EFFICIENT ALTERNATIVE FOOD SYSTEMS FOR EARTH AND SPACE

By

Kyle A. Alvarado

A Thesis Submitted in Partial Fulfillment of the Requirements

for the Degree of

Master of Science

in

Mechanical Engineering

University of Alaska Fairbanks

December 2020

APPROVED:

David Denkenberger, PhD, Committee Chair
Silke Schiewer, PhD, Committee Member
Meriam Karlsson, PhD, Committee Member
Rorik Peterson, PhD, Chair
Department of Mechanical Engineering
William Schnabel, PhD, Dean
College of Engineering and Mines
Richard Collins, PhD, *Director of the Graduate School*

Abstract

Alternative foods are a source of human-edible calories derived from an unconventional source or process. This thesis includes two alternative foods: (i) crops grown under low-tech greenhouses in low sunlight environments and (ii) hydrogen-oxidizing bacteria (HOB) in space and Earth refuges, such as to repopulate the Earth. The purpose of alternative foods is to ensure food security for human survival. During a global catastrophic risk (GCR) scenario, such as nuclear winter or super volcanic eruption, the sun may be obscured, causing lack of crop production and therefore global food shortages. The purpose of this thesis was to improve the cost and energy use of producing food during a GCR by avoiding the need to use artificial light photosynthesis. As a solution, a low-tech greenhouse scaling method was designed that could feed the Earth as quickly and cost-effectively as possible during a GCR, such as nuclear winter. Using concepts derived for scaling HOB single cell protein (SCP), a cost analysis was conducted for space that relates to Earth refuges. The cost of HOB was compared to that of microalgae SCP and of dry prepackaged food in a closed-loop system. Low-tech greenhouses were designed with basic materials to continue the production of non-cold tolerant crops at low cost; cold tolerant crops would be able to grow outside of greenhouses where it does not freeze. Scaling of low-tech greenhouses, which would add a cost to food of $2.30 /kg dry, is currently one of the most effective alternative foods for Earth. HOB is an effective method of converting electrical energy into food, having an electricity to biomass energy conversion efficiency of 18% versus 4.0% for artificial light (vertical farming) of microalgae (other crops would be even less efficient).

Table of Contents

Acknowledgements

I thank my family for emotional and financial support. I thank my father specifically for guiding me toward my career by promoting creativity and dedication. I thank my advisory committee chair, Dr. David Denkenberger, for demonstrating his unique approach to engineering and research. I thank my advisory committee members, Dr. Meriam Karlsson and Dr. Silke Schiewer, for giving me the education necessary to complete this thesis. I thank my close friends, Chris Pascale, Darion Heald, Joshua VanderMartin, Emily Browning, and Chinmay Shah for advice and support. I thank the coauthors of the articles included here, Dr. Joshua Pearce, Aron Mill, Juan García Martínez, Dr. Silvio Matassa, Joseph Egbejimba, and Alexander Vocaet. I thank the effective altruist members of the Alliance to Feed the Earth in Disasters. I thank Dr. John Hogan at NASA Ames Research Center for useful discussions and furthering my adoration for and understanding of space operations. I also thank my undergraduate advisor, USAF Major General Randy Kee, for influencing my professional development and personal character. Additionally, this thesis would not have been completed without funding from the Alaska Space Grant Program and a robust education provided by the University of Alaska system. Thank you.

List of Figures

List of Tables

Chapter 1 General Introduction

There is a research gap related to feeding people quickly and cost effectively in scenarios that prevent crop growth. A class of solutions is alternative food production. An alternative food is a source of calories that is viable despite catastrophic conditions, often relying on biomass, fossil fuels, or low intensity sunlight. This often involves retrofitting, recycling, or diverting processes and materials to food production. In many scenarios, if outdoor photosynthesis is not possible, then the apparent solution is to grow crops using artificial light photosynthesis ("vertical farming"); however, this would be extremely expensive and energy intensive. Thus, an important goal of alternative foods is obviating the production of food using artificial light. Alternative foods are still maturing as technologies and face challenges with nutritional diversity and cultural acceptance. Realistically, artificial light food production would remain an option for the wealthy population since it is more established and can be practiced also in nontropical countries. Two studies are presented that have developed cost estimates from the design of alternative foods for Earth during a global catastrophic risk (GCR) event and for space or Earth refuges; however, it should be noted that the cost for the latter study for space is not represented with currency values, however with mass. The first study is a design to scale the production of non-cold tolerant crops with construction of low-tech greenhouses during sun-obscuring conditions. Low-tech greenhouses are an implementation of appropriate technology; wherein they are designed to be lower cost and greater food production than the leading alternative, i.e. artificial light photosynthesis. The setting considered is a sun-obscuring GCR event, specifically nuclear winter, during which about 50% of solar irradiation is blocked and an average global temperature drop is approximately 10 degrees Celsius. This would inhibit the growth of any crop that is not cold tolerant nearly everywhere. Furthermore, almost no crop would be able to grow outside of the tropics. Therefore, an industrialized scaling approach was needed that could employ commonly produced global resources, such as polymer and timber, to feed the Earth as quickly and cost-effectively as possible. The second study relates to a food production method using hydrogen-oxidizing bacteria (HOB), specifically *Cupriavidus necator*. The product of separating and pasteurizing this HOB from its solution is single cell protein (SCP), which is an edible source of calories. A scaling approach was conducted separately, and from there, another study was applied to feeding a small group of people in a closed-loop system, specifically a crew of five astronauts in space. The cost of food in space is essentially its mass, considering that the amount of fuel to propel a unit of mass is the dominant cost of a space mission. The National Aeronautics and Space Administration (NASA), the funder of this study through the Alaska Space Grant, uses an equivalent system mass (ESM) method to compare alternatives in space. This study compared growing HOB to two leading alternatives for space food, including dry prepackaged food and growing microalgae with artificial light photosynthesis. The elements of an ESM include its physical mass as well as other components, including, for example, power requirement, heat rejection, and pressurized volume. This study also relates to feeding people in a closed system refuge, such as to repopulate the Earth, under similar circumstances.

There were many uncertainties considered while developing the articles in this thesis. For instance, relatively little research has been conducted on GCR conditions. Chapter 2, containing the published article titled "Scaling of greenhouse crop production in low sunlight environments," uses a global weather prediction model for nuclear winter conditions. Several models like it were produced year-by-year specifically for studying GCR weather conditions and it was noted that these models are only estimations and include a number of considerations. A nuclear winter weather scenario was selected to represent a GCR because it has one of the highest probabilities of occurring, about a 10% chance this century, even though it is one of the most preventable. Under the conditions for this greenhouse study specifically, global industry would remain intact and the current population would remain unchanged. Furthermore, this first study involved determining scalable monthly values on global markets of materials such as polymer film, timber, construction aggregates, and steel nails, which often involved extrapolation from large annual values. Economies of scale were not employed for this analysis, which may introduce additional uncertainty. Uncertainties for the latter study, Chapter 3, titled "Food in space from hydrogen-oxidizing bacteria," which is currently an article in press, include most prominently that alternative foods for space are not likely to be considered for a while since space technology and systems development are still emerging and being tested. Space programs such as NASA currently consider prepackaged food for astronaut's food supply because it is simple and reliable. For any of these uncertainties, the studies are rigorous enough to determine rough estimates for their conclusions. Moreover, the calculated estimates are more accurate than simply being within an order of magnitude of their true value. The methods in these studies were built from established literature. Neither study created a uniquely new technology, such as new greenhouses or bioreactors, ensuring that they are more likely to succeed if deployed. Furthermore, experts from around the world in science, technology, and engineering aided in the development of these studies. In each study, the alternative food was compared pessimistically by giving conservative advantages to the comparative foods, such as artificial-light grown food, where appropriate. Topics used in these studies include mechanical engineering, specifically (i) manufacturing engineering, related to production processes, (ii) industrial engineering, related to materials requirements, project management, production planning, production control, industrial management, and operations research, and (iii) basic concepts of astronautical engineering. The low-tech greenhouse study used basic concepts of horticultural engineering, engineering economy, and environmental science. The HOB study used graduate-level education in biotechnology and basic concepts of space science and systems development.

Chapter 2 [1]Scaling of greenhouse crop production in low sunlight environments

Abstract

During a global catastrophe such as a nuclear winter, in which sunlight and temperatures are reduced across every latitude, to maintain global agricultural output it is necessary to grow some crops under structures. Although the greenhouse industry has developed many appropriate structures, they do not fabricate them on the scale necessary to provide a significant fraction of human food. This study designs a method for scaling up crop production in low-tech greenhouses to contribute to global food sustainability during global catastrophic conditions. Constructing low-tech greenhouses would obviate growing crops using more expensive and energy intensive artificial light. The greenhouse structures are designed to utilize global markets of timber, polymer film, construction aggregates, and steel nails. The limiting market is found that determines the growth rate of the greenhouses as a whole. The limiting market that determines the growth rate of the greenhouses is the rate at which polymer film and sheet are currently extruded. The analysis shows that the added cost of low-tech greenhouses is almost two orders of magnitude lower than the added cost of artificial light growth. The retail cost of food from these low-tech greenhouses will be ~2.30 USD/kg dry food higher than current prices. According to the proposed scaling method, the greenhouses will provide 40% of food requirements for everyone by the end of the first year, and feed everyone after 27 months.

[1] K.A. Alvarado, A. Mill, J.M. Pearce, A. Vocaet, D. Denkenberger, Scaling of greenhouse crop production in low sunlight scenarios, Science of The Total Environment. (2019) 136012. https://doi.org/10.1016/j.scitotenv.2019.136012.

2.1 Introduction

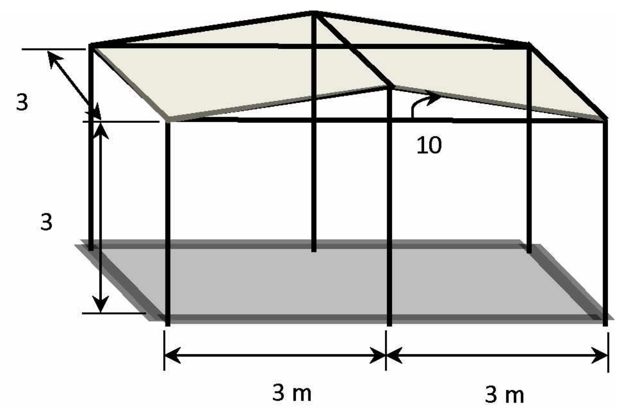
There are several global catastrophic risks (GCRs) that could partially block the sun and render conventional agriculture incapable of preventing mass human starvation (D. C. Denkenberger & Pearce, 2015). The most probable of these sun-obscuring events, which humanity currently has the most control over, is nuclear war with the burning of cities (sometimes called nuclear winter or to a lesser degree nuclear autumn) (Baum, 2015; E. Marshall, 1987; Robock, Oman, & Stenchikov, 2007). Disturbingly, two quantitative models have the probability of full-scale nuclear war at about 1% per annum (Barrett, Baum, & Hostetler, 2013; Hellman, 2008) in part because most countries with nuclear weapons have more than the pragmatic limit of nuclear weapons, where the direct negative consequences of nuclear weapons use are counter to national interests (J. Pearce & Denkenberger, 2018). Either a small regional nuclear war such as India vs Pakistan (Mills, Toon, Turco, Kinnison, & Garcia, 2008; Robock & Toon, 2010) or a minor one-sided nuclear assault on population centers (J. Pearce & Denkenberger, 2018) could catalyze a global nuclear autumn, which would starve millions of people (Mills et al., 2008; J. Pearce & Denkenberger, 2018; Robock & Toon, 2010, 2012; Toon, Robock, & Turco, 2014). Although the probabilities are lower, there are several more types of GCRs that could occur naturally with the same outcome including i) asteroid or comet impact (Baum, 2018) and ii) super volcanic eruption or continental basalt flows (Bostrom & Cirkovic, 2011; Donovan & Oppenheimer, 2018; Newhall, Self, & Robock, 2018). In an event that causes sunlight and temperatures to decrease over the entirety of earth, such as nuclear war, most crops will be too frost sensitive to be grown outside the tropics (Doorenbos & Kassam, 1979). Crops that rely on flowering require certain temperatures even if the ground does not freeze (Wani & Herath, 2018), so even the tropics will require an alternative method to growing crops than simply conventional growth outdoors. The sun will be obscured, though not completely absent. Tropical crops including bananas, sweet potatoes, and peanuts will not grow at all (Pereira, 1982). Since there will still be a demand for these crops, a method to create suitable conditions for growing them must be established that is low enough in cost to be globally deployable. There are many practical methods that might contribute to food supply in the event of a disaster (D. C. Denkenberger & Pearce, 2015; Humbird et al., 2011; Kennedy, 1993; Spinosa, Stamets, & Running, 2008; Unibio, 2014). It is well-established costs can be reduced (J. M. Pearce, 2012; J. M. Pearce & Mushtaq, 2009; Zelenika & Pearce, 2011) using appropriate technology (AT), which generally follow a technological choice that is small-scale, decentralized, labor-intensive, energy-efficient, environmentally sound, culturally acceptable, and locally autonomous (Hazeltine & Bull, 1998). Low-tech greenhouses are an AT that provide a potential cost and energy efficient solution. The alternative is to grow crops using high-tech energy-intensive methods, such as with artificial light, which is not economically feasible for feeding many people (Watson, Boudreau, & van Iersel, 2018; Wittwer & Castilla, 1995).

