Eat to Explore: A Modified Mediterranean Diet for Long Duration Spaceflight (Martian Hardtack)

By Stellie J. Ford

We as a people are on the forefront of a new frontier. The price of access to space is rapidly dropping and as more parties venture further, resource channels will build the highways for generations of colonists. That push out will be the greatest migration in the history and future of humanity. It will be a slow and laborious shift as every aspect of life adapts to the novel paradigm of life in space. A century from now the settled citizens of free space, Mars, the Moon, and other terrestrial bodies will have developed their own cultures that fit their lifestyle and environment. As with the colonization of the Americas the pieces of our societies and our culture that we bring with us will be reshaped by exigent need and magnified in historical reflection on this diaspora. Food is one area where social divergence is apparent and celebrated in modern culture and will likely be so in the future. By considering the dietary and culinary practices we bring with us, we can hope to shape the culture we are guiding.

Food is one of my personal favorite parts of culture in the distillation of preferences it can present. This can cause friction at times, but in accommodation to this more minor social interface we can provide space for greater connectivity. In the diet and food systems for the earliest deep space explorers what should we be eating to both keep us healthy and together as individuals and crews? In this paper I hope to address the core biological needs that must be met by diet during a long duration in space and get a sense of the implied gastronomy.

Mission Scope

The duration and conditions of any mission play a large role in defining food choice and consumption, but there are share similar conditions that must be met by all. Ideally, this allows for shared optimizations as well. Here I'm addressing the ~900+ day domain and NASA's Mars Design Reference Architecture v5.0. A 900-day characteristic maximum time between resupplies places missions like this at a pivotal time in exploration. These are the earliest ground truth missions and precursors colony efforts at not just Mars, but L5, Near Earth Asteroids, and free space as well. To make this feasible the ability to feed and nourish astronauts independent of

Earth will be a keystone technology for all deep space operations. This is a more significant isolation and self-reliance than is experienced in present day Antarctica or even the early American colonies.

Per the DRA, this will be an all- up conjunction class mission without the pre-deployment f supplies on a distant body, though they could presumably exist as a non-mission specific emergency cache. I will address limited ISRU potential, but the diet I'm outlining is intended to be independent of ISRU. I am basing the scale of this model around 10 astronauts who will transit from Earth to Mars on a purpose- built space station. Once there, they will orbit Mars and conduct surface operations including extended surface stays for nearly 500 days, all while remaining supplied by the station.

The station is thrust system agnostic and will be based on three primary research and habitat modules analogous to the Bigelow Aerospace BA 2100 design [e] along with ancillary modules for power of an estimated 1MW, propulsion, cooling, and support. A set of hydroponic systems will be incorporated into one of the station modules to provide a verdant greenhouse that will provide nearly half of the astronauts' food by volume. They will share a central water source that is connected to multiple growing systems e.g. enclosed aeroponics, nutrient film tubes (NFT), and porous capillary substrate growth medium. A wide array of produce will be available on the station supported by ultrasonic pollination and integrated semi-autonomous robotic farming equipment. Their yield and nutritional content can also be supplemented through biostimulants [aw]. The hydroponic beds will extend 10m axially across one hemisphere of one of the BA 2100 modules resulting in ~1090m$_3$ volume that will be further subdivided into two 2.25m high layers of ~188m$_2$ and 118m$_2$. These will be reduced to 170 m$_2$ and 100m$_2$, respectively due to a 2m x 18m x 4.5m tree region that will cover one end of the garden. While this design envisions a 1MW heat pipe reactor, similar designs could range from a few hundred kilowatts with very large solar arrays [j] to a few megawatts with larger micromodular reactors that are currently in development [k].

Pragmatic Nourishment

While there are many diets that purport to go beyond simple nutritional balance and offer significant benefits, there is currently no hardcoded diet for astronauts. Chris Hadfield's Space Kitchen videos [m] are often more reminiscent of dormitory cuisine than might be expected at a $120 billion research station. And while there was never a nutritionist monitoring my consumption of honey or ramen during college, my life rarely depended on my physical fitness. The isolation and extended duration of future missions will increase the importance diet of astronauts. The balance of nutrition, storage capability, and good consumption practices has given us wonderful creations life freeze dried ice cream, and MREs. Both effective, yet underwhelming solutions to our human needs. Holistic optimization can hopefully improve this balance by introducing more variety and compensatory benefit into the food system.

