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MELLiSSA

Memorandum of Understanding

ECT/FG/MMM/97.012

Technical Note 46.2

Area Requirements for Biomass Production Units (BPUs) Including current MELiSSA Candidate Crops

Version 1

Issue: 0

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January 2001

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ABSTRACT

Optimized menus for a bioregenerative life support system have been developed based on measures of crop productivity, food item acceptability, menu diversity, and nutritional requirements of crew. Crop specific biomass requirements were calculated from menu recipe demands while accounting for food processing and preparation losses. Cost of the bioregenerative food system is estimated at 439 Kg per menu cycle or 7.3 Kg ESM crew^{-1} day^{-1}, including agricultural waste processing costs. This number is high compared to the STS and ISS (non-regenerative) systems but reductions in ESM may be achieved through intensive crop productivity improvements, reductions in equipment masses associated with crop production and planning of production, processing and preparation to minimize the requirement for crew labour.

INTRODUCTION

Ideally, the majority of crops needed for the dietary fulfillment of crew in a long-term manned space mission (i.e. Mars) would be produced *in-situ*. This is the basis of the bioregenerative approach to life support. To calculate the total crop production area required to meet crew dietary demands it is necessary to define the cultural requirements of the full set of candidate crops used as ingredients in menus.

Design of the Planetary Life Support Systems Test Complex's Biomass Production Chambers (BPCs) has provision for a total crop production area of 164 m^2 (Barta *et al*, 1999). Although the BPC is expected to produce major staple crops (wheat, rice, white potato, sweet potato, soybean, peanut and dry bean) and fresh vegetables (lettuce, cabbage, spinach, chard, carrot, radish, tomato and onion) it is unknown whether the production area would be sufficient to meet the demands of optimized menus. Other estimates of crop production area have been provided by Drysdale *et al* (1994). This earlier work determined the baseline diet for a single person per day and used productivity data for lettuce, potato soybean and wheat to estimate production areas. The total production area was estimated to be 73 m^2. These estimates were not based on the results of menu optimization studies. Clearly, there is a need to establish estimates of production area requirements based on the dietary needs of crew and reliable crop productivity data so that human integration trials can be sized appropriately.

Integration of the microbiological components of the MELiSSA loop and the higher plant chamber (HPC) is envisioned and so proper scaling of the HPC is essential. These results will be used to establish realistic estimates of nutrient (NH_4^+ and NO_3^-) fluxes between MELiSSA compartments (Tamponnet, 1993; Poughon, 1997). The study presented in this paper is a direct result of the ESA-MELiSSA initiative in HPC modeling and MELiSSA loop integration.

Olabi and Hunter (1999) have developed cost estimates of a bio-regenerative diet assuming a high degree of food closure. These authors have developed a linear programming routine, which selects the lowest cost diet from a number of surveyed foods, subject to constraints on the crew's nutritional requirements, food acceptability and variety. The dietary cost estimates were calculated in equivalent system mass units (ESM) and these included the cost of crop production and associated waste processing (Olabi and Hunter, 1999; Drysdale *et al*, 1999; Drysdale 1998). The crop production ESM estimates are in turn based on crop productivity attained under a given set of lighting (intensity) and environment (atmospheric CO_2 concentration, temperature, photoperiod) conditions, time to crop grow out and labour requirements associated with crop production. Crop and food costs are expressed as Kg ESM / Kg (dwb).

The parameters and sets employed by Olabi and Hunter (1999) in their linear programming routine can be summarized as follows:

F = set of foods

N = set of 19 nutrients

B = breakfast foods

a_j = acceptability of food j in F

l_{ij} = amount of nutrient i in food j for all nutrients i in N,

c_j = cost of food j in F, where the cost of each food j was given by;

$$C_j = \Sigma g_{ij}P_{ij} + \Sigma r_{ij}S_{ij} + \Sigma t_{ij}E_{ij} + L_j \qquad [1]$$

where c_j is the cost of food j, the first term represents the mass of crops locally produced times their production costs and the ESM production costs of raw crops (including labour and waste processing costs), the second term represents the mass of non renewable (earth) ingredients times their packaging penalty, the third term represents the mass of locally produced intermediate ingredients (i.e. tofu, flour) times their production costs including processing equipment and losses and labour, and the fourth term represents food preparation labour cost.

Constraints were expressed as follows:

b = minimum average acceptability of foods (set at 6.5), $\sum x_j b_j \geq b$

n_i = minimum level of nutrient i in N, $n_i \leq \sum x_j l_{ij} \leq m_i$

m_i = maximum level of nutrient i in N,

x_j = number of servings of food j in the set (1 unit = 1 serving of food j).