This study addresses the feasibility of constructing greenhouses in the tropics, where conditions would be suitable to support year-long indoor agriculture in the case of nuclear winter. To significantly contribute to world-wide food demand, these greenhouses must be constructed quickly, cost-effectively, and in extreme quantity. To meet these requirements this study evaluates open source designs of structures constructed from transparent/translucent polymer, sawn wood, fasteners, and construction aggregates borrowed from current global production. First, the size of such structures is calculated, and a bill of materials is designed on a per unit area basis. An appropriate standard greenhouse design was chosen given consideration of imperfect materials from global supply, and design adjustments were made for environmental conditions of the tropical region during a global catastrophe. Next, the limitations of the global markets are determined for meeting the need. Specifically, calculations are made to determine whether or not the global supply of each material is sufficient for this project. Then, current global crop productivity both outdoors and indoors was examined using data from the Food and Agriculture Organization of the United Nations (FAO), with a particular emphasis on outdoor farming for more applicable estimates to low-tech greenhouses in nuclear winter tropical conditions. A final comparison was made to the alternative, which is to use artificial light to grow any crops that are not cold-tolerant. Crops that do not rely on temperature for flowering, the beginning of reproduction, are cold tolerant (Wani & Herath, 2018).

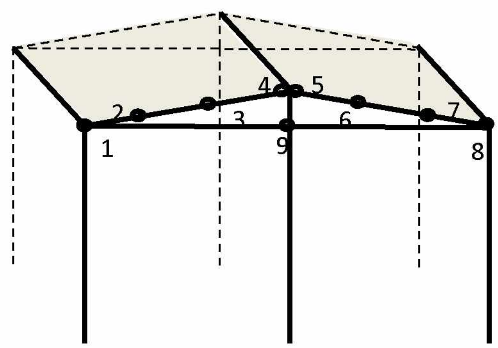
2.2 Methods

2.2.1 Greenhouse Design

Design of low-tech greenhouses typically relies on low-cost materials (Baird, 2011; Jha, Paikra, & Sahu, 2013; R. Marshall, 2006; Von Zabeltitz & Baudoin, 1999). Most commonly used designs for low-tech greenhouses are hoop-houses and A-frames (Osentowski, 2015; Rakow & Lee, 2011). The A-frame design was selected to maximize light transmission and enhance structural stability for connecting structures without needing to bend or further manipulate rigid wood. A series of connected structures, illustrated by Fig. 1, employs a rectangular ground perimeter that maximizes crop-growing area. A simple roof truss supports the lightweight polymer cover.



(a)



(b)

Figure 2.1 Low-tech greenhouse design indicating (a) approximate structural dimensions of one unit cell, (b) fastener distribution; the fastener distribution is roughly indexed by the number of nails for frame joints, 1,4,5,8,9, and for polymer cover, 2,3,6,7. *Figure 2.1 continued on next page.*

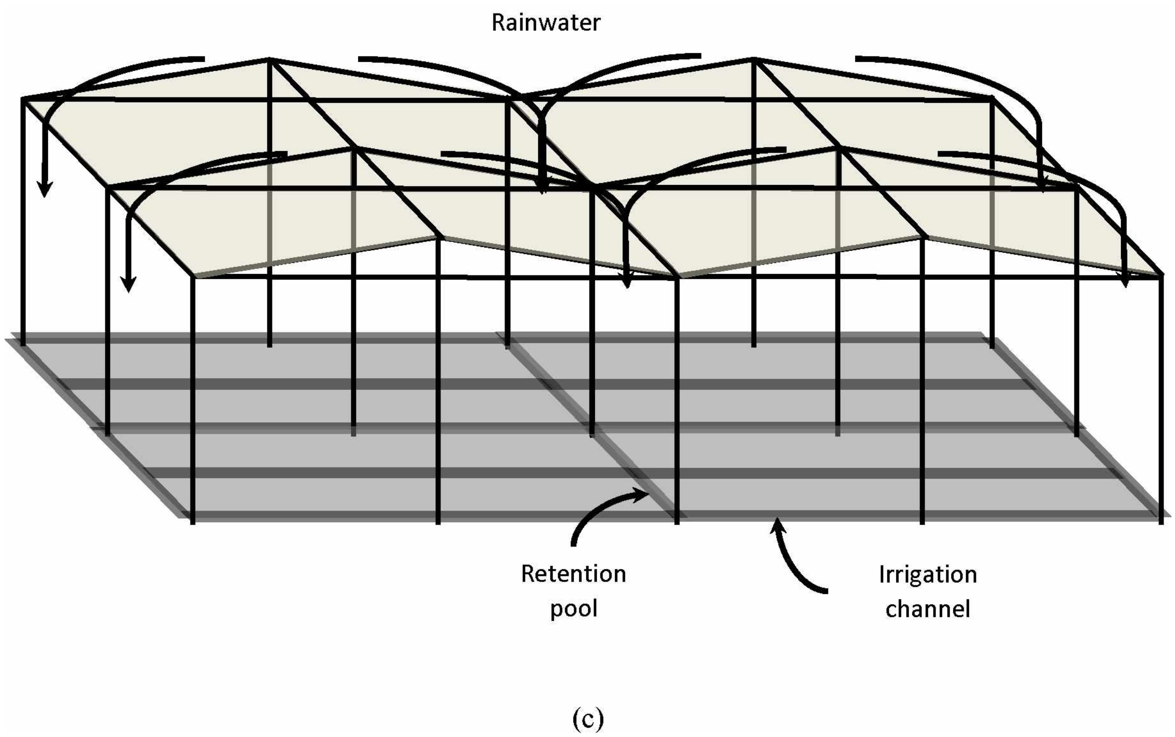


Figure 2.1 continued here. (c) Rainwater retention method.

The unit cell in Fig. 1a, which has been used in the field (Von Zabeltitz & Baudoin, 1999), continues in the left and right directions and is projected forward and backward, illustrated by Fig. 1c. The separation between each frame in the projected dimension should be dependent on the thickness of the polymer that is laid between. For thin polymer having thickness below the greenhouse plastics standard of 0.10 mm (Baudoin et al., 2013), the faces should be closer together. For thicker polymer, the faces may be farther apart. Polymer films may weave above and below beams to support film rigidity and reduce fastener requirement (Von Zabeltitz & Baudoin, 1999). Polymer films may be welded or glued together to better insulate the greenhouse. To further elevate internal temperature, the sides of each amalgamate structure must be covered with polymer. The frame should consist of material no smaller than 38-mm diameter, regardless of the material (Von Zabeltitz & Baudoin, 1999). The most advantageous material is timber due to its flexibility and convenience of fastening the polymer cover to the frame using any available fastener if nails do not meet the requirement. If a steel frame is used, it should be protected against corrosion.

The number of fasteners used, numbered 1-9 on Fig. 1b, shows an estimate of the minimum requirement of nails to effectively support the frame and secure the polymer cover. Consideration should be taken when using timber of particular size. For instance, thicker cross-sectional timber should be prioritized for columns, while thinner timber should be prioritized for beams. It is common for a large scale low-cost greenhouse frame to be constructed of recycled or scavenged wood (R. Marshall, 2006). Columns should be inserted at least 65-100 cm into the ground to properly distribute the load from these low-cost materials (Baird, 2011; Von Zabeltitz & Baudoin, 1999). Diagonal bracing may be placed at the ends of the structure on either East-West or North-South faces. This load bearing system is devised specifically for enhancing strength against horizontal loads (Kolb, 2008).

Rainwater retention is an imperative function for large greenhouses. Pipes connecting to water storage tanks are a popular method for retaining rainwater. However, it is necessary to avoid increasing material requirements and taking up valuable growing space with piping and water tanks. A simple solution is to dig holes along the trough between A-frames, leaving gaps in the polymer cover, allowing water to flow down the roof slope and into the greenhouse where it may be retained on the ground in a channel lined with nonporous material (Fig. 1c) (Miller & Spoolman, 2011). Lining the channel with material such as clay and gravel or polymer is necessary because falling water will damage and oversaturate the soil of surrounding plants or the structural columns. Although some rainwater should be allowed to penetrate the soil it is necessary to either distribute the fallen rainwater with additional labor or allow it to flow through channels dug into the ground. Additional sources of irrigation, including current irrigation infrastructure, groundwater, and freshwater bodies, are abundant in agricultural regions of the tropics (Food and Agriculture Organization of the United Nations, 2012, 2016a).

In order to maximize crop output, it is necessary to reasonably cover as much area as possible before closing off the ends of a structure. Since it is already feasible to achieve greenhouse sizes in the magnitude of 1 hectare (Aznar-Sánchez, Galdeano-Gómez, & Pérez-Mesa, 2011), the design of these greenhouses was taken to be 1 hectare in ground area for calculation simplicity, considering that there may be sloped topography and imperfect construction. The entire ground area will not be used exclusively for crop growth. Allowing space for pathways, structural supports, and rainwater channels, the effective growing space will equal about 80% of the covered ground area (Bartok, 2015a). The height may be manipulated if constructing on unlevel ground. A height of 3 m permits taller crops to grow within these greenhouses and accommodates the usage of vehicles such as small tractors or supplementary machines. The 10-degree roof slope in Fig. 1a will allow rainwater to flow into the troughs without much reduction of the amount of incident sunlight that transmits into the greenhouse (Bartok, 2015a).

The most critical factor for continual greenhouse scaling is the time in which the polymer cover degrades. Polymer with a thickness of roughly 0.10-0.15 mm that is not treated with sunlight radiation stabilizers will not last much more than three years (Bartok, 2015b). If there were constant polymer production, after this point in time, greenhouse construction will cease, and all extruded polymer will be reallocated to replacing greenhouse covers that have approached the end of their usable life. Scaling up of UV stabilizers would extend the life of the polymer, but since the critical time for food production is the first year, this was not investigated. Table 1 is a bill of materials (BOM) for one unit cell of the low-tech greenhouse design from Fig. 1a.

Table 2.1 Bill of materials of a 6-m x 3-m unit cell of the low-tech greenhouse design from Fig. 1a.