Healthy eating could be a key component to the endurance [a] and resilience needed for space exploration. At the same time astronauts must find the food palatable to ensure that they are eating enough throughout the mission. A reduced sense of smell is a common problem among astronauts [n] and can limit appetite. ISS crew members were found to consume only 80% of their recommended daily calories leading to reduced weight upon return [x]. Selecting foods based on what individual astronauts prefer on Earth will maximize the psychological benefit that they derive from eating. One key example of this is the inclusion of onions. While they are culinarily flexible, a subsistence crop around the globe and have high yields, the smell is intolerable to many, particularly in a closed environment. Milder variants like shallots could mitigate the problem somewhat. The galley can also serve as a control point for smells, high throughput activated carbon filters could minimize both the spread and duration of any odors and serve as a zonal ECLSS element.

Food as Culture

The relationship between food culture and regional health is quite strong on Earth and can serve as a model for the anticipated food culture of space explorers. In their 2007 review paper, Whalqvist and Lee isolate the problem thus:

> *“*The challenge is to respect and retain *traditional food knowledge* and *sustainable food systems*, with *good governance* for food security*”*

By applying the data analytics and high-level modeling and management that is already ubiquitous in space systems, we will be able to meet these goals in seamless accord with the advancement of humanity. Future space explorers will have a tremendous wealth of traditional food knowledge to draw from, not just in terms of biometrically documented physical and metabolic impact, but AI driven awareness of delicious food pairings [ay]. Unlike previous voyages, this one will be backed by genetic screening for dangerous dietary predispositions an astronaut and be able to adapt stocking accordingly. While present day screening can identify some conditions like lactose intolerance [ba], Favism or Lathyrism susceptibility [h] it is still limited from true personalization [bb]. To prepare for long duration exploration we must improve our dietary models with pre-flight characterization of astronauts, a higher resolution view of what is being eaten by early astronauts during their missions, and its impact on their biosystems [bf].

Thorough modeling of the quality of stored food over the mission duration and modeling of the output of the hydroponic system we will provide a more accurate and reliable prediction of what is actually available to explorers to be ingested. Along with the increased focus on testing astronauts, characterization of traditional nutrient levels [bd] and the phytonutrients that help reduce oxidative damage [bc] will help quantify their impact. A massive increase in the availability and ease of MS testing [g][be] is making its way into the world quite rapidly and will allow for the extremely precise identification of the chemical constituents of a substance. This not only allows for knowledge of nutritional content but helps identify when spoilage has begun and can provide a certainty of safety when accessing long stored supplies. Advanced optical monitoring will also be used on our crops. This will help prevent pathogens [bg][bh] from taking root in the system and provide an ongoing assessment of yield [bi].

No matter the detail of these tools nor the thoroughness of analysis, the management and planning of missions will be critical to their success. The implementation of Artificial Intelligence based systems management [bj] is another example where a fundamental need ion space will drive the development of technology that helps the world. What we teach this AI to value will dictate much of the comfort and holistic satisfaction we derive from its action. To guide this and our own actions, Whalqvist and Lee provide additional support by identifying the key factors in table 1. These are higher level design goals that can help shape implementation, the tolerable differences they identify in particular can help inform the culinary diversity and agricultural needs on the station. Through the definition of these broader governing parameters we can hope to characterize some of the features of long-term space diets.