The objective function of their linear programming routine was defined as:

$$z = \min \Sigma c_j x_j \qquad \text{where } j \; e \; F \qquad [2]$$

The solution to the above minimization equation was the set of the number of servings of food j, x_j, such that overall cost of the resulting diet was minimized.

Olabi and Hunter (1999) have obtained the acceptability of a food component by using sensory panel data collected using a 9 point hedonic scale (9 is best, 1 is worst). The sensory panel had 48 subjects.

The authors handled dietary variety by imposing constraints on the number of servings allowed per food (degree of repetition) and the total number of servings of food in the diet.

The findings of Olabi and Hunter (1999) are important from a horticultural perspective. The menus define the set of crops to be grown locally. Secondly, cost minimization is conducted at the diet formulation level rather than at the crop production level. This means that crops, in effect, compete for inclusion in the optimized menu based partly on their productivity. Focus can therefore be directed to the minimization of crop production costs. The manipulation of growing environment conditions, such as the use of inner canopy illumination (Stasiak *et al*, 1999), the selection of high yielding or low light cultivars and the selection of crops with high harvest indices are means to influence the cost and quality of a bioregenerative diet. While this may come as no surprise, it is important to note that little information has been published on basic productivity for many of the crops used as ingredients in the menus of Olabi and Hunter (1999). Further broad surveys of cultivars and new commodities are severely lacking in the controlled environment literature.

Much of the crop productivity data used in original diet optimization trials were therefore taken from field production literature, with the exception of crops for which controlled environment or greenhouse production data were readily available.

The purpose of the work presented in this paper is i) to define a set of reasonable cultural conditions and associated productivity data for candidate crops included in recipes, ii) to determine the optimized diet based on these productivity and crop production data and waste processing ESM estimates, iii) to determine the amount of biomass of each crop required to meet menu demands incorporating food preparation and processing losses, iv) to estimate the production area requirements and ESM values for the optimized menu under conditions of staggered (continuous) planting and finally, v) to introduce techniques which may account for variability in crop productivity.

METHODOLOGY

The findings presented in this paper are the result of linear optimization runs using crop productivity data collected from the controlled environment literature and the subsequent back calculation of crop biomass requirements. The techniques and assumptions underlying this study are presented below.

ESTIMATING CROP PRODUCTIVITY AND COST - Crop productivity data were collected through a review of controlled environment literature. This included both greenhouse and chamber grown crops. The challenge in compiling these data was in the assessment of their applicability to operating assumptions of a BLS system. Candidate lighting technology requirements and configurations (i.e. overhead vs. inner-canopy illumination) have not been well defined. Since light is likely to be the most limiting factor in crop production, yield estimates needed to be obtained for crops grown under realistic light intensities. While some productivity data, such as those reported by Bugbee and Salisbury (1988) for wheat grown at high light intensity (~ 2000 μmolm^{-2}s^{-1} PAR) are high, data for crops grown under a more conservative range of light intensities were selected. Where possible, productivity data was collected from experiments in which i) CO_2 enrichment was employed at levels near 1000 ppm, and ii) light intensity ranged between 600 and 800 μmolm^{-2}s^{-1} PAR. When this was not possible, productivity estimates were adjusted based on light response curves collected for similar crops. Reported yields were extrapolated to those expected under 600 μmolm^{-2}s^{-1} PAR in the cases of broccoli, cauliflower, kale and spinach, using light responses estimated by Glenn *et al* (1984). Yields for snap bean, as presented by Jollife and Ehret (1985), were extrapolated to those expected under 600 μmolm^{-2} s^{-1} using a light curve established for a soybean canopy by Stasiak *et al* (1999). This amounted to providing a correction factor of 0.89% total plant dry weight increase per 1% increase in PPF for the first set of crops and a factor of 0.87% total plant dry weight increase per 1% increase in PPF for bean. Productivity data collected for wheat at 1300 μmolm^{-2} s^{-1} PAR and for rice at 1000 μmolm^{-2} s^{-1} PAR were not adjusted downward because their inclusion in the optimized menu was considered essential. This procedure allowed for the use of productivity estimates under comparable lighting conditions. Productivity data for CO_2 concentrations below 1000 ppm were not adjusted because crop response to long term enrichment is not easy to quantify (Zheng, 1999) and no systematic treatment of crop response to CO_2 was deemed reliable.

Productivity data were translated into crop production ESM (Kg ESM per Kg edible dry weight; Kg ESM Kg^{-1} dwb) estimates using mass equivalencies for a Mars surface installation, assuming 1800 days of production without end effects (Drysdale and Hanford, 1999). Assumptions were that 1.98, 400W HPS lamps per square meter could provide 1000 μmolm^{-2}s^{-1} PAR at canopy height under a light conversion and delivery efficiency of 0.360 and 0.7 respectively. ESM was calculated using the set of productivity data, inedible biomass yields (to calculate agricultural waste processing costs), and associated lighting conditions for each crop. In the case of crops for which no reliable productivity data could be obtained, crop production ESM was estimated as an average of ESM for potato, chard, cabbage, lettuce, sweet potato, tomato, spinach and dry bean (19.06 Kg ESM Kg^{-1} dwb).