Component	Qty	Description	Density (kg/m^3)	Mass (kg)
1	7	Round beam 50 ϕ (3 m)	600[a]	25
2	2	Round column 80 ϕ (3 m)	600[a]	18.1
3	1	Round column 80 ϕ (3.5 m)	600[a]	10.6
4	2	Polymer film 0.10 mm x 3 m x 3 m	950[b]	1.70
5	18 pieces	Nails, ties, lashing, or glue welds	-	-
6	0.03 m^3	Gravel & clay	2700[c]	90

[a](Reyes, Brown, Chapman, & Lugo, 1992), [b](Chanda, Roy, & Roy, 2008), [c](Sverdrup, Koca, & Schlyter, 2017)

2.2.2 Global Market for Components

The design of these greenhouses replicates common low-tech greenhouse designs in order to be as cost-effective and scalable as possible. Construction will principally employ materials obtained from current global production. For the purpose of feeding as many people as quickly as possible, supplemental materials will be required to accommodate for deficits in global markets. A summary of usable markets is shown in Table 2. During a global catastrophe, the immense acquisition of such materials will increase their unit price, however it will be economically justified when the demand for crops is high enough. Today, greenhouse construction is trending upward (Harrison, 2003) as the state of the art becomes more widely adopted in developed nations (Bernhardt & Milberg, 2011). Technological improvements have reduced labor intensity for growing plants (Janick, 1986) and induces quicker, more fruitful yields (Kitinoja, Saran, Roy, & Kader, 2011; Tigchelaar & Foley, 1991). However, to build as quickly as possible, advanced technology will not be the emphasis of this solution. Rather, a fast construction scaling method paired with a plant transplantation technique will be used to maximize output. Profitability will result from the high demand of crops, such as bananas or groundnuts, that would alternatively need to be grown with artificial light.

Table 2.2 An assembly of global markets of the materials required for scaling low-tech greenhouse construction; each market is represented by an annual value that is considered to be scalable to a monthly level.

Year	Component	Element	Value	Unit
	Forestry products			
2017		Sawn wood production	480,000,000[a]	m^3
2017		Sawn wood export quantity	153,000,000[a]	m^3
2017		Sawn wood export value	39,100,000,000[a]	USD
2017		Wood fuels production	1,890,000,000[a]	m^3
2017		Wood fuels export quantity	8,270,000[a]	m^3
2017		Wood fuels export value	483,000,000[a]	USD

Table 2.2 continued

2017	Industrial roundwood production	1,900,000,000[a]	m^3
Polymer film and sheet			
2016	Market volume	46,300,000[b]	tons
2017	Market value	101,000,000,000[c]	USD
Fasteners			
2006	Steel nails, U.S. imports	842,000[d]	tons
2006	Steel nails, U.S. import value	861,000,000[d]	USD
2018	Fasteners, global market value	83,000,000,000[e]	USD
Construction aggregates			
2019	Market volume	51,700,000,000[f]	m^3
2019	Market value	406,000,000,000[g]	USD

a(Food and Agriculture Organization of the United Nations, 2017), b(Grand View Research, Inc., 2017), c((HeraldKeeper, 2019), d(Barton, 2018), e(Grand View Research, Inc., 2019), f(Freedonia Group et al., 2016), g(PRNewswire, 2019)

2.2.2.1 Forestry Products

There are 210 billion tons of aboveground live forest biomass in the tropical and temperate domains (Pan, Birdsey, Phillips, & Jackson, 2013). The harvest of this biomass is separated by FAO into categories, of which only industrial roundwood, sawn wood, and wood fuels may be considered for greenhouse construction. In 2017, the total production volume of these categories was 4.28 billion m^3 (Food and Agriculture Organization of the United Nations, 2017). Cumulative length was calculated by relating the average diameter of trees in these latitudes and the method to processing timber. When roundwood is processed in a sawmill, lumber is sectioned from the log diameter in varying geometries (Nova Scotia Department of Lands and Forestry, 2019). The product is rough wood which is usually dressed (sanded) for construction. However, for time consideration, and to compensate requiring several times as much cutting from common 50-mm dimension-boards, the rough wood product may be used for greenhouse construction. Alternative materials are the other industrial roundwoods, which includes pulpwood and veneer logs, adding 25% to the available volume of timber for greenhouses (Food and Agriculture Organization of the United Nations, 2016b). In the event of a global catastrophe, there would be a worldwide recession that would greatly reduce new construction and usage of processing factories. Felled logs may then be intercepted before their processing stage, then cut with smaller scale tools such as table saws or power handsaws. Another option is to retrofit sawmills that produce panels, such as plywood, veneer, or hardwood, to instead produce planks of sawn wood.

2.2.2.2 Construction Aggregates

Construction aggregates may serve purposes in greenhouse construction and during operation. Wood stakes will be inserted below ground for foundational support. Construction aggregates, such as gravel, may line the holes in order to reduce deterioration of the wood. When the greenhouse is built, the design should allow for rainwater to enter the greenhouse to naturally saturate the soil. However, to avoid oversaturating the soil, thereby developing standing water, channels should be dug in the ground to distribute the flow. To add to soil protection, pools that initially retain the rainwater should be lined with clay. The channels may be lined with polymer (Von Zabeltitz & Baudoin, 1999), however since polymer may be a limiting factor to greenhouse construction scaling, they may also be lined with gravel. In 2019, construction aggregate demand was projected to reach 51 billion m^3 (Freedonia Group et al., 2016). Alternative materials are other wood elements, including wood chips and particles, wood pellets and residues, and mechanical wood pulp.

In 2017, about 593 million m^3 of these materials were produced (Food and Agriculture Organization of the United Nations, 2017). These materials should be used in appropriate situations since a mixture of wood and soil may actually reduce soil nitrogen (Allison, 1965; Fog, 1988). This decomposition releases CO_2 which is advantageous for plant growth.

2.2.2.3 Polymer Extrusion

The most applicable cover for inexpensive greenhouse applications is translucent/transparent film and sheet. Glass panels allow higher light transmission (Bartok, 2015b) however they are more expensive and in far less quantity than polymer film and sheet (Adroit Market Research, 2019). Polymers are the main components of plastics which also include additives, fillers and dyes. In 2016, 46 megatons (MT) of plastic film and sheet were extruded that could be used for greenhouse cover (Grand View Research, Inc., 2017). Plastic film and sheet have designated thicknesses of between 0.002 to 2 mm; where flexible (non-rigid) film is generally between 0.002 to 0.25 mm (Pardos, 2004). The expectation of global tonnage being all usable film and sheet is dependent upon the polymer extrusion machines having the capability to produce translucent polymer (by not adding dyes that are typically added) with adjustable extrusion dies. Most extrusion machines, which include blow film and cast film and sheet, are rated for extruding up to at least 0.15-mm thickness (Pardos, 2004). In this context, cast film and sheet extrusion is a process to "cast" melted resin through a die of equal size to its width onto a chilled roller (Harper & Petrie, 2003). It was estimated that the current extrusion capability of film and sheet is roughly 1.2 million km^2 in area per year. Since low-tech greenhouses use thicker plastic film–closer to 0.10 mm (Baudoin et al., 2013)–than the global average thickness, the global output at this desired thickness will drop to about 480,000 km^2 per year.

2.2.2.4 Steel Nail Production

The frame and polymer cover will be primarily fastened together by steel nails for cost effectiveness. The global consumption of steel nails in 2006 was found to be 5.1 MT (Barton, 2018). To estimate the number of nails, approximations were taken from the consumption of steel nails for residential housing construction. If there are approximately 100 nails per m^2 in a home, and home construction includes the highest consumption of steel nails (Pretzer, 1996), this means there are roughly 124,000 common (smooth, uncoated) steel nails per ton–if most sizes are 6d-8d (Schwartz, 1993). Having found the area of greenhouses that can be constructed given plastics for production, there may be up to 2 nails per m^2 greenhouse area. Additional fastening methods include wood glue, staples, zip ties, or screws, which would also require acquisition of additional tools. An alternative method is tying the frame together (lashing) with rope, strips of heat welded recycled PET, or even strips of fabric. Weaving elements of the frame could reduce fastener requirement (Von Zabeltitz & Baudoin, 1999).

2.2.3 Crop Resiliency and Global Crop Demand

Greenhouses enhance plant growth by controlling temperature and possibly water and CO_2. During circumstances with reduced sunlight and temperature, it is necessary to construct greenhouses to grow non cold tolerant plants in the tropics in a global sun-obscuring catastrophe. Sunlight will still be typically 12 hours per day throughout the year. Full-scale nuclear war, e.g. between U.S. and Russia, could inject 150 Teragrams (Tg) of black carbon into the stratosphere from burning cities. A general circulation model was used to predict the climate impacts shown in Fig. 2, in this case 12 months after the war (Coupe, Bardeen, Robock, & Toon, 2019). Rainfall during nuclear winter will be concentrated in certain tropical areas of the world. Outdoor growing may be possible with significantly lower precipitation, but because greenhouses elevate the temperature, this increases transpiration (though increased relative humidity decreases transpiration). Greenhouse plants require about 12 $L/m^2/day$ of water (equivalent to 12 mm/day precipitation) for optimal greenhouse operating conditions (Bartok, 2015a). However, in nuclear winter in the tropics, ambient temperatures will be lower, relative humidity will be higher, and there will be no direct sunlight, thus reducing water requirements. Fig. 2 shows that select regions of the tropics, for example parts of Indonesia, will have 5 mm and above of rainfall. Depending on the crop, a rudimentary requirement for growing most crops outdoors is about 4 mm/day (Food and Agriculture Organization, 2019). Since the temperatures in the greenhouse in the tropics and nuclear winter might be similar to the temperatures experienced by these outdoor crops, and yet the relative humidity in the greenhouses would be higher and solar intensity lower, these would further reduce water requirement. This would allow much more area to be utilized (Fig. 2).

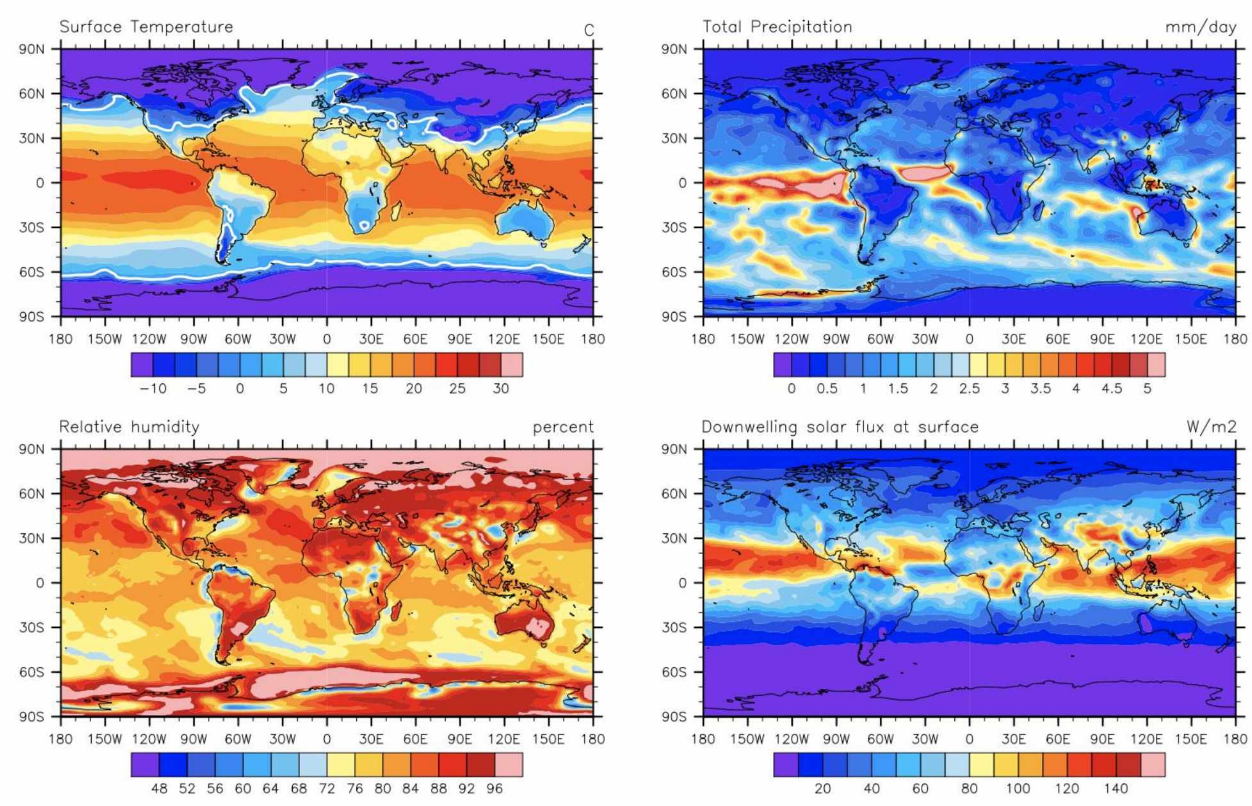


Figure 2.2 Global weather predictions during June, July, and August months 12 months after nuclear war; in order to provide high resolution for the climatic variables of interest, very high and low values were truncated, based on (Coupe et al., 2019).

