McCall (35% to 39%).

Regardless of the CO_2 concentration, seed protein levels from these studies conducted in controlled environments were higher than typical values reported for field-grown seed (33% to 34%; Duke and Atchley, 1986).

Protein levels of pods from both cultivars were low (3% to 5%) and tended to increase as CO_2 was increased (Table 3 and Fig. 1). Leaf protein levels ranged from 11% to 21% and were distinctly highest at the 5000 ubar concentration (Table 4 and Fig. 1). Stem protein levels ranged from 7% to 23% and in contrast to leaves were highest at 1000 ubar and lowest at 5000 ubar (Table 5 and Fig. 1). Other than seed, roots showed the highest protein levels, ranging from 20% to 25% for both cultivars (Table 6 and Fig. 1), but no consistent trends were apparent regarding root protein and CO_2 concentration.

Fat. Seed fat levels ranged from about 14% to 21%, with the highest levels clearly occurring at 2000 ubar CO_2 (Table 2 and Fig. 2). With exception of the 1000 ubar treatment, Pixie seeds tended to have slightly higher fat levels than cv. McCall. The fat levels of the seed from these tests ranged from 16% to 21% and were slightly greater than fat levels reported for field-grown seed (15% to 18%; Duke and Atchley, 1986).

The high fat content of the 2000 ubar seed seems anomalous in comparison to the other treatments. For the sake of experimental uniformity, all plants in these studies were harvested at 90 days after planting, but plants grown at 2000 ubar CO_2 had a greater proportion of green and immature pods at this stage than the other treatments. Although fat (oil) and protein can accumulate at similar rates during seed development (Yazdi-Samadi

et al., 1977), generally fat accumulation is relatively early in soybean seed development, while protein accumulation is relatively late (Wilson, 1987). Thus the proportionately high fat and low protein of the 2000 ubar seed may be a result of a greater quantity of immature pods and seeds at harvest, rather than a true CO_2 concentration effect.

Fat levels in other plant parts were very low (typically below 4%), and tended to decrease with increased CO_2 concentration (Tables 3-6 and Fig. 2).

Carbohydrate. Seed carbohydrate levels ranged from 21% to 31% and tended to decrease as CO_2 was increased (Table 2). The highest seed carbohydrate levels occurred at 500 ubar CO_2 and lowest at 2000 ubar (Table 2 and Fig. 3). McCall seeds consistently showed higher carbohydrate level than Pixie seeds (27% to 31% vs 21% to 28%). Carbohydrate levels for both cultivars were lower than levels for typical field-grown seed (34% to 35%; Duke and Atchley, 1986).

Carbohydrate levels in seed pods ranged from 42% to 60% with the highest concentration occurring at 2000 ubar and the lowest at 5000 ubar (Table 3 and Fig. 3). The high carbohydrate levels at 2000 also may be related to the delay in seed and pod maturity of the plants in this treatment. Leaf carbohydrate levels ranged from approximately 39% to 59%, with the highest level for both cultivars occurring at 1000 ubar and the lowest at 5000 ubar (Table 4 and Fig. 3). Carbohydrate in stems ranged from approximately 29% to 46% and tended to decrease in response to in-

creased CO_2 (Table 5 and Fig. 3). Root carbohydrate levels ranged from approximatley 26% to 38% and showed no clear trends in response to CO_2 concentration (Table 6 and Fig. 3).

In all the assays, it is important to note that carbohydrate levels were determined by a difference method; hence it is possible that levels may be slightly overestimated if some cellulose or other insoluble, structural compounds were partially broken down and not reported as a portion of crude fiber. This is supported by evidence from other studies which have shown that specific carbohydrates in soybean seed (i.e., starch, raffinose, stachyose, and sucrose) have totaled only 10-15% of the seed dry weight (Yazdi-Samadi et al., 1977; Brown and Huber, 1987) compared to 30-35% reported from analyses using standard proximate procedures (Duke and Atchley, 1986).

Crude fiber. Seed crude fiber levels were lowest for both cultivars at 1000 ubar CO_2 (approximately 6%) and increased to approximately 13% for cv. Pixie at 2000 ubar and 12% for cv. McCall at 5000 ubar (Table 2). Except for seed from 1000 ubar CO_2, crude fiber levels were higher than levels reported for field-grown seed (4% to 6%; Duke and Atchley, 1986).