Crop production ESM, ingredient processing costs and recipe preparation labour estimates were then used to establish individual ESM costs per serving of each recipe. This was done as outlined above and in Olabi and Hunter (1999).

MENU OPTIMIZATION - Menu optimization was conducted using the methodology of Olabi and Hunter (1999). The following changes were made to the original methodology in order to improve the quality of the resulting optimized diet.

1) the maximum allowable number of servings per recipe within the 10 day menu cycle was set at 1, with the exception of breakfast foods which were set at a maximum number of servings of 2 (since there were fewer breakfast food choices in the food set),

2) the recipes were divided into different food categories and a given number of recipes was constrained to be selected from each food category. Examples of food categories include appetizers, beverages, main dishes, breads, soups, salads and side dishes.

The optimization procedure selected from a total of 199 possible recipes and generated a 10-day menu cycle consisting of 98 dishes. Labour ESM equivalency was set at 0.5 Kg ESM per crew man hour.

DETERMINATION OF CROP BIOMASS REQUIREMENTS - The number of servings of each food in the optimized 10 day menu cycle was used to estimate the amount of ingredient required to feed 6 crew members. In the case of un-processed (fresh) ingredients (such as lettuce, potato, bell peppers) trimming losses were applied to recipe ingredient mass demands. The food preparation studies of Rovers and Hunter (1999) and Grange (2000) were used to provide preparation losses on a usable ingredient fresh weight basis. Crop fresh weight requirements were converted to dry weight requirements using moisture contents from the Nutritionist IV software package.

In the case of processed crops ingredient-to-crop equivalencies were used as established by Hunter. These equivalencies provided conversion yield efficiencies of the amount of crop dry weight required to produce a unit fresh weight of ingredient. For example, 0.937 Kg of dry, threshed wheat berries (dwb) was required to produce 1 Kg of Whole Wheat Pasta. The apparent 'expansion' of crop into finished ingredient is a result of ingredient moisture content. Crop moisture contents were taken from either of the Nutritionist IV software database for processed food to express menu mass demands on a dry weight basis.

The sum of all crop masses required to produce the full complement of optimized menu recipes was determined. Production area and the total ESM of crops required to meet menu demands were determined from the area based productivity data derived from literature review.

DETERMINATION OF AREA REQUIREMENTS FOR CONTINUOUS CROP PRODUCTION - Area based productivity estimates were used to determine crop production area requirements assuming cultural conditions identical to those reported in the source literature. The growout time (time from seeding to harvest) was divided by the menu cycle length to quantify the number of staggered planting blocks. For example, wheat, which required 82 days to harvest, would be grown at 10-day staggered planting intervals (requiring 9 planting blocks). The interval between staggered plantings set to the length of the menu cycle. The production areas required to meet the demands of 6 crew in a single menu cycle were also calculated.

THE INFLUENCE OF CROP YIELD VARIABILITY ON PRODUCTION AREA REQUIREMENTS - Production area requirements were re-calculated for wheat based on an assumed t-distribution of crop yields. These area requirements were chosen so that there was only, p, probability that the crop would fail to meet menu biomass demands. This assumed a t-distribution in crop yield and standard errors of the mean crop yield as determined from a range of simulated coefficients of variance (df=30). Standard errors of plant yield were calculated across the range of coefficients of variance simulated and critical t-values were selected at a given probability to yield one sided confidence bounds. Production area requirements were re-calculated at probabilities of 'crop failure' (i.e. not meeting menu demands) ranging from $p = 0.01$ to 0.45. Because few of the papers used to generate the productivity data in Table 1 reported standard errors in crop yield, this type of simulation could only be performed for wheat.

RESULTS & DISCUSSION

ESTIMATIONS OF CROP PRODUCTIVITY AND COST - The results of the literature review conducted to estimate crop productivity in closed environments are presented in Table 1. This information was used to update the crop productivity and ESM calculations prepared by Olabi and Hunter (1999). Reliable information on productivity in tightly controlled environments was lacking for some of the crops used as ingredients in the food list. In such cases productivity data from the NASA BVAD document (Drysdale and Hanford, 1999) were used. The planting density, light intensity (PPF), photoperiod (hrs of daylight), thermoperiod (day/night temperature regimes), and the harvest index values are as presented in the source paper or calculated from extrapolations to higher light intensities (as described in the methodology).