The global reduction of daily sunlight will impact most crops. Long-day obligate crops that require photoperiods of more than 12 hours to flower, which principally include oats (Hari, 2019), dill, and sweet peas (Cox, 2009), will require supplemental light in the greenhouses. A minimum of 110 lux light intensity is required for night lighting systems (Cox, 2009), whereas full direct sunlight is 200,000 lux (Nahar, Naqvi, & Basir, 2004). Wheat and rye, which are long-day facultative crops, will still flower under shorter photoperiods, but are more accelerated under long photoperiod conditions (Hopkins, 1999). The lighting systems would operate during very few hours of the night (as little as one hour for some crops) and would not be needed the entire growing season. The capital and electricity cost to enable the growth of these plants using minimum requirements would be far less than for purely artificial light systems. Short-day crops, such as blueberries or sweet potatoes, will still flower and yield properly experiencing 12-hour days with reduced sunlight (Craufurd & Wheeler, 2009). Eight common crops consumed globally (potato, yam, sweet potato, rice paddy, shell groundnut, wheat, lentil, and cassava) were averaged and used for consideration of food balance and to form a rough crop yield estimate (Food and Agriculture Organization, 2019; Oke, Redhead, & Hussain, 1990). Extrapolating these values suggests that the annual production is roughly 3.1 dry tons/ha/yr. Crop production is reported in relation to dry carbohydrate, with an energy density taken to be 4 kcal/g (D. C. Denkenberger & Pearce, 2015) (weighed dry yield is higher because of the fiber content). The methodology for calculating the amount of people fed will be based on a 2,100 kcal per person daily diet (Kummu et al., 2012).

2.2.3.1 Expansion Rate

Optimizing the expansion rate will be achieved by using all materials as effectively as possible. Every interior unit cell of ground space should require the list of materials assembled in Table 1. Aside from construction aggregates, each material could enable a very similar area covered by greenhouses each year. Since there are many alternatives for fasteners and framing materials (sticks, salvage, metal and plastic piping, steel beams), the limiting factor for expansion is polymer film and sheet extrusion, which allows roughly 41 million hectares of greenhouses to be built each year. This would amount to sustainably feeding 15% of world population after the first 12 months. Since the first 12 months after the catastrophe are the most critical for scaling, more greenhouse area should be covered by extruding more polymer film. Since polymer extruders already operate continuously (Giles, Mount, & Wagner, 2004), additional extruders must be manufactured. The cost of one cast-film extruder is 1.98 million USD (Mitchell, 1996). The same source indicates that the output of this extruder is 1,160 tons/yr if run continuously. In order to match the current output of polymer film and sheet, 46.3 MT, this would require 40,000 extruders. The amount of area covered would double if all current extruders were exclusively producing polymer for greenhouses, with a delay from the first month due to manufacturing new extruders. There will be a global recession caused by the catastrophe, reducing current uses of polymer film. Also, rapid construction of extruders that will be used for a limited time will increase the price of polymer film, further decreasing the quantity demanded for other uses. We estimate that these two factors would reduce the use of polymer film to half as much as current. Therefore, if 60,000 extruders were manufactured (1.5 times as many as currently in service), the polymer film production for greenhouses could be twice as much as current polymer for production (because a small fraction of current production would go to greenhouses). Industrial capital expenditures (CapEx) was 2,700 billion USD in 2015 (Van der Meer, 2017). The capital cost of new extruders that would provide one-and-a-half as much polymer as current production would be 123 billion USD in one month, including the increased cost of fast construction (Cates et al. "Fast Construction of Factories" To be published). This would require 71% of the industrial CapEx; after subtracting the cost of another alternative food produced from chemical plant retrofitting (Throup et al. "Retrofitting Industry for Food" To be published). New extruders would take polymer resin from other polymer uses. Total polymer production was 348 MT in 2017 (PlasticsEurope, 2018), so the additional 69 MT per year would represent 23% of the part not currently going to polymer film. Since the recession would reduce demand for these non-film uses, this should cause minimal disruption. Table 3 shows a summary of constructible hectares relative to each material's current global demand, including twice the amount of polymer extruders. If timber would not offer enough supply in view of insufficient wood cutting machines, alternatives, including metal, PVC, or scrap still apply (R. Marshall, 2006).

Table 2.3 Approximate number of hectares achievable to construct each year according to each material's supply.

Component	Hectares (yr^{-1})
Sawn wood and wood fuels	95,000,000
Polymer film	83,000,000
Steel nails	126,000,000

2.2.3.2 Labor Requirements

The final and most variable consideration was labor. There are two required sources of labor: construction and farming. A structure made of lumber and polymer requires four people for framing and roofing at a rate of about 11 m^2 per hour (Truini, 2002). A 60-hour work week per laborer (Edmundson & Sukhatme, 1990) allows a builder to cover 725 m^2 per month. For the desired ground coverage, this translates to a construction labor requirement of 96 million builders. In reality, there will be many factors that will both speed up and delay the construction process, such as laborer exhaustion (Cates et al. "Fast Construction of Factories" To be published), loss in productive activity (Edmundson & Sukhatme, 1990), problems in shipping (Weintrit & Neumann, 2011), or material losses inherent in the construction industry (Berge, 2009). Since the overall rate of construction will be constant each month, the construction labor requirement will not change during the first three years. After three years, when the polymer cover begins to degrade, construction will stop, and the construction labor force will be reduced to about half its requirement to begin replacing polymer from day one. At this point all polymer film extrusion will be dedicated to the replacement of used polymer. Additionally at this point in time, the farming labor will stop increasing since ground coverage remains fixed. Requirements for farming labor in a greenhouse varies depending on species. Plants grown in greenhouses may require more labor than plants grown outside because of their particular growing environment being less mechanized than, for instance, wheat or maize agriculture. Farming labor will be borrowed from the current agricultural labor force, particularly from local regions, which mostly encompass developing nations where farming is extensive (Food and Agriculture Organization of the United Nations, 2019).

2.3 Solution

2.3.1 Scaling Approach

Transplanting crops enables faster food production with the same greenhouse area. One reason indoor horticulture is more labor intensive than outdoor agriculture is because many plants in greenhouses are grown in greater density per unit area. This is feasible because crops require less space during the first eight weeks of growth, up to the flowering phase (Lamont, Kelly, & Sellmer, 2017). Utilizing this knowledge, these low-tech greenhouses may be planted at higher density initially, then crops may be transplanted later when more greenhouse space is constructed. When replacing a plant, the root system must remain undamaged for optimal yield. Transplantation should occur when the plant is young, and the root-to-shoot ratio is still high (Forbes, Forbes, & Watson, 1992). Properly implemented, transplantation will yield more greenhouse-occupied time than if not transplanted, as represented by Fig. 3.

time passed (months)	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
planting density	crop age (months)																	
x1	0	1	2	3	4	5	1	2	3	4	5	1	2	3	4	5	1	2
x1		0	1	2	3	4	5	1	2	3	4	5	1	2	3	4	5	1
x1			0	1	2	3	4	5	1	2	3	4	5	1	2	3	4	5
x1				0	1	2	3	4	5	1	2	3	4	5	1	2	3	4
x1					0	1	2	3	4	5	1	2	3	4	5	1	2	3
x1						0	1	2	3	4	5	1	2	3	4	5	1	2
x1							0	1	2	3	4	5	1	2	3	4	5	1
x1								0	1	2	3	4	5	1	2	3	4	5
x1									0	1	2	3	4	5	1	2	3	4
x1										0	1	2	3	4	5	1	2	3
x1											0	1	2	3	4	5	1	2
x1												0	1	2	3	4	5	1
x1													0	1	2	3	4	5
x1														0	1	2	3	4
x1															0	1	2	3
x1																0	1	2
x1																	0	1
x1																		0
age of all crops	0	1	3	6	10	15	16	18	21	25	30	31	33	36	40	45	46	48
cumulative	0	1	4	10	20	35	51	69	90	115	145	176	209	245	285	330	376	424

(a)

time passed (months)	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
planting density	crop age (months)																	
x3	0	1	2	3	4	5	3	4	5	3	4	5	3	4	5	3	4	5
-		0	2	3	4	5	3	4	5	3	4	5	3	4	5	3	4	5
-			2	3	4	5	3	4	5	3	4	5	3	4	5	3	4	5
x6				0	1	2	3	4	5	3	4	5	3	4	5	3	4	5
-					0	2	3	4	5	3	4	5	3	4	5	3	4	5
-						2	3	4	5	3	4	5	3	4	5	3	4	5
x9							0	1	2	3	4	5	3	4	5	3	4	5
-								0	2	3	4	5	3	4	5	3	4	5
-									2	3	4	5	3	4	5	3	4	5
x12										0	1	2	3	4	5	3	4	5
-											0	2	3	4	5	3	4	5
-												2	3	4	5	3	4	5
x15													0	1	2	3	4	5
-														0	2	3	4	5
-															2	3	4	5
x18																0	1	2
-																	0	2
-																		2
age of all crops	0	1	6	9	13	21	18	25	36	27	37	51	36	49	66	45	61	81
cumulative	0	1	7	16	29	50	68	93	129	156	193	244	280	329	395	440	501	582

(b)

Figure 2.3 Visual representation of the number of greenhouse-occupied months per plant employing (a) the simple plant and wait method that is typically used for outdoor growing and (b) a transplantation method; for example, the top highlighted cells (lightest shade of grey) follow the greenhouse crops' age, in months, from left to right, where at five months they are mature; after 6 months of transplanting, greenhouses will have gained 3 additional months of growing time; the difference between these two diagrams shows the bulk of planting on the right, in which new seeds are not planted immediately after a greenhouse has been constructed; rather, the new space is used for transplanting the flowering crops.

The limit to how dense the greenhouses may be planted depends on how much greenhouse space will be available when it is time to transplant. The densities increase with each planting because greenhouse space is gained from both harvesting and constructing. From employing this transplanting method, there is a 39% increase in greenhouse-occupied days from each harvest. This is illustrated by Fig. 4. This method is meant to yield as much output as quickly as possible. On that note, this means that crops will be harvested in bulk every three months for a crop that matures in five months. Nevertheless, this method yields more edible mass than the plant and wait technique. For example, after constructing greenhouses for 12 months, and first planting 2 months after the catastrophe, the cumulative crop output would equal roughly 140 dry MT. By transplanting during each interval listed in Fig. 3b, the cumulative crop output would equal roughly 321 dry MT over the same area. A pivotal consideration is the amount of harvested edible mass that is actually consumed. Currently, 35% of food is wasted during the stages between harvest and consumption, but technical feasibility was estimated at 12% waste (D. Denkenberger & Pearce, 2014). The values in crop output for consumption represent the consideration of lost edible mass. Considering the large gap in time before significant crop production is achieved, some amount of artificial light will be required to grow crops in order to meet demand of wealthy consumers. Artificial light will phase out as low-tech greenhouse crops meet this demand.