Pod crude fiber levels were typically near 30% with the exception of cv. Pixie at 2000 ubar, which dropped to 19.5% (Table 3). This low crude fiber level for 2000-Pixie occurred in conjunction with high a carbohydrate level, which again may be related to the immature stage of pods at harvest. With the exception of cv. Pixie at 1000 ubar, leaf crude fiber levels increased with increased CO_2, with both cultivars ranging from approximately 10% to 15% (Table 4). Stem crude fiber levels also

showed a distinctive increase in response to increased CO_2, with cv. McCall increasing from approximately 44% to 56% and cv. Pixie from 26% to 47% (Table 5). Crude fiber levels of cv. McCall roots tended to increase with increased CO_2 (31% to 41%) but cv. Pixie roots showed no clear trend in response to CO_2 and ranged from approximately 27% to 35% (Table 6).

Ash. Ash levels from seed were highest at 1000 ubar and lowest at 2000 ubar and ranged from approximately 6% to 8% for both cultivars over all CO_2 treatments. This is higher than the 4% to 6% levels of ash reported for field-grown seed (Duke and Atchley, 1986). Pod ash levels also were lowest at 2000 ubar but highest at 5000 ubar and ranged from approximately 13% to 19% for both cultivars over all the treatments (Table 3). Leaf ash levels were highest at 5000 ubar and lowest at 1000 ubar and ranged from approximately 16% to 23% for both cultivars over all treatments (Table 4). Stem ash levels were highest at 500 ubar and lowest at 2000 ubar and ranged from approximately 6% to 11% for both cultivars over all treatments (Table 5). Root ash levels were highest for both cultivars at 1000 ubar (approximately 15%) and lowest for cv. McCall at 5000 ubar (10%) and lowest for cv. Pixie at 2000 ubar (12%) (Table 6).

Calories. Of all the plant components, seeds showed the highest calorie (energy) values, both in terms of calculated dietary energy and from bomb calorimeter measurements (Tables 2-6). This is likely a result of the much higher fat content of the seeds in comparison to other plant parts. Estimates of dietary calorie content of leaves, stems, and roots tended to

decrease with increasing CO_2, while bomb calorimeter measurements of total energy content showed no clear trends regarding CO_2 concentration.

Applications for Human Life Support

Seed represented over 45% of the total biomass in several treatments in this study (Table 1), and clearly the main reason for growing soybeans in a life support system would be for seed production (Tibbitts and Alford, 1982; Hoff et al., 1982). By combining the yield data from Table 1 and the composition of the seed from the different environments (Table 2), it is apparent that the best yield for total seed protein and carbohydrate per unit area was obtained from cv. McCall plants grown at 1000 ubar CO_2 (Table 7). Total fat (oil) production from seeds was equally high from McCall plants grown at 1000 or 2000 ubar CO_2 (Table 7). Thus the changes in total seed yield resulting from CO_2 concentration outweighed any potential advantages from changes in seed composition associated with CO_2 concentration. This suggests that soybean crops used for space life support should be managed foremost to maximize seed yield, which in turn should maximize returns of protein, fat, and carbohydrate.

The "vegetative" response with lower seed set (i.e. low harvest index) at 2000 and 5000 ubar suggests that very high CO_2 concentrations may be unfavorable for maximum seed yield from soybeans in a life support farm. Despite the importance of seed production, if food can be recovered effectively from inedible plant parts, the high total biomass yield from the high CO_2 concentrations may be important. Analyses of young soybean leaves have shown that CO_2 enrichment can double starch levels (Hrubec

et al., 1985; Allen et al., 1988), thus there may be potential for recovering useful carbohydrate from the inedible parts. In addition, structural carbohydrates in leaves and stems could be broken down enzymatically to yield simple sugars (Wilke et al., 1983), or the inedible biomass might be used to culture edible organisms such as Pleurotus ostreatus (oyster mushroom) (Calzada et al., 1987). In either case, the effective harvest index (i.e., percent edible yield) would be increased beyond the seed harvest alone.

Although certain trends were apparent with regard to CO_2 effects on tissue composition, a strong case can be made for the absence of any major changes. Aside from higher seed fat levels at 2000 ubar (Table 2, Fig. 2), the results indicate that varying CO_2 concentrations between 500 and 5000 ubar should not have any major influence on seed composition. This may be an important characteristic for crops used in tightly closed systems (e.g. a CELSS), where CO_2 concentrations may vary depending on the ratio of humans to plants, capacity of system gas reservoirs, or even diurnal light/dark cycles. The apparent resilience of soybeans with regard to total plant growth and seed composition over a wide range of CO_2 concentrations may be an important consideration for their inclusion in a CELSS.

LITERATURE CITED

1. Acock, B. and L.H. Allen. 1985. Crop responses to elevated carbon dioxide concentrations. In: B.R. Strain and J.D. Cure (eds.), Direct effects of increasing carbon dioxide on vegetation. DOE/ER-0238, U.S. Dept. of Energy, Washington, D.C.