The number of staggered plantings required to meet menu demands in perpetuity is also presented in Table 1 assuming a 10-day planting interval. This production scenario results in having a full complement of physiological/growth stages of each crop in a single growth chamber at all times. In the case of tomato and cucumber, crops that produce fruit repeatedly in the course of their growth period, absolute production areas were not calculated. Tomato dry, edible yields over a period of 177 days have been reported to be 12.2 Kg per plant (Kimball and Mitchell, 1978). Cucumber dry edible yields over a period of 110 days have been reported to be 1.8 Kg per plant (Ito, 1978). It is estimated that a single tomato and cucumber plant would survive over 20.3 and 24.4 menu cycles respectively. Assuming a planting density of 5 plants m^{-2} for each crop, 2 m^2 of production area total would more than satisfy menu demands. Staggered production within each area could be used to ensure a continuity in the supply of biomass between trusses.

Estimates of crop ESM (Kg ESM Kg^{-1} dwb) are presented in the fifth column of Table 2. Drastic differences in crop production ESM are due to differences in crop productivity, harvest index and rotation period. Cauliflower was determined to be the most expensive crop to produce (highest ESM cost) owing to its relatively low harvest index, long rotation time and low planting density (Table 1). Lettuce was the cheapest (lowest ESM) because of its higher harvest index and high productivity.

MENU OPTIMIZATION & THE DETERMINATION OF CROP BIOMASS REQUIREMENTS - The biomass requirements of the optimized menu is presented in Table 2. In total, the optimized menu required 66.7 Kg of dry, edible crop biomass to feed a 6 member crew for the 10-day menu cycle. This number accounts for processing and food preparation losses. Biomass was supplied from a total of 26 crops and 15 herbs (e.g. dill, garlic, coriander, parsley and cilantro). Ingredients that could not be derived from locally produced crops were assumed to be earth/re-supply ingredients. In total, the 10-day optimized menu required 4.6 Kg (fresh weight) of earth ingredients, including salt, flavourings, and sucralose (sweetener). The menu demanded 26.2 Kg (26.2 L) of water for food preparation for 6 crew in the 10-day cycle not including water used for washing and clean-up. About 94% of total menu dry mass requirements was derived from locally produced crops (water requirement is excluded from the total).

Crop biomass requirements were converted to ESM estimates using crop production ESM and associated inedible biomass processing ESM. The ESM equivalency of crop biomass that was demanded by a single menu cycle is presented in Table 2, column 6. In total, crop production ESM is 439.3 Kg per menu cycle. Crop production ESM is also expressed on a per crew per day basis (7.3 Kg ESM $crew^{-1}$ day^{-1}). When compared to the STS food supply composed of pre-packaged food with water content (1.82 Kg ESM $crew^{-1}$ day^{-1}) or with the ISS packaged food with water (2.3 Kg ESM $crew^{-1}$ day^{-1}) it is seen that the bioregenerative approach to food production demands an ESM which is between 300 and 400% higher. It is important to note, however, that the STS and ISS food systems do not meet nutritional requirements for long-duration spaceflight (Drysdale and Hanford, 1999). Further, the bioregenerative system would meet some, if not all of the air revitalization requirements of crew. The ESM savings associated with this task is not included in the STS food system ESM.

A total of 103.5 Kg of inedible biomass (agricultural wastes) is expected to be produced by the crops within the 10-day menu cycle (Table 2). In addition, menu preparation is expected to yield more than 1572 g of waste biomass in the 10-day cycle. These losses are mainly from the trimming/preparation of potato, pepper, mushroom and carrot. The total cost of the waste treatment system (including a grinder, rapid-cycle bioreactor, solids separator and dryer) is estimated at 105.1 Kg. It is important to note that an ESM cost of the MELiSSA reactors has not yet been determined but must be considered in the future and should replace these estimates of the waste processing system cost.

Table 2 presents the total production area of crops required to meet menu demands in perpetuity. The total production area required to meet the 10-day menu cycle assuming continuous (staggered production) is estimated to be at least 453.0 m^2. Production area requirements for wheat, peanut, rice, soybean and potato are among the highest. This is not surprising since many of the secondary or processed ingredients used in recipes (flour, breads, tofu, syrup, oil) are derived from these crops. This production area will change as area based productivity estimates are updated (i.e. mushrooms, green onions, etc.).