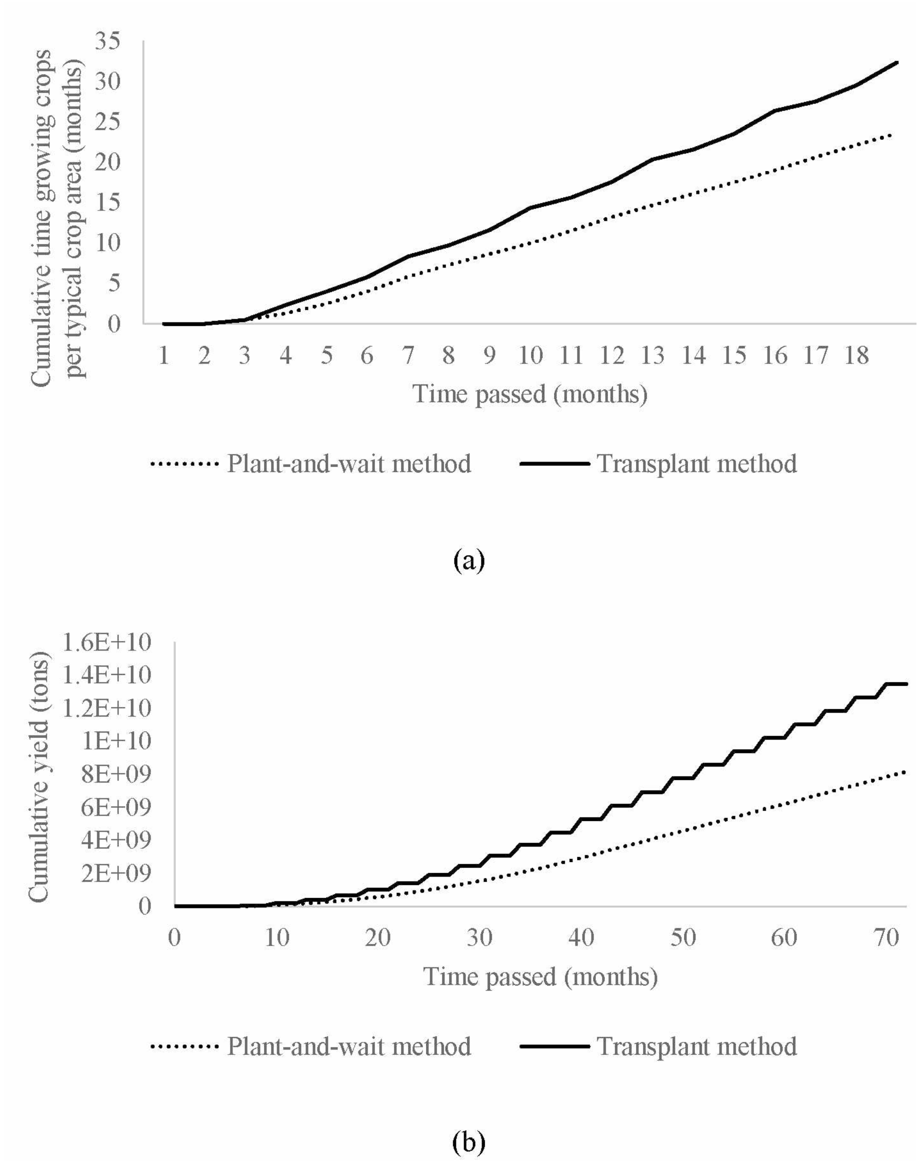


Figure 2.4 Crop productivity during greenhouse scaling for a common crop that flowers in two months and is harvested in five months; the transplanting method diverges from the common plant-and-wait method, with a harvest every few months, but with a factor of increase each time; greenhouse area reaches a maximum after 37 months of construction; the divergence of these methods is synonymously seen in both (a) the cumulative age of crops in a greenhouse and (b) the cumulative crop yield of greenhouses.

2.3.2 Economic Analysis

The cost of construction was the only component considered in the economic analysis of these low-tech greenhouses; this includes the cost of materials and construction labor. The final cost will be the added cost of food produced in the low-tech greenhouses. There are two stages of construction: the initial 36 months will be nonstop construction of structures, and the second stage will be replacement of polymer cover due to wear. The second stage will only include the cost of polymer and replacement labor, which will be at about half the cost and labor requirements. Other costs have been considered but do not apply to the comparison between low-tech greenhouses and artificial light, such as seed costs and farming labor. The cost of each greenhouse was determined by the cost for constructing it and then replacing the polymer cover. The total cost of all constructed greenhouses will be paid off over 72 months, which is the expected duration of the intense phase of the catastrophe. A wholesale unit price was estimated by extrapolating from the global market of each material (see Table 2). Each material was assumed to have a uniform unit price. The capital cost of a one-hectare greenhouse was then calculated by the amount of each material needed per unit cell (see Table 1) with added polymer and diagonal bracing on the ends. For large scale construction such as this, materials are approximately 70% of total cost, and the remaining 30% is labor (Bingham, 1982; Gichuhi, 2013). However, this is only applicable for the first stage of construction. During the polymer replacement stage, labor will be closer to 50% of the total cost since the work is more focused toward the low-cost polymer (Gichuhi, 2013). The cost of replacing the polymer cover is a future cost. In order to bring the cost to present, P, the following value of money formula is used:

$$P = F * \frac{1}{(1+i)^n} \tag{1}$$

Where the equivalent interest rate, i, of 8% is used (Humbird et al., 2011) to discount the cost of polymer replacement 3 years (n) in the future (F). Then for each greenhouse, the cost of construction and replacement to cover 72 months of life will be 2.30 USD/m^2. At constant expansion for 36 months, the cumulative ground coverage will equal 2.5 million km^2, amounting to an annual cost of 670 billion USD.

2.3.2.1 Comparison to Environmental Control Chambers

It is apparent by name that low-tech greenhouses are less expensive than closed artificial light growing systems, so a comparison is instead meant to show the difference in magnitude between capital costs. The concluding comparison to these closed systems was made with cost per dry kilogram produced. This cost represents the retail cost, which is roughly double the wholesale cost (McCray, 2010). The added cost to food from these low-tech greenhouses was calculated to be 2.30 USD/dry kg; whereas a closed artificial light growing system is ~600 USD/dry kg (D. Denkenberger, Pearce, Taylor, & Black, 2019). A unit area cost for closed systems is determined by the operating cost and equipment cost. The closed system uses exclusively artificial light to grow crops, meaning they are required to provide similar amounts of radiation to sunlight, which is a significant expense; for this reason, it is scarcely quantified (Kozai, Ohyama, & Chun, 2005; Morrow, 2008; Ohyama, 1998). This would be required for areas in higher latitudes in view of limited solar radiation (see Fig. 2) if local production were required, but even airplane transport of greenhouse grown food would be much less expensive than artificial light food. By maximizing a plant's photosynthetic efficiency, closed systems are more productive than common outdoor growing methods (Castilla & Hernandez, 2007; Kozai et al., 2005). Such systems may be as much as 20 times more efficient with a properly controlled artificial climate, predominantly by controlling soil moisture, CO_2 and temperature (Watson et al., 2018). In Table 4, productivity of a low-tech greenhouse is measured by irradiance, taken to be 100 W/m^2, and approximate temperature increase provided by the insulation of the polymer cover (Bakker, 1995) to nullify the reduced outdoor temperature. This insulation would also allow continual growth throughout the year. Fig. 2 shows the distribution of average annual temperature and irradiance in the tropics during nuclear winter. Current irradiance in the tropics is taken to be 200 W/m^2 averaged over day and night (World Bank Group, 2016). A crop's net primary productivity (NPP) is an indicator of sustainable intensification of agriculture (HarvestChoice, 2014). NPP will be impacted if the temperature (or soil moisture or CO_2) is altered significantly from usual operating conditions in low-light environments (Tait & Schiel, 2013). Closed systems can artificially provide the typical values of irradiance for optimal growing. In which case, low-tech greenhouses will produce crops less effectively, but at a much lower cost. Compared to the dry mass cost of the low-tech greenhouses, the closed artificial light growing system is two orders of magnitude more expensive. Therefore, low-tech greenhouses are the solution to avoiding high cost, high energy use food. Any amount of artificial light would take a tremendous amount of energy away from more efficient alternative foods. If artificial light is used for the initial 3-6 months, the capital cost is distributed over much less food produced, meaning it would be even more expensive.

2.4 Discussion

Indoor agriculture is labor-intensive, but an effective method of growing a full diversity of food. Large facilities are often constructed in developed countries outfitted with modern technology that causes them to be expensive, but still profitable. Greenhouse area today covers roughly 5,000 km^2 globally (ProduceGrower, 2019). Using an average outdoor crop productivity of 3.1 dry T/ha/yr (not growing continuously throughout the year) (Food and Agriculture Organization of the United Nations, 2019), to meet global demand for crops in response to a global catastrophe, greenhouses would need to cover 380 times more area. If this were done with closed artificial light growing systems, the cost, energy, and industrial scaling requirements would be very high. Therefore, it is clear that lower-cost, lower-tech greenhouses are a more appropriate technology for such scenarios. In-situ assets and supplies will be limited since these greenhouses will be constructed with haste and nearly exclusively in developing regions of the world. Crops grown in a closed system yield more mass indoors than outdoors (Tiwari & Nigam, 2019). There are many factors that contribute to such a significant difference, mostly attributable to a growing environment that is both naturally and artificially maintained to be conducive for ideal photosynthetic efficiency. The concept of a closed growing chamber is to retain heat, elevate the humidity, and protect crops from weather and disease (Upson, 2014). This can be achieved, though less precisely, simply by sheltering the crop field with a translucent cover (Espi, Salmeron, Fontecha, García, & Real, 2006; Hoxey & Richardson, 1983; Orgaz, Fernández, Bonachela, Gallardo, & Fereres, 2005). This scaling method will feed 40% of global population after 12 months of construction and reach 100% at month 27 (Fig. 5). Other uses for crop production in today's global demand that were not included in this analysis include crops not grown for human consumption, such as forage for animals, which can be fed using greenhouse residues and grass grown outside of the tropics (O'Leary et al. "The Potential for Cattle" To be published). Crops that take years to develop, such as tree nuts or temperate trees, which could potentially be relocated to current tropical forests, were also not included. Crops that are cold tolerant, such as potatoes, will not be grown using low-tech greenhouses and instead can be grown outdoors in tropical regions. Today's entire crop demand is more than 3.5 GT of dry mass per year (Food and Agriculture Organization of the United Nations, 2019). To meet all current human and non-ruminant uses, removing forage and fiber yields, requires an upper bound crop production of 2.6 dry GT carbohydrate per year. The low-tech greenhouse scaling method would meet potentially 96% of this demand, or 160% of the food needed to feed the global population.

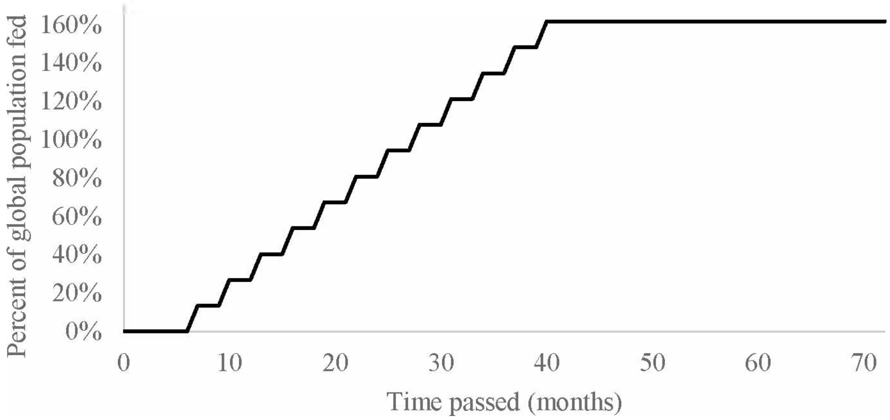


Figure 2.5 Percent of global crop need for feeding the human population and meeting current demand using this low-tech greenhouse scaling method; a one-month delay is included after the catastrophe to compensate for attaining global situational awareness.