2. Allen, L.H., J.C.V. Vu, R.R. Valle, K.J. Boote, and P.H. Jones. 1988. Nonstructural carbohydrates and nitrogen of soybean grown under carbon dioxide enrichment. Crop Sci. 28:84-94.

3. AOAC. 1984. Official methods of analysis (14th edn). Association of Official Analytical Chemists, Washington, DC.

4. Baker, J.T., L.H. Allen, K.J. Boote, P. Jones, and J.W. Jones. 1989. Response of soybean to air temperature and carbon dioxide concentration. Crop Sci. 29:98-105.

5. Brown, C.S. and S.C. Huber. 1987. Photosynthesis, reserve mobilization and enzymes of sucrose metabolism in soybean (Glycine max) cotyledons. Physiol. Plant. 70:537-543.

6.Calzada, S.W., A.G. de Leon, M.L. de Arriloa, and C. Rolz. 1987. Growth of mushrooms on wheat straw and coffee pulp: strain selection. Biological Wastes, 20:217-226.

7. Duke, J.A. and A.A. Atchley. 1986. Handbook of proximate analysis tables of higher plants. CRC Press, Inc. Boca Raton, FL.

8. Hoff, J.E., J.M. Howe, and C.A. Mitchell. 1982. Nutritional and cultural aspects of plant species selection for a regenerative life support system. Contract report to NASA Ames Research Center, Grants 2401 and 2404.

9. Hrubec, T.C., J.M. Robinson, and R.P. Donaldson. 1985. Effects of CO_2 enrichment and carbohydrate content on the dark respiration of soybeans. Plant Physiol. 79:684-689.

10. Jones, P, L.H. Allen, J.W. Jones, and R. Valle. 1985. Photosynthesis and transpiration responses of soybean canopies to short- and long-term CO_2 treatments. Agron. J. 119-126.

11. Kramer, P.J. 1981. Carbon dioxide concentration, photosynthesis, and dry matter production. BioScience 31:29-33.

12. Krober, O.A. and S.J. Gibbons. 1962. Nonprotein nitrogen in soybeans. Agricul. Food Chem. 10:57-59.

13. MacElroy, R.D., and J. Bredt. 1985. Controlled ecological life support system. Current concepts and future directions of CELSS. NASA Conf. Pub. 2378 from XXV COSPAR mtg. Graz, Austria.

14. Mackowiak, C.L., L.P. Owens, C.R. Hinkle, and R.P. Prince. 1989. Continuous hydroponic wheat production using a recirculating system. NASA Tech. Memorandum 102784, Kennedy Space Center, FL.

15. Pace, G.M., C.T. MacKown, and R.J. Volk. 1982. Minimizing nitrate reduction during Kjeldahl digestion of plant tissue extracts and stem exudates. Plant Physiol. 69:32-36.

16. Prince, R.P., W.M. Knott, J.C. Sager, and S.E. Hilding. 1987. Design and performance of the KSC biomass production chamber. SAE Tech. Paper 871437, Soc. Sutomotive Eng. Conf., Seattle, WA, July 1987.

17. Raper, C.D. and J.F. Thomas. 1978. Photoperiodic alteration of dry matter partitioning and seed yield in soybeans. Crop Sci. 18:654-656.

18. Rogers, H.H., N Sionit, J.D. Cure, J.M. Smith, G. E. Bingham. 1984. Influence of elevated carbon dioxide on water relations of soybeans. Plant Physiol. 74:233-238.

19. Ross, C.E. 1973. Skylab 1/2 preliminary biomedical report. JSC Internal Note 08439, Johnson Space Center, Houston, TX.

20. Thomas, J.F. and C.D. Raper. 1976. Photoperiodic control of seed filling for soybeans. Crop Sci. 16:667-672.

21. Tibbitts, T.W. and D.K. Alford. 1982. Controlled ecological life support system. Use of higher plants. NASA Conf. Pub. 2231

22. Tolley-Henry, L. and C.D. Raper. 1986a. Utilization of ammonium as a nitrogen source. Effects of ambient acidity on growth and nitrogen accumulation by soybean. Plant Physiol. 82:54-60.

23. Tolley-Henry, L. and C.D. Raper. 1986b. Nitrogen and dry-matter partitioning in soybean plants during onset of and recovery from nitrogen stress. Bot. Gaz. 147:392-399.