No attempt to assess the air revitalization capacity of this crop set is done in this paper. However, Barta and Henderson (1998) reported that the wheat production area of 11.2 m^2 was sufficient to support the air revitalization requirements for a single crew member. It is therefore expected that the full complement of crops used in this optimized menu would be sufficient to support a crew of six since the area demanded by the optimized menu is about 40 times higher than that of the Variable Pressure Growth Chamber (Barta and Henderson, 1998). Barta and Henderson's estimate is based on data collected from the vegetative phase of wheat grown under very high light intensities. The estimates presented in this body of work are based on multiple crops and multiple physiological stages of each crop grown at lower light intensities and the regeneration of CO_2 from inedible biomass. It is therefore important to assess the air revitalization capacity of integrated production (multiple crops, multiple physiological stages) systems empirically.

A sensitivity analysis was conducted to examine the relative contributions of equipment mass, labour, and power and cooling to the menu demanded ESM (data not shown). On average, about 60% of the system mass is tied up in equipment, 26% in labour and 14% in power and cooling assuming a uniform ESM equivalency for crew labour. It is important to note that the nature of the optimization requires the ESM cost of labour to be a constant. It was therefore not possible to use the Levri-Vaccari model for crew labour, which allows labour cost to increase as the total number of hours available for work is consumed (Drysdale and Hanford, 1999). It is possible, however to run the optimization iteratively at different values of the

ESM labour cost and then to re-calculate available labour and labour ESM using the Levri-Vaccari model. At the convergence of the Levri-Vaccari labour price and the labour price used in the optimzation, the optimization result at the true price of crew labour is achieved. This will be investigated in future studies.

It is important to note that significant reductions in food system ESM may be achieved through an optimization of crop production and cultural practices. The use of inner canopy illumination, the selection of high-yielding (increased harvest indices) cultivars, optimization of the nutrient delivery system and mechanization of crop maintenance requirements are all techniques currently being investigated to reduce crop production cost. Methods of increasing productivity and reducing the mass of the lighting and nutrient delivery systems are the most important areas for research.

QUALITY AND COMPOSITION OF THE OPTIMIZED MENU - The nutritional quality of the optimized menu relative to recommended daily allowances is presented in Table 3 Table 4 shows the number of servings of each food item selected in the optimization for a single crew member over the 10-day menu cycle. Food items in this table contribute to an average acceptability of 6.9 – well above the constraint value of 6.5. Overall, the nutritional quality of the diet is excellent with all minimum recommended daily allowances being met with the exception of calcium and biotin. The diet had higher iron contents than was recommended for long duration space flight, but this is acceptable since the bio-availability of iron in vegetarian diets is much less than 20% (Monsen, 1988). These deviations in nutritional quality are the combined result of a relaxation in nutritional quality constraints to obtain a feasible solution in the linear optimization and the fact that some nutrients (e.g. calcium) are inherently difficult to supply adequately from plant based diets.

ASSESSING THE IMPACT OF CROP VARIABILITY ON PRODUCTION AREA REQUIREMENTS - In any given planting there is some probability of crop failure, that is, failure to meet menu demands for that crop in that planting cycle. Production area requirements for perpetual production should include a safety factor against the possibility of a crop shortfall or even a catastrophic failure.

As a demonstration, planting area requirements were re-calculated for wheat based on an assumed t-distribution of crop yields , as a function of the probability p that the crop would fail to meet the required production. This assumed a t-distribution in crop yield and standard errors of the mean crop yield as determined from a range of simulated coefficients of variance (df=30). Standard errors of plant yield were calculated across the range of coefficients of variance simulated and critical t-values were selected at a given probability to yield one sided confidence bounds. Production area requirements were re-calculated at probabilities of ‘crop failure’ (i.e. not meeting menu demands) ranging from p = 0.01 to 0.45. Because few of the papers used to generate the productivity data in Table 1 reported standard errors in crop yield, this type of simulation could only be performed for wheat.

CONCLUSION

Crop production areas required to meet a 10-day menu cycle for a crew of 6 total 453 m^2. This number assumes continuous production and will therefore meet menu demands in perpetuity. An estimate of total food production system ESM is 439 Kg per menu cycle or 7.3 Kg ESM $crew^{-1}$ day^{-1}, including agricultural and food preparation waste processing costs. While this estimate is high compared to STS and ISS food systems’ ESM values, the bioregenerative food production system would provide all the air revitalization capacity and water production for the crew. Significant reductions in food subsystem ESM can be made by increasing crop productivity and by streamlining food processing and preparation methods.