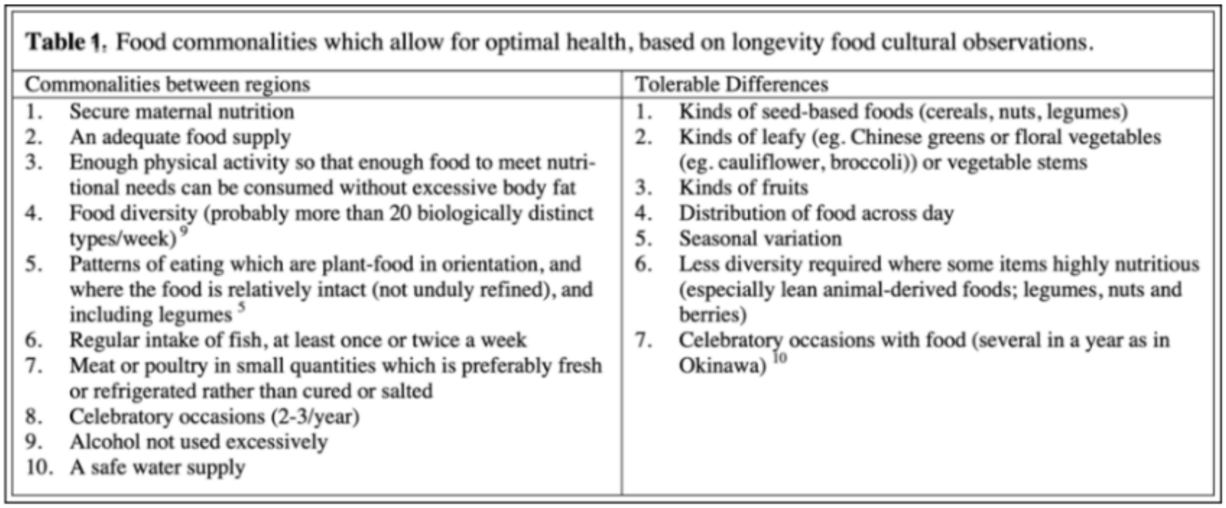


Table 1. Food commonalities which allow for optimal health, based on longevity food cultural observations.

Commonalities between regions	Tolerable Differences
1. Secure maternal nutrition	1. Kinds of seed-based foods (cereals, nuts, legumes)
2. An adequate food supply	2. Kinds of leafy (eg. Chinese greens or floral vegetables (eg. cauliflower, broccoli)) or vegetable stems
3. Enough physical activity so that enough food to meet nutritional needs can be consumed without excessive body fat	3. Kinds of fruits
4. Food diversity (probably more than 20 biologically distinct types/week) [9]	4. Distribution of food across day
5. Patterns of eating which are plant-food in orientation, and where the food is relatively intact (not unduly refined), and including legumes [5]	5. Seasonal variation
6. Regular intake of fish, at least once or twice a week	6. Less diversity required where some items highly nutritious (especially lean animal-derived foods; legumes, nuts and berries)
7. Meat or poultry in small quantities which is preferably fresh or refrigerated rather than cured or salted	7. Celebratory occasions with food (several in a year as in Okinawa) [10]
8. Celebratory occasions (2-3/year)	
9. Alcohol not used excessively	
10. A safe water supply	

Table 1: Modified from Whalqvist and Lee (2007) [t]

Diet

For long duration space flight, I am advocating adherence to a Mediterranean diet

modified with some substitute protein sources and with the flexible inclusion of intermittent fasting. The Mediterranean diet's [bl] heavy focus on fresh fruits and vegetables as its foundation maximizes the value of in-space produce production capacity and provides a wealth of physiological benefits. The diet has been found to be broadly neuroprotective [bk], reduce oxidative stress, and even reduce depression in younger adults [aq] [u]. The diet is low in saturated fats with fat overall constituting 35-40% of the diet. Proteins make up 15-20% of dietary calories and the remaining 40-50% ideally comes from carbohydrates from non-sugary sources. Of the ~900kg of food that NASA recommends per person per year [ab] the bulk of the calories needed by astronauts will come from prepackaged foods that are preserved and shelf stabilized with the ability to be stored for up to 5 years [f]. This is the current gold standard, and while it does produce a substantial amount of packaging waste, it is not mass limiting in comparison to the infrastructure for food production. Further the reliability of these products as the current commercial solution for NASA adds a comfort from credibility that is necessary for long duration space missions.

In practice there will be minimal processing of food before consumption. This may extend to thawing, heating, hydrating, and limited combination of sub ingredients e.g. boil in bag or assembly, but all food cargo will be either ready to eat or readily edible. In practice prepackaged and stored foodstuffs will be primarily from the upper three layers of the food pyramid below (fig 1). The need for efficiency and adherence to a Mediterranean theme will minimize the inclusion of some higher fat products like potatoes and soy [bl], but they will still be consumed in moderation. A range of processed and prepackaged meats will be available including jerky, precooked chicken as sandwich or dish ingredient, and prepared full meals that only require heating and rehydration. Beans will be included as a higher protein starch. Bioreactors to produce mycoprotein will be included as a supplemental protein [as] and will become more valuable in the later stage of the mission. The fermented mycoprotein is combined with powdered egg whites, seasoning, and vegetable starch before being cooked. While somewhat intensive, the ability to synthesize a palatable protein source dramatically increases the food stability of the voyage. Only 2kg wheat are required to produce 1kg mycoprotein [at] making the trade-off sustainable and offering the option to forgo some pick and eat food for the ability to produce more protein.