24. Wheeler, R.M., K.A. Corey, J.C. Sager, C.L. Mackowiak, and W.M. Knott. 1990. Gas excahnge rates by a stand of soybeans grown in a tightly sealed chamber. HortScience Abstracts.

25. Wilke, C.R., B. Maiorella, A. Sciamanna, K. Tangnu, D. Wiley, and H. Wong. 1983. Enzymatic hydrolysis of cellulose. Theory and application. Noyes Data Corp. Park Ridge, NJ, USA.

26. Wilson, R.F. 1987. Seed metabolism. In: J.R. Wilcox (ed.), Soybeans: Improvement, Production, and Uses. Amer. Soc. of Agron. Publishers, Madison, WI, USA.

27. Yazdi-Samadi, B., R.W. Rinne, and R.D. Seif. 1977. Components of developing soybean seeds: Oil, protein, sugars, starch, organic acids, and amino acids. Agron. J. 69:481-486.

Table 1. Dry weight yield of soybean plants grown under at four CO_2 concentrations.

CO_2	Cultivar	Seed Dry Weight	Total Plant[1] Dry Weight	Harvest[2] Index
(ubar)		($g\ m^{-2}$)	($g\ m^{-2}$)	(%)
500	McCall	621	1336	46
	Pixie	282	705	40
1000	McCall	766	1701	45
	Pixie	267	787	34
2000	McCall	593	1480	40
	Pixie	231	756	31
5000	McCall	613	1568	39
	Pixie	269	737	36

1 Includes: leaves, stems, roots, seeds, and pods.

2 Harvest index = seed DW / total plant DW.

Table 2. Proximate analysis of seed from soybean plants grown at four CO_2 concentrations. Data are expressed as a percent of total dry weight.

CO_2	cv	Protein	Fat	Carbohydrate	Crude Fiber	Ash	Calories[1]	Bomb Cal.
(ubar)		(%)	(%)	(%)	(%)	(%)	(kcal/g)	(kcal/g)
500	McCall	37.7	16.1	31.5	7.7	6.9	4.2	5.4
	Pixie	38.9	17.3	28.4	8.6	6.7	4.3	5.5
1000	McCall	39.3	16.5	30.4	5.9	7.1	4.3	5.5
	Pixie	41.9	16.8	27.1	5.7	8.1	4.3	5.5
2000	McCall	34.7	21.2	26.9	10.7	6.3	4.4	5.3
	Pixie	38.9	20.9	20.8	13.1	6.1	4.3	5.4
5000	McCall	38.1	13.6	29.0	12.0	6.8	3.9	5.4
	Pixie	40.0	16.6	23.8	12.0	7.1	4.0	5.5

1 Calculated by assuming 4 kcal g^{-1} carbohydrate, 4 kcal g^{-1} protein, and 9 kcal g^{-1} fat.

Table 3. Proximate analysis of seed pods from soybean plants grown at four CO_2 concentrations. Data are expressed as a percent of total dry weight.

CO_2	cv	Protein	Fat	Carbohydrate	Crude Fiber	Ash	Calories[1]	Bomb Cal.
(ubar)		(%)	(%)	(%)	(%)	(%)	(kcal/g)	(kcal/g)
500	McCall	3.6	2.2	46.1	32.8	14.7	2.2	3.7
	Pixie	4.7	1.8	48.3	29.6	15.4	2.3	3.6
1000	McCall	3.3	0.8	45.6	33.9	15.8	2.0	3.6
	Pixie	4.7	0.6	45.0	32.7	16.3	2.0	3.5
2000	McCall	3.9	1.2	50.1	31.3	13.2	2.3	3.5
	Pixie	5.1	0.7	60.2	19.5	14.2	2.7	3.5
5000	McCall	4.8	0.6	42.9	33.6	17.3	2.0	3.7
	Pixie	5.1	0.6	42.0	32.1	19.0	1.9	3.6

1 Calculated by assuming 4 kcal g^{-1} carbohydrate, 4 kcal g^{-1} protein, and 9 kcal g^{-1} fat.

Table 4. Proximate analysis of leaves from soybean plants grown at four CO_2 concentrations. Data are expressed as a percent of total dry weight.