ACKNOWLEDGEMENTS

This project was made possible by grants from the European Space Agency MELiSSA program, NASA Grant 5-4222, Centre of Research in Earth and Space Technology (Ontario) and Agriculture and Agri-food Canada

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DEFINITIONS, ACRONYMS, ABBREVIATIONS

CREW: A single crew member

DW, DWB, D.B.: Dry weight or dry weight basis

ESM: Equivalent System Mass. This measure converts non-mass physical inputs to an equivalent mass using appropriate mass penalties. Such a metric allows for the comparison of two life support systems with different parameters using a single scale – mass. ESM measures for crop production include power, infrastructure mass, heating/cooling costs, volume and labour equivalencies

HARVEST INDEX: The ratio of edible to inedible biomass expressed on a dry weight basis

PHOTOPERIOD: The length of plant day in hours

PPF: Photosynthetic Photon Flux, expressed in $\mu molm^{-2}s^{-1}$ PAR (Photosynthetically Active Radiation)

Crop	Density (plants m^{-2})	PPF (µmol m^{-2} s^{-1}) PAR	Photo-period (hrs)	^{o}C (day/night)	Edible Biomass (g plant^{-1}, dwb)	Harvest Index (%)	Days to Harvest	Number of Staggered Plantings	Source
Broccoli	5.5	600	16	20/15	130.4	35	83	9	Reekie *et al* (1998)
Beet	39	700	14	18/18	25.5	98	84	9	Wurr *et al* (1998)
Bean	81	600	16	26/20	28.5	72	55	6	Jolliffe and Ehret (1985)
Cauliflower	5.5	600	16	20/15	114.1	20	83	9	Reekie *et al* (1998)
Carrot	307	640	16	17/11	8.7	63	86	9	Mortensen (1994)
Kale	5.5	600	16	20/15	28.7	80	43	5	Reekie *et al* (1998)
Lettuce	30.4	640	16	17/11	6.4	94	26	3	Wheeler *et al* (1994)
Onion	76.2	640	16	17/11	16.8	66	93	10	Mortensen (1994)
Potato	5.88	800	12	16/16	383.3	79	90	9	Wheeler *et al* (1991)
Rice	235	1000	12	31	10	47	110	11	Bugbee (website)
Sweet Potato	--	800	13	28/24	900	38	112	12	Goins *et al* (1999)
Soybean	24	600	9	26/20	76	45	90	9	Sionit *et al* (1987)
Spinach	39	600	16	24/18	12.8	74	33	4	Both *et al* (1995)
Wheat	1000	1300	24	23	2	37	82	9	Barta & Henderson (1998)
Cabbage	30.7	640	16	17/11	51.4	--	67	7	Mortensen (1994)

TABLE 1. Crop cultural conditions used to establish menu ingredient ESM and to determine production area requirements. Planting density, light intensity (PPF), photoperiod (hrs of daylight) and day night temperature regimes are presented. Edible biomass estimates were as presented by the source authors. Some yields were scaled to comparable light intensities using representative light response curves (see methodology). Days to harvest and the number of staggered plantings given a menu cycle of 10 days are also presented. Missing values were also missing in the source literature.

Crop	Crop Productivity (Kg edible dw m^{-2} day^{-1})	Dry Weight Required in Menu Cycle (g)	Area (m^2) (Continuous Production)	Kg ESM/ usable Kg dry weight	Kg ESM/ menu cycle	Kg ESM crew^{-1} day^{-1}	Inedible Biomass Produced in Menu Cycle (g, dwb)
Broccoli	0.00300	26.30	0.95	30.91	0.81	0.01	48.85
Beet	0.01180	175.31	1.59	9.12	1.60	0.03	3.58
Bean	0.04200	2704.40	7.02	2.39	6.46	0.11	1051.71
Cauliflower	0.00150	0.00	0.00	65.74	0.00	0.00	0.00
Carrot	0.03110	406.53	1.37	2.88	1.17	0.02	238.75
Cucumber	0.04094	19.99	See Text	19.06	0.38	0.01	See Text
Herbs	0.01500	0.95	0.01	19.06	0.02	0.00	0.24
Kale	0.02040	47.61	0.27	4.03	0.19	0.00	11.90
Lettuce	0.07480	19.54	0.03	1.31	0.03	0.00	1.25
Onion	0.01380	381.82	2.98	7.4	2.83	0.05	196.70
Green Onion	0.01500	2.85	0.02	7.4	0.02	0.00	0.18
Peppers	0.00601	543.96	See Text	19.06	10.37	0.17	See Text
Peanut	0.00450	9733.52	216.30	9.27	90.23	1.50	38934.10
Potato	0.02500	1215.82	4.86	3.47	4.22	0.07	323.19
Rice	0.01000	5123.78	51.24	8.04	41.20	0.69	5777.88
Sweet Potato	0.02050	3051.79	14.89	4.72	14.40	0.24	4979.24
Swiss Chard	0.00500	0.00	0.00	26.65	0.00	0.00	0.00
Soybean	0.02030	6987.97	34.42	3.87	27.04	0.45	8540.85
Spinach	0.01510	105.14	0.84	6.38	0.67	0.01	36.94
Tomato	0.00970	10483.88	See Text	8.4	88.06	1.47	See Text
Wheat	0.02440	25323.55	113.91	5.69	144.09	2.40	43118.48
Alfalfa	0.01500	30.68	0.22	19.06	0.58	0.01	52.23
Cabbage	0.00900	17.52	0.19	7.53	0.13	0.00	1.12
Chili Peppers	0.01500	3.65	0.03	19.06	0.07	0.00	1.68
Mushrooms	0.01500	179.55	1.29	19.06	3.42	0.06	119.70
Snow Peas	0.01500	41.37	0.30	19.06	0.79	0.01	16.09
Squash	0.01500	27.79	0.21	19.06	0.53	0.01	18.53
Crop Total		**66655.25**	**452.94**	**-----------**	**439.32**	**7.32**	**103473.18**
Water (L)		26.18					
Earth Ingredients (fresh)	**Closure = 94 %**	**4598.10**					