Two Mediterranean icons, olives and nuts, will be included in the menu. Olives have been shown to retain certain beneficial phenolic compounds like hydroxytyrosol after multiple years of preservation and deliver their benefits with moderate consumption of ~20 olives/day [bm]. Irradiated nuts will be a further source of unsaturated fats and when preserved with silver nanoparticle impregnated packaging are shelf stable for up to 20 months [ar]. Olive oil will also taper off in quality by the end of the mission and see significant oxidation by the start of year two but is still edible [au]. Infusion with distillates of antioxidants are one option for extending the shelf life of this commodity but may lead to obscure flavor combinations due to the available antioxidant sources. There is the potential to produce oil from grown on the ship, but this requires drying and processing that is time, labor, and equipment intensive. As another supplement to the culinary and nutrient diversity of the explorers’ diet, powdered eggs [i], milk, and cheese products will be included. These provide high quality proteins help to ameliorate the discomfort of such a remote journey, but work may still need to be done on the quality of options that meet the stability requirements of space travel.

The benefit of food can be found in its association to ritual and the comforting times we associate with it as well. A variety of dry tea and coffee will be included and be available for the duration of the journey. Happily, many commercial snack foods are also shelf stable for over two years and won't be left off of the menu. While they don't contribute to nutrition significantly, they provide a measure of familiarity and joy to the dining experience that can make the obscurity of space cuisine easier to swallow.