CO_2	cv	Protein	Fat	Carbohydrate	Crude Fiber	Ash	Calories[1]	Bomb Cal.
(ubar)		(%)	(%)	(%)	(%)	(%)	(kcal/g)	(kcal/g)
500	McCall	12.7	4.3	51.4	11.2	19.9	3.0	3.5
	Pixie	13.2	3.9	51.8	12.1	18.4	3.2	3.7
1000	McCall	11.2	3.0	54.8	12.2	18.3	2.9	3.6
	Pixie	12.0	2.5	58.8	9.9	16.4	3.1	3.7
2000	McCall	13.3	2.8	49.9	14.2	19.4	2.8	3.4
	Pixie	15.5	2.5	51.3	13.1	17.1	2.9	3.6
5000	McCall	18.8	2.1	40.1	15.3	22.6	2.6	3.6
	Pixie	21.1	1.8	38.8	15.0	22.4	2.6	3.7

1 Calculated by assuming 4 kcal g^{-1} carbohydrate, 4 kcal g^{-1} protein, and 9 kcal g^{-1} fat.

Table 5. Proximate analysis of stems from soybean plants grown at four CO_2 concentrations. Data are expressed as a percent of total dry weight.

CO_2	cv	Protein	Fat	Carbo-hydrate	Crude Fiber	Ash	Calories[1]	Bomb Cal.
(ubar)		(%)	(%)	(%)	(%)	(%)	(kcal/g)	(kcal/g)
500	McCall	9.8	2.2	36.3	43.6	7.7	2.1	4.1
	Pixie	13.3	2.4	46.2	26.4	11.3	2.6	3.9
1000	McCall	13.3	1.4	30.3	47.0	7.5	1.9	4.1
	Pixie	22.7	1.0	36.6	31.4	8.1	2.5	3.9
2000	McCall	11.7	0.9	30.6	50.3	6.1	1.8	4.0
	Pixie	18.5	1.0	36.0	36.4	7.8	2.3	3.9
5000	McCall	7.4	0.7	28.9	55.6	6.7	1.5	4.4
	Pixie	8.8	0.7	31.8	47.5	10.7	1.7	4.2

1 Calculated by assuming 4 kcal g^{-1} carbohydrate, 4 kcal g^{-1} protein, and 9 kcal g^{-1} fat.

Table 6. Proximate analysis of roots from soybeans grown at four CO_2 concentrations. Data are expressed as a percent of total dry weight.

CO_2	cv	Protein	Fat	Carbo-hydrat	Crude Fiber	Ash	Calories[1]	Bomb Cal.
(ubar)		(%)	(%)	(%)	(%)	(%)	(kcal/g)	(kcal)
500	McCall	20.9	3.7	29.1	31.2	14.7	2.3	3.8
	Pixie	20.8	2.6	32.8	29.9	13.6	2.4	3.8
1000	McCall	21.9	1.7	27.9	33.3	14.8	2.2	3.9
	Pixie	25.3	1.6	30.3	26.7	15.2	2.4	3.9
2000	McCall	23.2	1.5	31.0	33.3	10.6	2.3	3.8
	Pixie	22.0	1.2	38.0	26.7	11.7	2.5	3.7
5000	McCall	20.4	1.6	26.2	40.7	9.9	2.0	4.0
	Pixie	23.2	1.0	27.2	35.0	12.3	2.1	4.1

1 Calculated by assuming 4 kcal g^{-1} carbohydrate, 4 kcal g^{-1} protein, and 9 kcal g^{-1} fat.

Table 7. Protein, fat, and carbohydrate yields per unit area from soybean seed grown at four different CO_2 concentrations.

CO_2	Cultivar	Total Protein Yield	Total Fat Yield	Total Carbohydrate Yield
(ubar)		($g\ m^{-2}$)	($g\ m^{-2}$)	($g\ m^{-2}$)
500	McCall	234	100	196
	Pixie	110	49	80
1000	McCall	301	126	233
	Pixie	112	45	72
2000	McCall	206	126	159
	Pixie	90	48	48
5000	McCall	234	84	178
	Pixie	108	45	64