Ongoing research includes other alternative methods for supplying food quickly during a global catastrophe (Baum, 2015). These methods differ in cost as well as scaling ability; however together, they have potential to provide a diverse diet that can meet nutritional needs (J. Pearce & Denkenberger, 2018). Alternatives include and are not limited to seaweed, cellulosic sugar, single-cell protein, and ruminants. Future work should include a method for integrating these alternative foods to determine the extent for scaling the AT of low-tech greenhouses. High-tech greenhouses that control temperature and perhaps CO_2 would have greater productivity than low-tech greenhouses. They would require the scaling of significantly more technology and infrastructure but would better utilize limited polymer. Future work could estimate the cost and scaling of food from this type of system. As mentioned, some artificial light will be required to grow crops in the beginning of a catastrophe and as supplemental lighting for long-day crops. Future research could determine the cost and scaling ability of these long day crops. Additional future work is investigating options for nontropical trees–whether they could be transplanted to tropical greenhouses. No particular crop was used in this analysis, so future work is suggested to analyze individual crop types for more accurate productivity, cost, and scaling. The usable land was estimated using FAO databases. Specific locations should be selected that satisfy their crops' needs appropriately, and a spatial analysis should be conducted to ensure that there is enough land for meeting the demand.

2.5 Conclusions

In the event of a global catastrophe, to feed the world using greenhouses, the rate at which greenhouse expansion occurs depends on global production of all required materials. If the world is prepared, it will be able to quickly mobilize the construction of greenhouses in the event of a global catastrophe. Scaling construction for 12 months will provide food for 40% of global population. After 27 months, the population could be completely fed by food production from low-tech greenhouses. In order to provide diet diversity to the global wealthy, some artificial light will be required primarily in the first several months as greenhouses scale. The results of this study clearly show that the economical solution is to construct low-tech greenhouses, having an added retail food cost of ~2.30 USD/dry kg, versus artificial light adding hundreds of dollars per kg.

Acknowledgements: The authors would like to thank Meriam Karlsson for field insight and advice, Stephan Kabasci for providing helpful comments and expertise in plastics manufacturing, and Charles Bardeen and team for global climate forecasts during a nuclear winter.

2.6 References

Adroit Market Research. (2019, April 24). Flat Glass Market to hit $150.40 Billion by 2025 - Global Analysis by Price Trends, Size, Share, Business Opportunities and Key Players: Adroit Market Research. Retrieved August 26, 2019, from GlobeNewswire News Room website: http://www.globenewswire.com/news-release/2019/04/24/1808642/0/en/Flat-Glass-Market-to-hit-150-40-Billion-by-2025-Global-Analysis-by-Price-Trends-Size-Share-Business-Opportunities-and-Key-Players-Adroit-Market-Research.html

Allison, F. E. (1965). *Decomposition of wood and bark sawdusts in soil, nitrogen requirements and effects on plants*. U.S. Dept. of Agriculture.

Aznar-Sánchez, J. A., Galdeano-Gómez, E., & Pérez-Mesa, J. C. (2011). Intensive Horticulture in Almería (Spain): A Counterpoint to Current European Rural Policy Strategies. *Journal of Agrarian Change*, *11*(2), 241–261. https://doi.org/10.1111/j.1471-0366.2011.00301.x

Baird, C. (2011). *The Complete Guide to Building Your Own Greenhouse: Everything You Need to Know Explained Simply*. Atlantic Publishing Company.

Bakker, J. C. (1995). *Greenhouse Climate Control: An Integrated Approach*. Wageningen Academic Pub.

Barrett, A. M., Baum, S. D., & Hostetler, K. (2013). Analyzing and Reducing the Risks of Inadvertent Nuclear War Between the United States and Russia. *Science & Global Security*, *21*(2), 106–133. https://doi.org/10.1080/08929882.2013.798984

Bartok, J. W. (2015a, March 6). Design and Layout of a Small Commercial Greenhouse Operation [Text]. Retrieved June 12, 2019, from Center for Agriculture, Food and the Environment website: https://ag.umass.edu/greenhouse-floriculture/fact-sheets/design-layout-of-small-commercial-greenhouse-operation

Bartok, J. W. (2015b, March 6). Plastic Greenhouse Film Update [Text]. Retrieved June 12, 2019, from Center for Agriculture, Food and the Environment website: https://ag.umass.edu/greenhouse-floriculture/fact-sheets/plastic-greenhouse-film-update

Barton, L. (2018, December 3). Steel Nails From China; Institution of a Five-Year Review. Retrieved June 12, 2019, from Federal Register website: https://www.federalregister.gov/documents/2018/12/03/2018-26136/steel-nails-from-china-institution-of-a-five-year-review

Baudoin, W. (ed), Nono-Womdim, R. (ed), Lutaladio, N. (ed), Hodder, A. (ed), Castilla, N. (ed), Leonardi, C. (ed), … Duffy, R. (ed). (2013). Good Agricultural Practices for greenhouse vegetable crops: Principles for Mediterranean climate areas. *FAO Plant Production and Protection Paper (FAO)*. Retrieved from http://agris.fao.org/agris-search/search.do?recordID=XF2013001549

Baum, S. D. (2015). Confronting the threat of nuclear winter. *Futures*, *72*, 69–79. https://doi.org/10.1016/j.futures.2015.03.004

Baum, S. D. (2018). Uncertain human consequences in asteroid risk analysis and the global catastrophe threshold. *Natural Hazards*, *94*(2), 759–775. https://doi.org/10.1007/s11069-018-3419-4

Berge, B. (2009). *The Ecology of Building Materials*. Routledge.

Bernhardt, T., & Milberg, W. (2011). *Does Economic Upgrading Generate Social Upgrading? Insights from the Horticulture, Apparel, Mobile Phones and Tourism Sectors* (SSRN Scholarly Paper No. ID 1987694). Retrieved from Social Science Research Network website: https://papers.ssrn.com/abstract=1987694

Bingham, B. J. (1982). *Labor and material requirements for commercial office building construction*. U.S. Department of Labor, Bureau of Labor Statistics.

Bostrom, N., & Cirkovic, M. M. (2011). *Global Catastrophic Risks*. OUP Oxford.

Castilla, N., & Hernandez, J. (2007). GREENHOUSE TECHNOLOGICAL PACKAGES FOR HIGH-QUALITY CROP PRODUCTION. *Acta Horticulturae*, (761), 285–297. https://doi.org/10.17660/ActaHortic.2007.761.38

Chanda, M., Roy, S. K., & Roy, S. K. (2008). *Industrial Polymers, Specialty Polymers, and Their Applications*. https://doi.org/10.1201/9781420080599

Coupe, J., Bardeen, C. G., Robock, A., & Toon, O. B. (2019). Nuclear Winter Responses to Nuclear War Between the United States and Russia in the Whole Atmosphere Community Climate Model Version 4 and the Goddard Institute for Space Studies ModelE. *Journal of Geophysical Research: Atmospheres*, 2019JD030509. https://doi.org/10.1029/2019JD030509

Cox, D. (2009). Photoperiod and bedding plants. *Floral Notes Newsletter*, *22*(1), 2–4.

Craufurd, P. Q., & Wheeler, T. R. (2009). Climate change and the flowering time of annual crops. *Journal of Experimental Botany*, *60*(9), 2529–2539. https://doi.org/10.1093/jxb/erp196

Denkenberger, D. C., & Pearce, J. M. (2015). Feeding everyone: Solving the food crisis in event of global catastrophes that kill crops or obscure the sun. *Futures*, *72*, 57–68. https://doi.org/10.1016/j.futures.2014.11.008

Denkenberger, D., & Pearce, J. M. (2014). *Feeding Everyone No Matter What: Managing Food Security After Global Catastrophe*. Academic Press.

Denkenberger, D., Pearce, J., Taylor, A. R., & Black, R. (2019). Food without sun: Price and life-saving potential. *Foresight*, *21*(1), 118–129.

Donovan, A., & Oppenheimer, C. (2018). Imagining the Unimaginable: Communicating Extreme Volcanic Risk. In C. J. Fearnley, D. K. Bird, K. Haynes, W. J. McGuire, & G. Jolly (Eds.), *Observing the Volcano World: Volcano Crisis Communication* (pp. 149–163). https://doi.org/10.1007/11157_2015_16

Doorenbos, J., & Kassam, A. H. (1979). Yield response to water. *Irrigation and Drainage Paper*, *33*, 257.

Edmundson, W. C., & Sukhatme, P. V. (1990). Food and Work: Poverty and Hunger? *Economic Development and Cultural Change*, *38*(2), 263–280. https://doi.org/10.1086/451792

Espi, E., Salmeron, A., Fontecha, A., García, Y., & Real, A. I. (2006). Plastic films for agricultural applications. *Journal of Plastic Film & Sheeting*, *22*(2), 85–102.

Fog, K. (1988). The Effect of Added Nitrogen on the Rate of Decomposition of Organic Matter. *Biological Reviews*, *63*(3), 433–462. https://doi.org/10.1111/j.1469-185X.1988.tb00725.x

Food and Agriculture Organization. (2019). Land & Water. Retrieved August 14, 2019, from http://www.fao.org/land-water/databases-and-software/crop-information/maize/en/

Food and Agriculture Organization of the United Nations. (2012). AQUAMAPS | Land & Water. Retrieved August 26, 2019, from http://www.fao.org/land-water/databases-and-software/aquamaps/en/

Food and Agriculture Organization of the United Nations. (2016a). Countries. Retrieved August 26, 2019, from http://www.fao.org/countryprofiles/en/

Food and Agriculture Organization of the United Nations. (2016b). *GLOBAL FOREST PRODUCTS FACTS AND FIGURES 2016*. 20.

Food and Agriculture Organization of the United Nations. (2017). Forest products statistics. Retrieved June 12, 2019, from http://www.fao.org/forestry/statistics/80938/en/

Food and Agriculture Organization of the United Nations. (2019). Crop farming. Retrieved June 12, 2019, from http://www.fao.org/rural-employment/agricultural-sub-sectors/crop-farming/en/

Forbes, J. C., Forbes, J. C., & Watson, D. (1992). *Plants in Agriculture*. Cambridge University Press.

Freedonia Group, Contact, P., Agreement, U., Policy, P., FAQs/Help, Map, S., … LinkedIn. (2016). World Construction Aggregates. Retrieved June 27, 2019, from The Freedonia Group website: https://www.freedoniagroup.com/industry-study/world-construction-aggregates-3389.htm

Gichuhi, F. (2013, April 26). PERCENTAGE OF COST BREAKDOWN BETWEEN LABOUR, MATERIALS AND CONTRACTOR PROFIT IN CONSTRUCTION. Retrieved June 27, 2019, from A4architect.com website: https://www.a4architect.com/2013/04/percentage-of-cost-breakdown-between-labour-materials-and-contractor-profit-in-construction/

Giles, H. F., Mount, E. M., & Wagner, J. R. (2004). *Extrusion: The Definitive Processing Guide and Handbook*. William Andrew.

Grand View Research, Inc. (2017). Plastic Films & Sheets Market Size, Share | Industry Report, 2018-2025. Retrieved June 12, 2019, from https://www.grandviewresearch.com/industry-analysis/plastic-films-and-sheets-market

Grand View Research, Inc. (2019). Global Industrial Fasteners Market Size | Industry Report, 2019-2025. Retrieved August 26, 2019, from https://www.grandviewresearch.com/industry-analysis/industrial-fasteners-market

Hari, D. V. (2019). *PLANT FOODS FOR NUTRITIONAL GOOD HEALTH*. Notion Press.

Harper, C. A., & Petrie, E. M. (2003). *Plastics Materials and Processes: A Concise Encyclopedia*. John Wiley & Sons.

Harrison, K. M. (2003). WORLD TRENDS DRIVING HORTICULTURE EXPANSION IN EMERGING ECONOMIES. *Acta Horticulturae*, (621), 115–125. https://doi.org/10.17660/ActaHortic.2003.621.13

HarvestChoice. (2014). Net Primary Productivity and Sustainable Intensification: An Exploratory Exercise. Retrieved August 26, 2019, from https://harvestchoice.org/labs/net-primary-productivity-and-sustainable-intensification-exploratory-exercise

Hazeltine, B., & Bull, C. (1998). *Appropriate Technology; Tools, Choices, and Implications*. Academic Press, Inc.