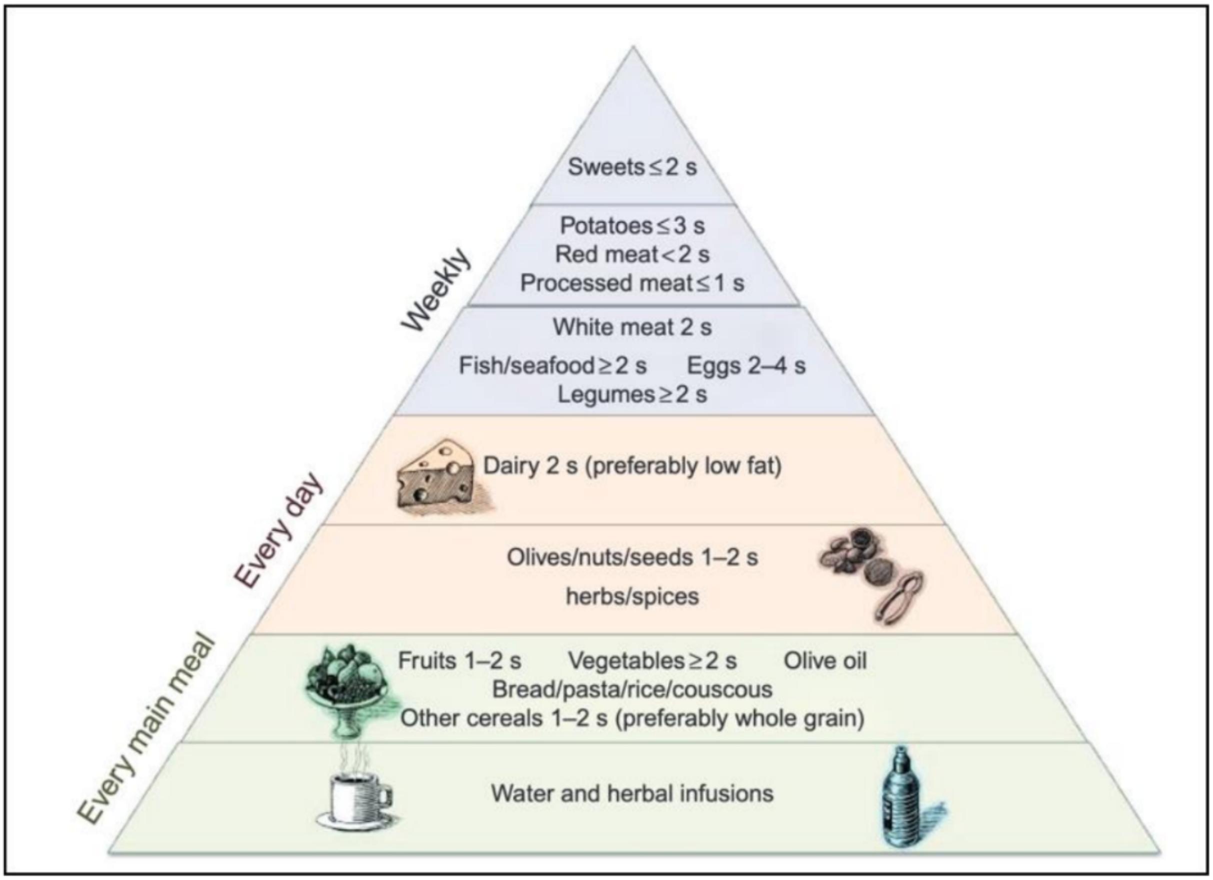
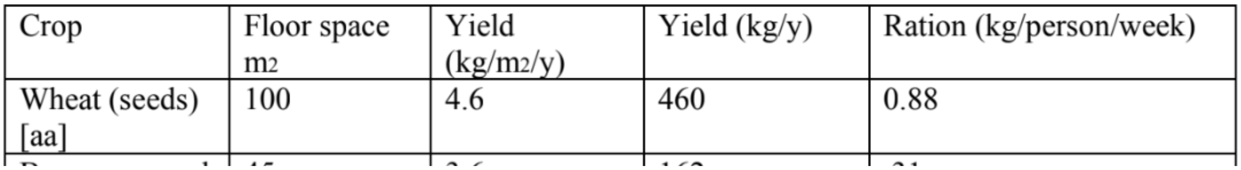
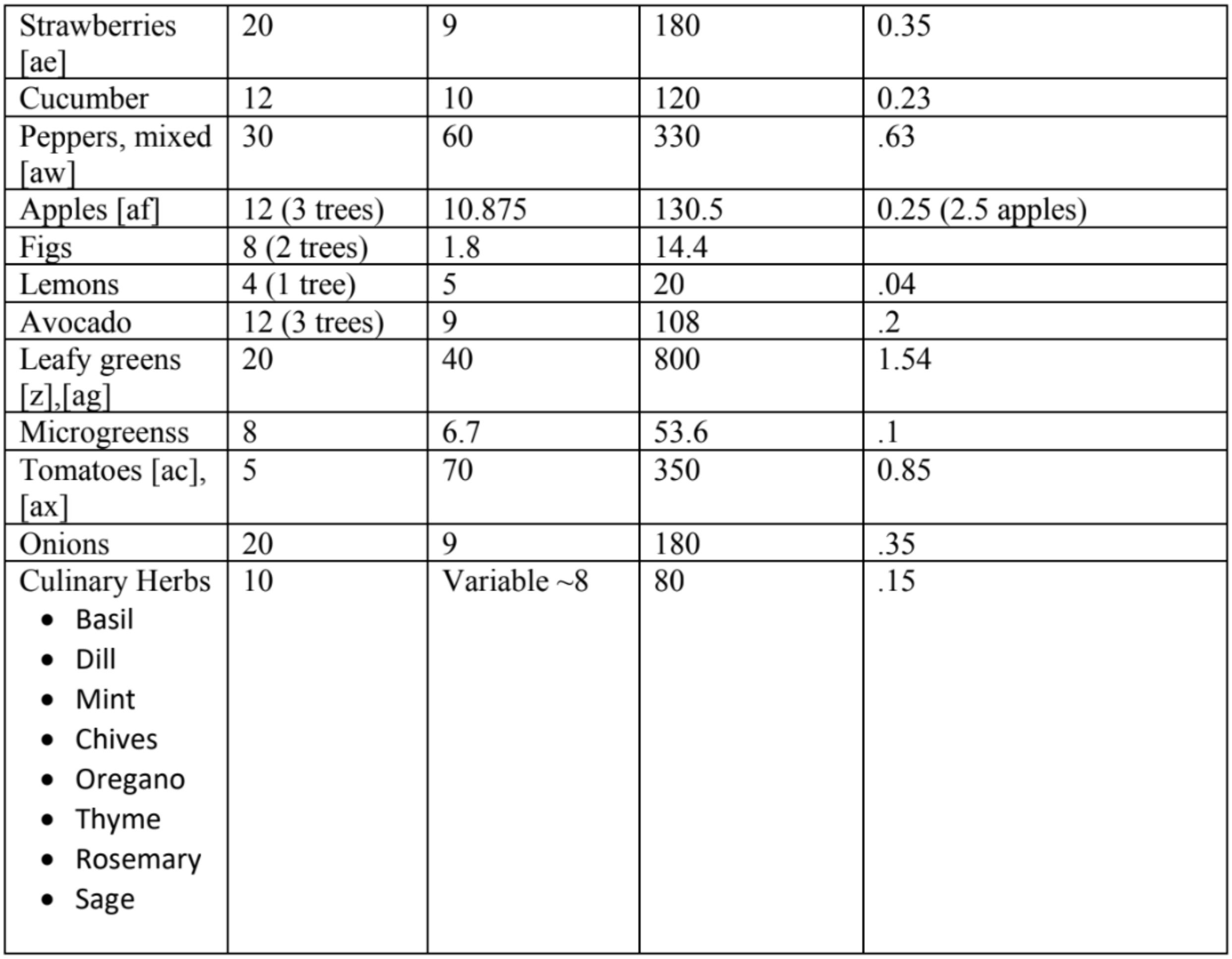