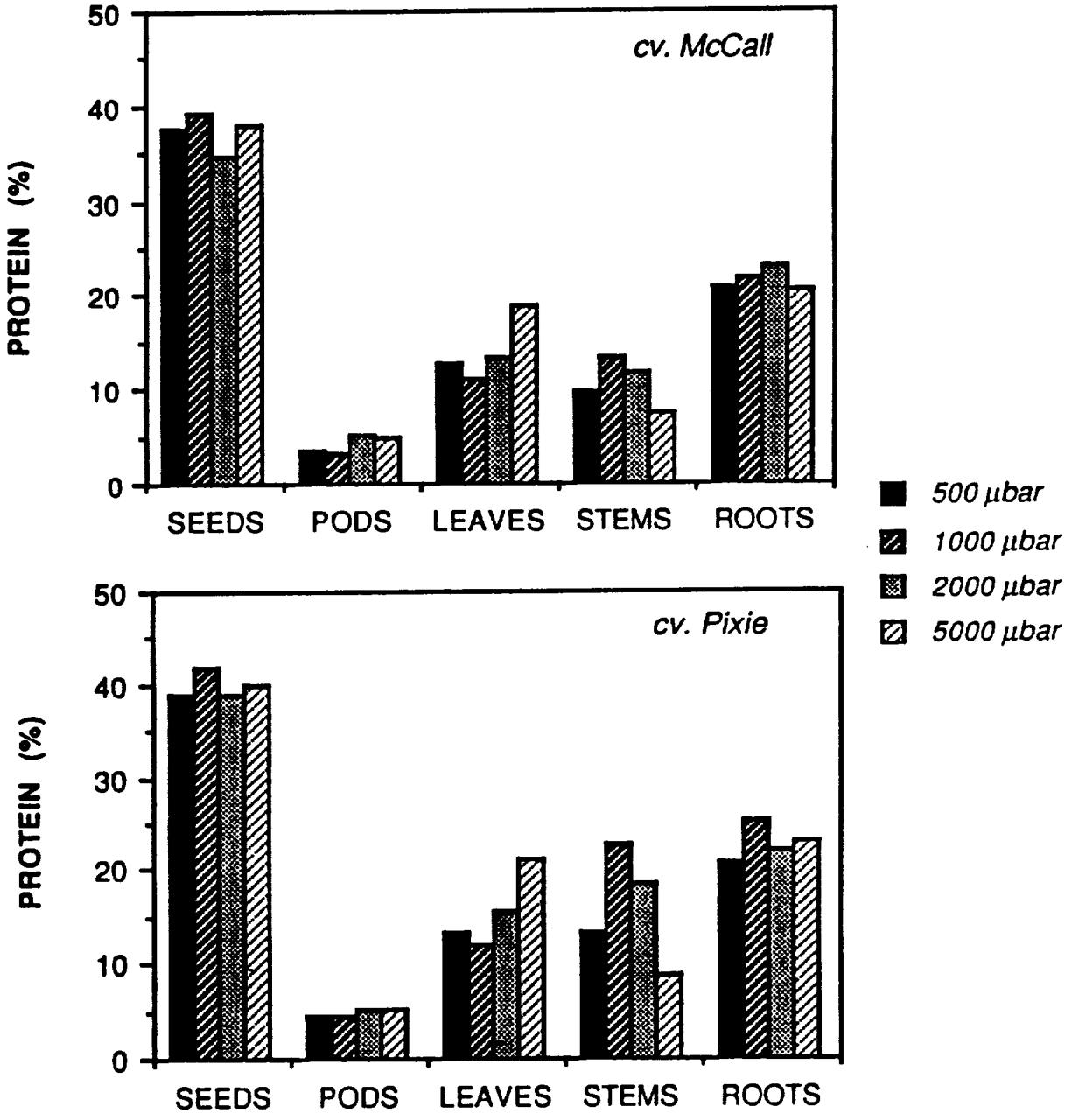

Figure 1. Protein content of soybean plants grown at four different carbon dioxide concentrations.