TABLE 2. Dry weight requirements and ESM of crops required in optimized menu. Crop specific total ESM (Kg) and Kg ESM per unit dry weight are presented for a single menu cycle. These ESM values include crop production and inedible biomass processing costs. The amount of inedible biomass produced by each crop (excluding food preparation losses) is presented based on harvest index data and menu demands for edible biomass.

Nutrient	Recommended Level	Level in Optimized Diet
Calories	Men: 3.0 (11.6 W+879) kcal/day Women: 3.0 (8.7W+829) kcal/day	2900 cal
Protein	12-15% of total caloric intake for 2000 cal: 60-75 g	107.5 g
Carbohydrate	50-55% of total caloric intake for 3000 cal: 250-275 g	415 g
Total Dietary Fiber	10-25 g	50.8 g
Fat	30-35% of total caloric intake for 3000 cal: 66.67-77.78g	98.5 g
Sodium	1500-3500 mg	3832.7 mg
Iron	< 10 mg	34.7 mg
Calcium	1000-1200 mg	711.7 mg
Magnesium	350 mg	540.5 mg
Vitamin A	1000 µg	2060 µg
Vitamin E	20 mg	28.4 mg
Thiamin	1.5 mg	2.6 mg
Riboflavin	2.0 mg	23.0 mg
Niacin	20 mg	26.1 mg
Vitamin B6	2.0 mg	2.3 mg
Folate	400 µg	601.5 µg
Pantothenic Acid	5.0 mg	23.0 mg
Biotin	100 µg	20.6 µg
Vitamin C	100 mg	256.3 mg

TABLE 3. Recommended nutrient levels and those obtained in the optimized diet. Recommended daily intakes are for long term space flights less than 360 days (JSC Report 28038) and are not those for long duration space missions.