Hellman, M. E. (2008). Risk analysis of nuclear deterrence. *The Bent of Tau Beta Pi*, *99*(2), 14.

HeraldKeeper. (2019). Plastic Films and Sheets Market 2019 Global Analysis, Opportunities And Forecast To 2026. Retrieved June 12, 2019, from MarketWatch website: https://www.marketwatch.com/press-release/plastic-films-and-sheets-market-2019-global-analysis-opportunities-and-forecast-to-2026-2019-01-23

Hopkins, W. G. (1999). *Introduction to plant physiology.* John Wiley and Sons.

Hoxey, R. P., & Richardson, G. M. (1983). Wind loads on film plastic greenhouses. *Journal of Wind Engineering and Industrial Aerodynamics*, *11*(1–3), 225–237.

Humbird, D., Davis, R., Tao, L., Kinchin, C., Hsu, D., Aden, A., … Worley, M. (2011). *Process design and economics for biochemical conversion of lignocellulosic biomass to ethanol: Dilute-acid pretreatment and enzymatic hydrolysis of corn stover*. National Renewable Energy Lab.(NREL), Golden, CO (United States).

Janick, J. (1986). *Horticultural Science*. Macmillan.

Jha, M. K., Paikra, S. S., & Sahu, M. R. (2013). *Protected Cultivation of Horticulture Crops*. Educreation Publishing.

Kennedy, D. (1993). Leaf concentrate: A field guide for small scale programs. *Leaf for Life: Interlachen, FL, USA*.

Kitinoja, L., Saran, S., Roy, S. K., & Kader, A. A. (2011). Postharvest technology for developing countries: Challenges and opportunities in research, outreach and advocacy. *Journal of the Science of Food and Agriculture*, *91*(4), 597–603.

Kolb, J. (2008). *Systems in timber engineering: Loadbearing structures and component layers*. Walter de Gruyter.

Kozai, T., Ohyama, K., & Chun, C. (2005). Commercialized closed systems with artificial lighting for plant production. *V International Symposium on Artificial Lighting in Horticulture 711*, 61–70.

Kummu, M., De Moel, H., Porkka, M., Siebert, S., Varis, O., & Ward, P. J. (2012). Lost food, wasted resources: Global food supply chain losses and their impacts on freshwater, cropland, and fertiliser use. *Science of the Total Environment*, *438*, 477–489.

Lamont, P., Kelly, K., & Sellmer, J. (2017, October 19). Transplanting Annuals into the Garden. Retrieved June 12, 2019, from Penn State Extension website: https://extension.psu.edu/transplanting-annuals-into-the-garden

Marshall, E. (1987). Nuclear winter debate heats up; a study by the National Center for Atmospheric Research suggests most of the world would experience a mild nuclear winter, not a deep freeze. *Science*, *235*, 271–274.

Marshall, R. (2006). *How to build your own greenhouse: Designs and plans to meet your growing needs*. Storey Publishing.

McCray, B. (2010, November 29). How to set retail prices and markups. Retrieved June 12, 2019, from Small Biz Survival website: https://smallbizsurvival.com/2010/11/how-to-set-retail-prices-and-markups.html

Miller, G. T., & Spoolman, S. (2011). *Living in the environment: Principles, connections, and solutions*. Nelson Education.

Mills, M. J., Toon, O. B., Turco, R. P., Kinnison, D. E., & Garcia, R. R. (2008). Massive global ozone loss predicted following regional nuclear conflict. *Proceedings of the National Academy of Sciences*, *105*(14), 5307–5312.

Mitchell, P. (1996). *Tool and manufacturing engineers handbook: Plastic part manufacturing* (Vol. 8). Society of Manufacturing Engineers.

Morrow, R. C. (2008). LED lighting in horticulture. *HortScience*, *43*(7), 1947–1950.

Nahar, P., Naqvi, A., & Basir, S. F. (2004). Sunlight-mediated activation of an inert polymer surface for covalent immobilization of a protein. *Analytical Biochemistry*, *327*(2), 162–164. https://doi.org/10.1016/j.ab.2003.11.030

Newhall, C., Self, S., & Robock, A. (2018). Anticipating future Volcanic Explosivity Index (VEI) 7 eruptions and their chilling impacts. *Geosphere*, *14*(2), 572–603.

Nova Scotia Department of Lands and Forestry. (2019). Module 17: Beneath Your Feet: A Woodland Owner's Guide To Mineral and Geological Resources | Woodlot Management—Home Study Program. Retrieved June 12, 2019, from https://woodlot.novascotia.ca/content/module-17-beneath-your-feet-woodland-owners-guide-mineral-and-geological-resources-0

Ohyama, K. (1998). Estimating electric enegy consumption and its cost in a transplant production factory: A case study. *J. High Technol. Agric.*, *10*, 96–107.

Oke, O. L., Redhead, J., & Hussain, M. A. (1990). Roots, tubers, plantains and bananas in human nutrition. *FAO Food and Nutrition Series*, *24*, 182.

Orgaz, F., Fernández, M. D., Bonachela, S., Gallardo, M., & Fereres, E. (2005). Evapotranspiration of horticultural crops in an unheated plastic greenhouse. *Agricultural Water Management*, *72*(2), 81–96.

Osentowski, J. (2015). *The Forest Garden Greenhouse: How to Design and Manage an Indoor Permaculture Oasis*. Chelsea Green Publishing.

Pan, Y., Birdsey, R. A., Phillips, O. L., & Jackson, R. B. (2013). The structure, distribution, and biomass of the world's forests. *Annual Review of Ecology, Evolution, and Systematics*, *44*, 593–622.

Pardos, F. (2004). *Plastic Films: Situation and Outlook: a Rapra Market Report*. iSmithers Rapra Publishing.

Pearce, J., & Denkenberger, D. (2018). A national pragmatic safety limit for nuclear weapon quantities. *Safety*, *4*(2), 25.

Pearce, J. M. (2012). The case for open source appropriate technology. *Environment, Development and Sustainability*, *14*(3), 425–431.

Pearce, J. M., & Mushtaq, U. (2009). Overcoming technical constraints for obtaining sustainable development with open source appropriate technology. *2009 IEEE Toronto International Conference Science and Technology for Humanity (TIC-STH)*, 814–820. IEEE.

Pereira, A. R. (1982). Crop planning for different environments. *Agricultural Meteorology*, *27*(1), 71–77. https://doi.org/10.1016/0002-1571(82)90021-8

PlasticsEurope. (2018). *Plastics – the Facts 2018*. Retrieved from https://www.plasticseurope.org/application/files/6315/4510/9658/Plastics_the_facts_2018_AF_web.pdf

Pretzer, W. S. (1996). How Products Are Made. Retrieved August 26, 2019, from https://www.encyclopedia.com/science-and-technology/technology/technology-terms-and-concepts/nail

PRNewswire. (2019). The global construction aggregate market is expected to reach an estimated $452.4 billion by 2024 with a CAGR of 2.7% from 2019 to 2024. Retrieved August 26, 2019, from https://www.prnewswire.com/news-releases/the-global-construction-aggregate-market-is-expected-to-reach-an-estimated-452-4-billion-by-2024-with-a-cagr-of-2-7-from-2019-to-2024--300830222.html

ProduceGrower. (2019). Cuesta Roble releases 2019 global greenhouse statistics. Retrieved August 26, 2019, from https://www.producegrower.com/article/cuesta-roble-2019-global-greenhouse-statistics/

Rakow, D., & Lee, S. (2011). *Public garden management: A complete guide to the planning and administration of botanical gardens and arboreta*. John Wiley & Sons.

Reyes, G., Brown, S., Chapman, J., & Lugo, A. E. (1992). Wood densities of tropical tree species. *Gen. Tech. Rep. SO-88. New Orleans, LA: US Dept of Agriculture, Forest Service, Southern Forest Experiment Station. 15 p.*, *88*.

Robock, A., Oman, L., & Stenchikov, G. L. (2007). Nuclear winter revisited with a modern climate model and current nuclear arsenals: Still catastrophic consequences. *Journal of Geophysical Research: Atmospheres*, *112*(D13).

Robock, A., & Toon, O. B. (2010). Local nuclear war, global suffering. *Scientific American*, *302*(1), 74–81.

Robock, A., & Toon, O. B. (2012). Self-assured destruction: The climate impacts of nuclear war. *Bulletin of the Atomic Scientists*, *68*(5), 66–74.

Schwartz, M. (1993). *Basic Engineering for Builders*. Craftsman Book Company.

Spinosa, R., Stamets, P., & Running, M. (2008). Fungi and sustainability. *Fungi*, *1*(1), 38–43.

Sverdrup, H. U., Koca, D., & Schlyter, P. (2017). A simple system dynamics model for the global production rate of sand, gravel, crushed rock and stone, market prices and long-term supply embedded into the WORLD6 model. *Biophysical Economics and Resource Quality*, *2*(2), 8.

Tait, L. W., & Schiel, D. R. (2013). Impacts of temperature on primary productivity and respiration in naturally structured macroalgal assemblages. *PLoS One*, *8*(9), e74413.

Tigchelaar, E. C., & Foley, V. L. (1991). Horticultural technology: A case study. *HortTechnology*, *1*(1), 7–16.

Tiwari, A. K., & Nigam, V. K. (2019). Recent Bio-Processing Technologies for Value Added Horticultural Products. In *Applied Microbiology and Bioengineering* (pp. 57–67). Elsevier.

Toon, O. B., Robock, A., & Turco, R. P. (2014). Environmental consequences of nuclear war. *AIP Conference Proceedings*, *1596*, 65–73. AIP.

Truini, J. (2002). *Building a Shed: Expert Advice from Start to Finish*. Taunton Press.

Unibio. (2014). *What Is Uniprotein®?* Retrieved from http://www.unibio.dk/?page_id=47

Upson, S. (2014, February 1). Hoop house horticulture creates many benefits. Retrieved August 26, 2019, from https://www.noble.org/news/publications/ag-news-and-views/2014/february/hoop-house-horticulture-creates-many-benefits/

Van der Meer, T. (2017). *Industrial Capital Expenditure Survey*. Retrieved from https://www.arcadis.com/media/2/4/8/%7B2480D19F-439D-46BD-8A40-859A6865BD88%7DIndustrial%20Capital%20Expenditure%20Survey%202017.pdf

Von Zabeltitz, C., & Baudoin, W. O. (1999). Greenhouses and shelter structures for tropical regions. *FAO Plant Production and Protection Paper (FAO)*. Retrieved from http://agris.fao.org/agris-search/search.do?recordID=XF2000393179

Wani, S. H., & Herath, V. (Eds.). (2018). *Cold Tolerance in Plants: Physiological, Molecular and Genetic Perspectives*. Retrieved from https://www.springer.com/gp/book/9783030014148

Watson, R. T., Boudreau, M.-C., & van Iersel, M. W. (2018). Simulation of greenhouse energy use: An application of energy informatics. *Energy Informatics*, *1*(1), 1.

Weintrit, A., & Neumann, T. (2011). *Miscellaneous Problems in Maritime Navigation, Transport and Shipping: Marine Navigation and Safety of Sea Transportation*. CRC Press.

Wittwer, S. H., & Castilla, N. (1995). Protected cultivation of horticultural crops worldwide. *HortTechnology*, *5*(1), 6–23.

World Bank Group. (2016). Global Solar Atlas. Retrieved August 26, 2019, from https://globalsolaratlas.info/?c=34.79125,6.434321,2&s=0.4,37.85

Zelenika, I., & Pearce, J. (2011). *Barriers to appropriate technology growth in sustainable development*.