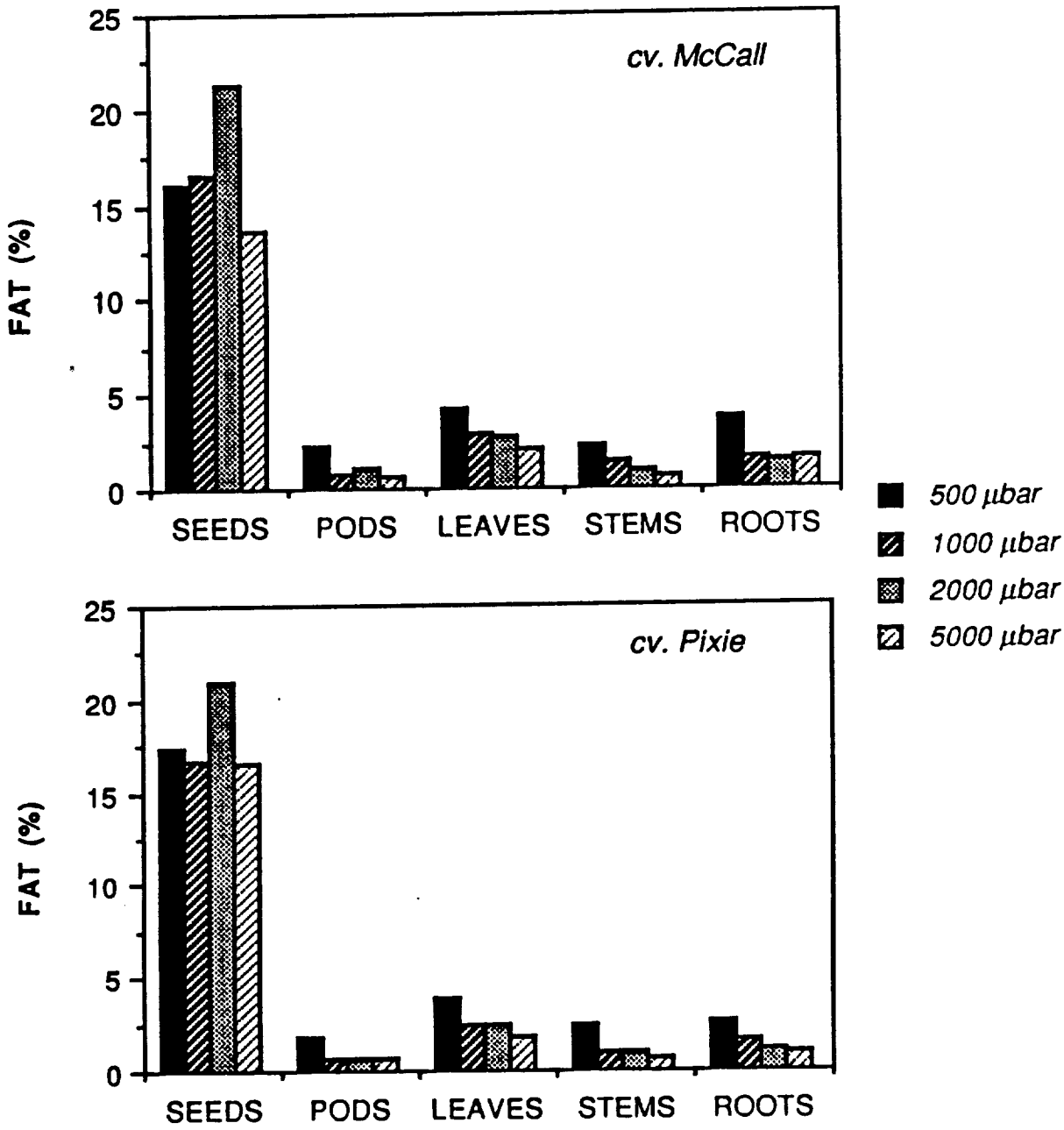

Figure 2. Fat content of soybean plants grown at four different carbon dioxide concentrations.