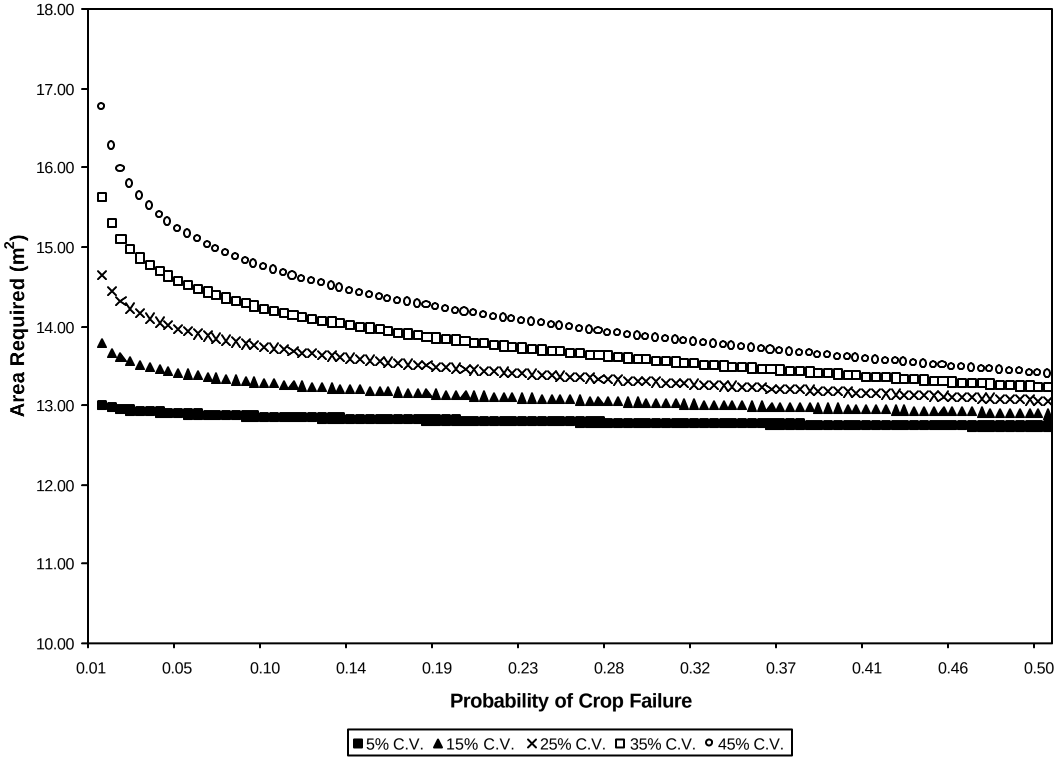

FIGURE 1. Production Area Contingencies for Crop Failure. Crop failure in this context refers to the probability (x-axis) of not meeting menu demands at the corresponding production area (y-axis). Production areas are based on one sided t-values derived from various coefficients of variance (C.V.) assuming df=30.

Food	# of Servings	Food	# of Servings	Food	# of Servings
Barbequed Tempeh Sandiwich	1	Melon Ginger Salad	2	Soysage	2
BBQ Seitan	0.36	Marinated Broccoli	1	Fresh Spinach & Mushroom Crouton Salad	1
Beets and Carrots in Lime Vinagrette	1	Marinated Tofu Appetizer	1	Spaghetti	1
Breaded Tofu Appetizer	1	Marinated Vegetable Salad	1	Sweet Potato and Red Pepper Homefry	1
Broccoli Pepper Salad	0.76	Melon Drink	1	Spicy Thai Style Noodle	0.35
Broiled Zucchini with Herbs	0.13	Mushroom Duxelles Spread	1	Spicy Oven Fries	1
Carrot Cookies	1	Mushroom Burger	1	Sweet Potato Salad	0.36
Carrot Drumsticks	1	Mushroom Medley	1	Sweet Potato Poundcake	2
Carrot Juice	0.62	Mushroom and Lentil Sandwich	1	Sweet Potato and Peanut Soup	1
Carrot Rice Loaf	1	North African Pizza	0.23	Spinach Side Dish (Tomato)	1
Carrot Soup	1	Orange Soy Yogurt	2	Summer Salad With Melons and Strawberries	1
Chocolate Soy Candy	1	Peanut Maple Topping for Pancakes	2	Strawberry Rice Drink	1
Chocolate Orange Rum sauce	1	Potato Onion Bread	0.33	Strawberry Sorbet	1
Cinnamon Peanut Rolls	2	Potato and Fresh Corriander Dish	1	Strawberry Topping	2
Coleslaw	1	Potato Salad	1	Stuffed Chard with Carrot Sauce	1
Creamy Herb Dressing	0.81	Peanut-Wheat Burger	0.40	Tarragon Sweet Beans, Onions and Potatoes #1	1
Creamy Onion Soup	1	Peanut Wheat Cereal	2	Tarragon, Sweet Beans, Onions and Potatoes #2	1
Dill Potatoes	1	Quick cream of mushroom soup	1	Tofu Custard Pie	1
Fatima Salad with Potatoes	1	Rice Amazake Pudding	1	Tofu Spinach Pie	1
Gado Gado with Peanut Dressing	1	Rice Milk	0.38	Tomato Cucumber Salad	1
Garden Style Stuffed Potatoes	1	Rice and Wheat Pancakes	2	Tomato Juice	1
Garlicy Scalloped Potatoes	1	Roasted Veggie Pizza	1	Tomato Lime Soup	1
Green Beans & Carrots in Tomato Sauce	0.87	Savory Herb Cracker	1	Tunisian Salad	1
Green Soybeans	1	Scalloped Potatoes and Carrots	1	Vichyssoise Cold Potato Soup	1
Greek Spinach Rice Balls	1	Scrambled Tofu	2	Roasted Veggie Sandwich	1
Herb Biscuits	0.67	Shiitake Consome with Greens	1	Vegetable Paella	1
Hot Wheat and Amasake Cereal	2	Sloppy Joe Tempeh	1	Veggie Salad with Snow Peas	0.89
Herbed Tofu Spread	1	Soybean Loaf	0.33	Wheat Amazake Waffles	2
Kale Soup	1	Soy Vanilla Pudding	1	Watercress and Sprouts	1
Lancashire Hot Pot	0.51	Soy Wheat Crepes	2	Wheat Berry and Rice Cereal	2
Lemon Poppy Seed Cake	1	Soya Mocha Beverage	1	Whole Wheat Amazake Bread	1
Lentil Loaf Sandwich	1				

TABLE 4. Selected foods in the optimized menu. The number of servings refers to the number of servings for a single crew member within the 10-day menu cycle. Since integer programming was not used, rational numbered servings would be handled by serving the a full serving of the item over a period longer than the 10-day menu cycle.