Figure 1: Adapted from Macpherson et al. (2015) [aq]

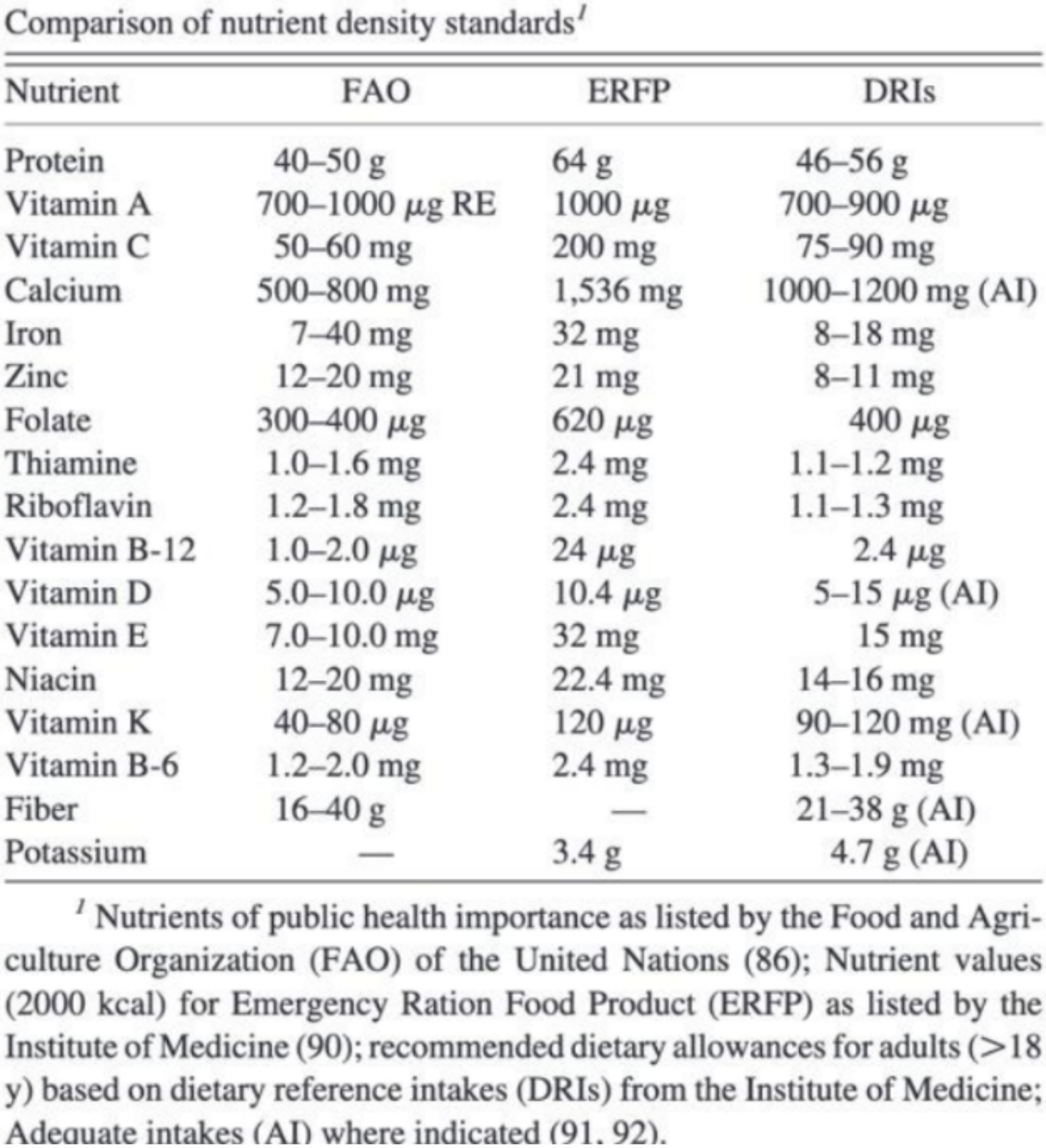
It is important to assess the availability of not just prepackaged food but produce that will be produced on the station. This will be primarily pick and eat or minimally processable crops. To facilitate convenience and diversity an 36m$_2$ tree loft has been included in the garden. This will allow approximately 9 dwarf fruit trees to be planted and provide convenient pick and eat foods. With yields ranging from 4.6kg/m$_2$/y edible seed mass for wheat to 90kg/m$_2$ for tomatoes [ac] and a combined 270m$_2$ of growing space a significant portion of the explorer's diet can be grown on the ship if sufficient power is available.