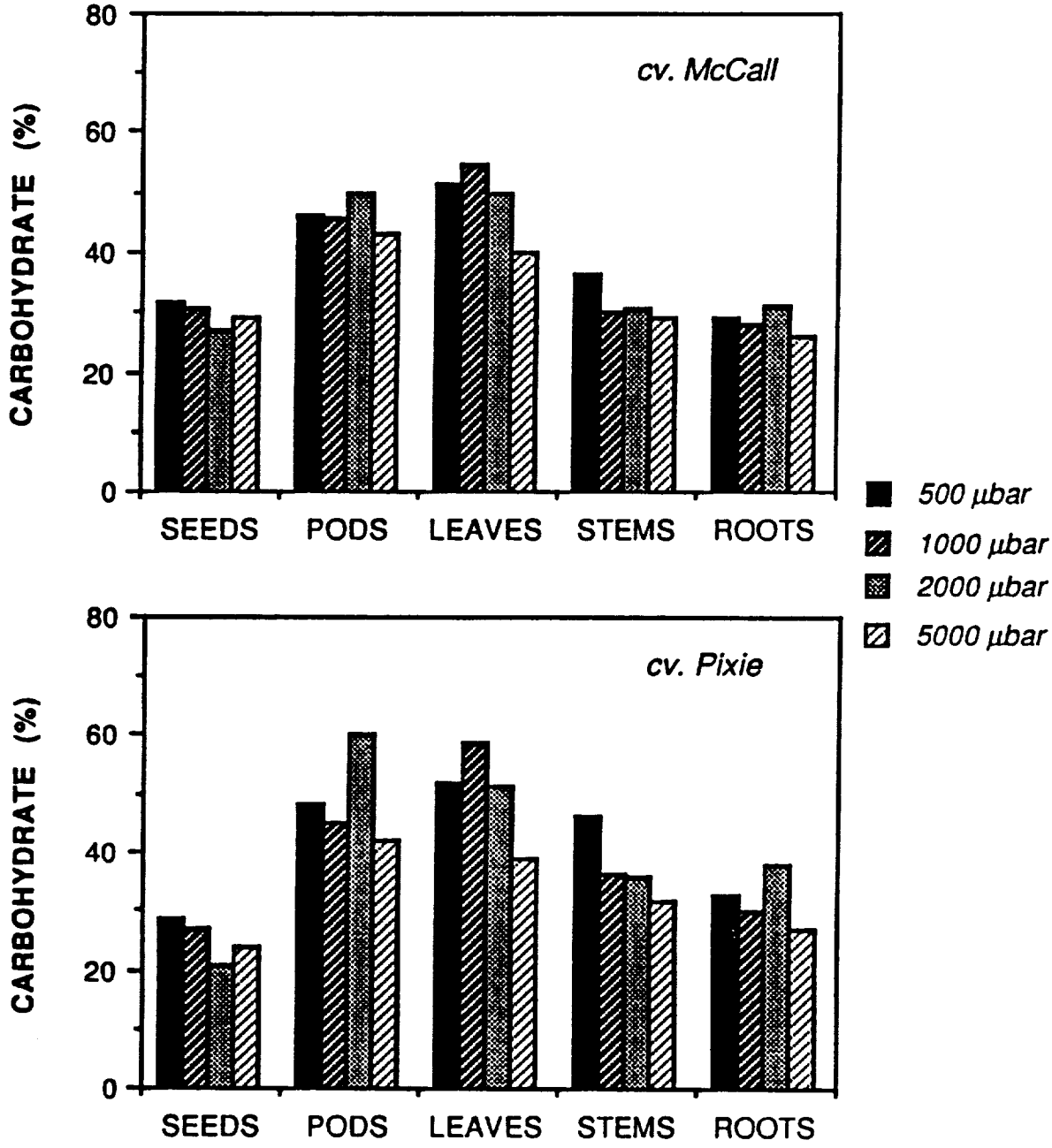

Figure 3. Carbohydrate content of soybean plants grown at four different carbon dioxide concentrations.

Report Documentation Page

National Aeronautics and Space Administration

1. Report No. NASA TM 103496	2. Government Accession No.
3. Recipient's Catalog No.	
4. Title and Subtitle: Proximate Composition of Seed and Biomass from Soybean Plants Grown at Different Carbon Dioxide (CO_2) Concentrations	5. Report Date: May 1990
	6. Performing Organization Code: BIO-3
7. Author(s): Wheeler, R.M., C.L. Mackowiak, and J.C. Sager	8. Performing Organization Report No.
	10. Work Unit No.
9. Performing Organization Name and Address: The Bionetics Corporation (RMW, CLM) NASA Biomedical Operations and Research (JCS) Kennedy Space Center, FL 32899	11. Contract or Grant No.
	13. Type of Report and Period Covered
12. Sponsoring Agency Name and Address	14. Sponsoring Agency Code: MD/RES
15. Supplementary Notes	

16. Abstract: Soybean plants (Glycine max cvs. McCall and Pixie) were grown for 90 days at 500, 1000, 2000, and 5000 ubar (ppm) carbon dioxide (CO_2) and compared for proximate nutritional value. For both cultivars (MC and PX), seed protein levels were highest at 1000 (39.3% and 41.9% for MC and PX) and lowest at 2000 (34.7% and 38.9% for MC and PX). Seed fat (oil) levels were highest at 2000 (21.2% and 20.9% for MC and PX) and lowest at 5000 (13.6% and 16.6% for MC and PX). Seed carbohydrate levels were highest at 500 (31.5% and 28.4% for MC and PX) and lowest at 2000 (20.9% and 20.8% for MC and PX). When adjusted for total seed yield per unit growing area, the highest production of protein and carbohydrate occurred with MC at 1000, while equally high amounts of fat were produced with MC at 1000 and 2000. Seed set and pod development at 2000 were delayed in comparison to other CO_2 treatments; thus the proportionately high fat and low protein at 2000 may have been a result of the delay in plant maturity rather than CO_2 concentration. Stem crude fiber and carbohydrate levels for both cultivars increased with increased CO_2. Leaf protein and crude fiber levels also tended to rise with increased CO_2 but leaf carbohydrate levels decreased as CO_2 was increased. The results suggest that CO_2 effects on total seed yield outweighed any potential advantages to changes in seed composition.

17. Key Words (Suggested by Author(s)): Carbon Dioxide, CO_2, Protein, Fat, Carbohydrate, Proximate Analysis, Controlled Ecological Life Support Systems, CELSS, Bioregenerative Life Support Systems

18. Distribution Statement

19. Security Classif. (of this report)	20. Security Classif. (of this page)	21. No. of pages	22. Price
Unclassified	Unclassified	28	

NASA FORM 1626 OCT 86