Crop	Floor space m2	Yield (kg/m2/y)	Yield (kg/y)	Ration (kg/person/week)
Wheat (seeds) [aa]	100	4.6	460	0.88
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
Strawberries [ae]	20	9	180	0.35
Cucumber	12	10	120	0.23
Peppers, mixed [aw]	30	60	330	.63
Apples [af]	12 (3 trees)	10.875	130.5	0.25 (2.5 apples)
Figs	8 (2 trees)	1.8	14.4	
Lemons	4 (1 tree)	5	20	.04
Avocado	12 (3 trees)	9	108	.2
Leafy greens [z],[ag]	20	40	800	1.54
Microgreenss	8	6.7	53.6	.1
Tomatoes [ac], [ax]	5	70	350	0.85
Onions	20	9	180	.35
Culinary Herbs • Basil • Dill • Mint • Chives • Oregano • Thyme • Rosemary • Sage	10	Variable ~8	80	.15

Table 2: Hydroponic Yields

With the exception of the trees, these crops can be raised without the need for structural media, lowering the overall mass and maintenance requirements for the system. While this technology has been proven in terrestrial situations, only minimally viable demonstrators have been flown to space [r]. The maturation of these systems will help ensure the long-term stability of long-term missions by producing vitamins and nutrients to supplement the bulk calorie consumption from packaged foods. A single tomato can provide up to 28% of the daily reference intake of vitamin C [bn].



Comparison of nutrient density standards[1]

Nutrient	FAO	ERFP	DRIs
Protein	40–50 g	64 g	46–56 g
Vitamin A	700–1000 μg RE	1000 μg	700–900 μg
Vitamin C	50–60 mg	200 mg	75–90 mg
Calcium	500–800 mg	1,536 mg	1000–1200 mg (AI)
Iron	7–40 mg	32 mg	8–18 mg
Zinc	12–20 mg	21 mg	8–11 mg
Folate	300–400 μg	620 μg	400 μg
Thiamine	1.0–1.6 mg	2.4 mg	1.1–1.2 mg
Riboflavin	1.2–1.8 mg	2.4 mg	1.1–1.3 mg
Vitamin B-12	1.0–2.0 μg	24 μg	2.4 μg
Vitamin D	5.0–10.0 μg	10.4 μg	5–15 μg (AI)
Vitamin E	7.0–10.0 mg	32 mg	15 mg
Niacin	12–20 mg	22.4 mg	14–16 mg
Vitamin K	40–80 μg	120 μg	90–120 mg (AI)
Vitamin B-6	1.2–2.0 mg	2.4 mg	1.3–1.9 mg
Fiber	16–40 g	—	21–38 g (AI)
Potassium	—	3.4 g	4.7 g (AI)

[1] Nutrients of public health importance as listed by the Food and Agriculture Organization (FAO) of the United Nations (86); Nutrient values (2000 kcal) for Emergency Ration Food Product (ERFP) as listed by the Institute of Medicine (90); recommended dietary allowances for adults (>18 y) based on dietary reference intakes (DRIs) from the Institute of Medicine; Adequate intakes (AI) where indicated (91, 92).

Table 3: Drewnowski (2005) Recommended Micronutrient Intake

At 10 people, this scenario is not large enough to support the composting of waste crop material e.g. stalks and inedible leaves. With the assumption that no media is used, reintroduction of compost leachate into the feedwater stream would require careful attention and potential biofiltration to ensure appropriate nutrient content. This is not compatible with this design, however if fish are used as a nitrate source for aquaculture, biofiltration elements are required and would improve the case for recycling biomass.

The available biohazard processing facilities should also be considered as an endpoint for crop waste. Orbital Syngas/Commodity Augmentation Reactor (OSCAR) is a design for an enclosed thermal oxidation system for the Deep Space Gateway [s]. OSCAR would allow for the combination of waste streams, including biohazards, which would then be processed to recover water and generate syngas which would be stored and used as a propellant. The system still generates solids, but they are now sterilized and significantly reduced from the initial waste stream.

Keto

I am not an advocate of the Ketogenic diet for deep space. At the highest level, the core intended benefit of enhanced ketogenic metabolism does not outweigh the significant costs of implementing this diet. It is reliant on prepackaged foods would conflict with goals of the Mediterranean diet as it dictates high-fat, moderate-protein, low-carbohydrate foods. In order to achieve ketosis an astronaut would need to consume less than 20g of carbohydrates per day, deviation from this requirement can quickly shift an individual back to a glycogen based metabolism and cause a ‘keto flu’ [p] that is associated with the start of a ketogenic diet. This can manifest as aches and pains, electrolyte imbalance, nausea, and fatigue occurring over weeks, potentially incapacitating astronauts at key times. At a biomolecular level the issues deepen. In their 2013 paper, Schönfeld and Reiser explain how the use of long chain fatty acids, which is increased during the switch to ketosis, can increase the risk of oxidative stress on cells [q]. Over a long period of time, a ketogenic diet does have the potential to improve glycemic control. This is a valuable trait given the increased potential for type 2 diabetes among astronauts but comes with serious risk. Zhang et al. (2016) [v], found that this comes with an increase in lipid accumulation outside of fatty acid tissue and liver fibrosis which subsequently promoted non-alcoholic fatty liver disease. The use of COTS pharmaceuticals like metformin [w] and less risky lifestyle intervention are a simpler preventative measure.

Intermittent fasting

Intermittent fasting is an alternative diet that when coupled with a well-planned baseline diet, offers potential benefits that could significantly improve quality of life on long duration space missions. In their review article Patterson and Sears identify 3 primary areas of study for intermittent fasting: (a) circadian biology, (b) the gut microbiome, and (c) modifiable lifestyle behaviors, such as sleep [aj]. Each of these is an area of study within space health research as well and relevant to human psychological comfort as well as physical health. Of the variations on this diet that are commonly practiced, two are suitable for space travel. The first is a 5:2 calorie restriction cycle is where individuals restrict energy intake on two non-consecutive days to <25% of their normal daily intake. This regimen has been observed to improve the body’s ghrelin response to food and satiation after eating[al] which is an important factor in maintaining overall energy intake. Ghrelin is also involved with the regulation of glucose and insulin [ak] helping to reduce systemic inflammation as well.

Time-restricted feeding is a form of fasting that is both beneficial too and compatible with the lifestyle of an astronaut. In this scheme, individuals refrain from eating for a period of at least 11 hours a day, typically centered around the nighttime sleeping schedule. As with 5:2, time-restricted feeding is associated with a more distinctive Ghrelin response and insulin regulation. LeSauter et al. (2009) detail how the regular spiking of Ghrelin can help to entrain the circadian rhythm during intermittent fasting. This is mediated primarily through the co- expression of PER1 and PER2 clock proteins with ghrelin in what they term Food-Entrainable Oscillators. These are especially useful for space exploration in that they show that the oscillators function independent of the day-night light cycle. The timeframe that is addressed in their paper is daily, but the implications for Ghrelin regulation on circadian rhythm could offer guidance to those option to pursue the 5:2 fasting cycle as well. Having consistent mealtimes post fast or on normal days, may further enhance the impact of fasting.

Conclusion

Regardless of what the early pioneers of long duration space flight are given to eat. It is how they respond to and how they build on those choices that will be remembered. We remember the simple pleasure of Tang over the bolus of sugar that it represents, and while administrators may focus on the chaos of crumbs from the first sandwich brought to space, I revel in viewing the attempt to bring a bit of comfort to a lonely situation. I cannot wait to sample what passes for comfort food from the explorers of Mars and expand my palette in ways not possible on this world.

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