Chapter 3 [2]Food in space from hydrogen oxidizing bacteria

Abstract

The cost of launching food into space is very high. An alternative is to make food during missions using methods such as artificial light photosynthesis, greenhouse, nonbiological synthesis of food, electrotrophic bacteria, and hydrogen oxidizing bacteria (HOB). This study compares prepackaged food, artificial light microalgae, and HOB. The dominant factor for each alternative is its relative mass due to high fuel cost needed to launch a payload into space. Thus, alternatives were evaluated using an equivalent system mass (ESM) technique developed by the National Aeronautics and Space Administration. Three distinct missions with a crew of 5 for a duration of 3 years were analyzed; including the International Space Station (ISS), the Moon, and Mars. The components of ESM considered were apparent mass, heat rejection, power, and pressurized volume. The selected power source for all systems was nuclear power. Electricity to biomass efficiencies were calculated for space to be 18% and 4.0% for HOB and microalgae, respectively. This study indicates that growing HOB is the least expensive alternative. The ESM of the HOB is on average a factor of 2.8 and 5.5 less than prepackaged food and microalgae, respectively. This alternative food study also relates to feeding Earth during a global agricultural catastrophe. Benefits of HOB include recycling wastes including CO_2 and producing O_2. Practical systems would involve a variety of food sources.

[2] K.A. Alvarado, J. B. García Martínez, Silvio Matassa, Joseph Egbejimba, David Denkenberger, Food in space from hydrogen oxidizing bacteria, Acta Astronautica. (In press).

3.1 Introduction

A food production method using hydrogen-oxidizing bacteria (HOB), a single cell protein (SCP) source, was first proposed by microbiologists in 1965 [1] and soon after experimented for applications in space by the National Aeronautics and Space Administration (NASA) [2]. This technology is currently being developed for human and animal consumption [3–5]. The process typically involves electrolysis; using electricity to split water into oxygen and hydrogen and provide them to hydrogen-oxidizing bacteria for their growth. HOB, specifically *Cupriavidus necator*, have been experimentally found to contain 63% protein content and 6% carbohydrate [6]. They have an amino acid composition similar to or better than algae or soybeans [7] and pasteurization and drying into a fine powder produces a texture comparable to dried milk [8]. According to a Finnish food company, Solar Foods, their HOB SCP product called Solein looks and tastes like wheat flour [9]. Growth occurs inside a bioreactor similar to other fermentation processes and requires nutrients including ammonia, sulfates, and phosphates. Using current technology, the efficiency of energy conversion from electricity to calories from SCP is around 20% [10]. By contrast, the conversion of electricity into food via photosynthesis is around 3% [11]. This alternative food source would be valuable in space missions and in Earth catastrophes that disrupt agriculture, such as abrupt climate change or supervolcanic eruption. Concurrent research has been completed on the subject of feeding Earth during a crop-inhibiting global catastrophe, such as nuclear winter. The research investigates feeding Earth using HOB quickly and cost effectively [12]. Similar concepts could be applied for feeding people in refuges to repopulate the Earth, which could be in space, underground, or under water [13,14]. In either case, HOB would need to be supplemented with other foods to form a complete diet. In space or refuges, this could take the form of electroactive bacteria (EAB) SCP, nonbiologically synthesized food, photosynthetically produced food with artificial light or greenhouses (space only), or prepackaged food. In the case of global catastrophes, other alternative foods include cellulosic sugar, seaweed, food grown in greenhouses [15], methane SCP, EAB SCP, nonbiological synthesized food, or ruminants from crop residues, grasses, and silage. Alternative foods differ in cost and scaling ability based on resource availability, however, they can potentially meet diverse nutritional needs [16].

This study compares the cost of current space food alternatives, including dry prepackaged food and photosynthetically grown microalgae SCP [17], to the cost of producing SCP from hydrogen using electrolysis. The cost to transport a payload, i.e. food, is proportional to the mass of that payload [18] and the fuel required increases exponentially with the velocity reached [19]; therefore, less mass launched means less cost for the mission. This project aims for the production of food for deep space and lunar exploration and increases the viable time in space through providing effectively produced food. Food is supplied to the International Space Station (ISS) in Low Earth Orbit (LEO) every 90 days [20], or approximately four times per year. These resupply missions could be significantly reduced by using a bioreactor system.

3.2 Methods

This study was completed from a synthesis of literature on emerging HOB technology, establishing the procedure for evaluating alternatives for space, and leveraging other investigations on alternative foods. For equitable comparison, each food alternative was treated as the exclusive food source for its mission. In practice, a variety of food sources should be used in space to provide nutritional diversity. Conservative estimates were used suitably to give an advantage to prepackaged food and microalgae SCP alternatives.

3.2.1 Calculation of equivalent system mass

Using NASA's equivalent system mass (ESM) method [18], the aggregate mass of each alternative was calculated for three distinct missions: the ISS, the Moon, and Mars. The equation for the ESM of a subsystem during a segment of the mission, with the applied location factor L_{eq}, is:

$$L_{eq} \,.\, [(M_I * SF_I) + (V_I * V_{eq}) + (P * P_{eq}) + (C * C_{eq}) + (CT * D * CT_{eq}) + (M_{TD} * D * SF_{TD}) + (V_{TD} * D * V_{eq})] \quad \text{(Eq. 1)}$$

The essential parameters, explained by [18], include mass, power, cooling (or in this study, heat rejection), and crew time. The ESM of a subsystem is the sum of the mass equivalencies of these parameters.

Variables of a subsystem include initial (or apparent) mass M_I, initial mass stowage factor SF_I, initial pressurized volume V_I, power P, heat rejection C, crew time CT, mission segment duration D, time- or event-dependent mass M_{TD}, mass stowage factor SF_{TD}, and pressurized volume V_{TD}, and mass equivalency factors for pressurized volume V_{eq}, power P_{eq}, heat rejection C_{eq}, and crew time CT_{eq}. Certain mission specifications are held the same for each mission to support comparability. The selected mission duration for each mission was 3 years with a crew of 5, similar to current proposed manned Mars missions [21].

Mass equivalency factors for pressurized volume, power, and heat rejection were collected from NASA's Baseline Values and Assumptions Document (BVAD) [22], unless otherwise specified. Mass equivalency factors for pressurized volume were obtained for a shielded aerodynamic crew capsule; 66.7 kg/m^3 for ISS missions, 80.8 kg/m^3 for Moon missions, and 215.5 kg/m^3 for Mars missions. The mass equivalency factor for powering the bioreactor systems, 76 $kg/kW_{electrical}$, was collected from a Brayton cycle nuclear reactor producing 20 $kW_{electrical}$. The same value was used for the prepackaged food alternative. Mass equivalency factors for heat rejection for Moon and Mars missions were obtained as 65 and 60 $kg/kW_{thermal}$, respectively. This value on ISS missions was calculated based on the ISS Heat Rejection System (HRS), which weighs 6,736 kg and has a capability of rejecting 70 kW [23]. Heat rejection from the nuclear reactor was not considered since, in practice, its heat would be rejected into space [22]; in addition, the selected nuclear reactor from the BVAD contains a heat rejection system and is included in the power requirement. Heat rejection for the bioreactors was considered the same as the power requirement since all power would end up as heat from growing food and human metabolism. Similarly, the power input to the ECLSS was considered to be rejected as heat. In reality, heat would be released by astronauts' metabolism, but energy is contained in the jettisoned methane, so we estimate that these effects counteract.

Missions were divided into segments to account for changing propulsion and changing ESM. A segmented approach was considered for this study to involve the progressively decreasing apparent mass of prepackaged food. Single factors that sum each mission's segments were estimated for simplicity. Location factors were found for different segments of Moon and Mars missions, summarized in Table 3.18 of the BVAD [22]. A reference of 1.0 was used for launching a payload to LEO. Six distinct segments for Moon and Mars missions involving fuel consumption include Earth's surface to LEO, LEO to a celestial body's orbit, orbit to surface, surface back to orbit, orbit to LEO, and LEO to Earth's surface. These segments were combined into one trip by applying known location factors from Table 3.18, involving: (1) the reference from Earth's surface to LEO, (2) LEO to the celestial body's orbit, (3) LEO to the celestial body's surface then back to the celestial body's orbit, and (4) LEO to the celestial body's orbit then back to LEO and down to Earth. Different vehicles were involved in developing the values in Table 3.18; however, the comparison between different food options is insensitive to these values as the same values are applied to all foods. One location factor, adding the six accelerations, was derived with the following arithmetic using the above notation: (1) + (2) + [(3) - (2)] + [(4) - (2)]. LEO to Earth's surface was considered to use negligible fuel. The location factors were estimated to be 1.0 for ISS missions, 16.6 for Moon missions, and 14.1 for Mars missions.

3.2.2 Design of alternatives

The mass of the prepackaged food would include the dry food mass and the equivalent mass of the Environmental Control Life Support System (ECLSS). A balanced diet of astronaut's meals [24] were assembled for the prepackaged food alternative that could calorically sustain a crew of five for three years. The mass of prepackaged food for each mission was calculated from a daily nutrition plan of 2,800 kcal per person [22]. For protein comparison, 2-3 servings of meat and 2-3 servings of dairy are suggested daily [24]. Considering 30 g and 10 g of protein per serving of meat and dairy, respectively, this equates to 80-120 g of protein daily, which aligns with the recommended protein intake for athletes [25], and would be about 15% of daily energy intake. For comparison, the protein content of microalgae, specifically *Spirulina spp.*, is about 60% [26], and *C. necator* is 63% [6]. The HOB system has an estimated efficiency of electrical to chemical energy of 15% to 21% and the microalgae system has an efficiency of 1% to 8%. For HOB, the energy efficiency was estimated in this study by calculating the energy requirements of each step in the process per unit of SCP produced. The mid-range value 18% was used in further calculations for a conservative estimate. The energy efficiency of microalgae was estimated mainly on the expected efficiency of each step, and the mid-range value of the expected range of efficiency was used (4%). Design and specifications for the microalgae setup were gathered from current literature [27,28]. The mass of HOB and microalgae systems includes the apparent mass of the bioreactor setup and the mass equivalent of the power generation system. The HOB setup includes the tank, fluids (essentially H_2O), microbial broth/media, electrolyzer, centrifuge, dryer, pumps, pipes, and connectors. By combining the mass, the mass of the setup would be approximately a factor of 3 heavier than the mass of the HOB fluids. The mass of the microalgae setup was calculated by adding two times the mass of the HOB fluids to the mass of the photobioreactor. The process flow diagram of electrolysis-based hydrogen SCP production is illustrated in an accompanying article for producing this food source for feeding the Earth [12].

3.2.3 Microbial energy efficiencies

The energy efficiency of HOB, more specifically *Cupriavidus necator*, was estimated by considering the electricity consumption of the five steps involved in the process: water electrolysis, CO_2 capture, HOB fermentation, centrifugation, and spray drying. On the ISS the electrolyzer has a thermodynamic efficiency of 80% [29]; the specific energy of hydrogen, 39.4 kWh/kg [30] and a requirement of 0.394 kg H_2/kg SCP [31] translates to an electrolysis energy requirement of 19.4 kWh/kg SCP produced. The fermentation energy consumption is 1.5 kWh for industrial scale [32]; allowing for a penalty of 3 times as much to account for the uncertainty of bacterial growth in space yields 4.5 kWh/kg for the high energy end. For CO_2 capture, current NASA equipment operates at a thermodynamic efficiency of 20% [33]. The thermodynamic minimum for the representative concentration and gas efficiency is approximately 21 kJ/mol CO_2 [34]. For a CO_2 requirement of 2.2 kg CO_2/kg SCP produced [31] the energy required is 1.45 kWh/kg SCP produced. For the water removal steps (centrifugation and drying), a range of values was considered to account for the uncertainty of performing the process in space. The range of solids content at the outlet of the bioreactor is 1%-3% of solids, which means between 0.03-0.10 m^3 water/kg SCP has to be separated. Considering a power consumption of centrifugation between 0.7 kWh/m^3 [35] and 8 kWh/m^3 [36] the energy required for the centrifugation step is in the range of 0.02-0.76 kWh/kg SCP for a solids concentration in the outlet of 22%. The energy requirements of spray drying are between 4,500-11,500 kJ/kg water [37]. This translates to a requirement of 4.4-10.3 kWh/kg SCP. Adding the consumption of all steps yields 26.8-37.5 kWh/kg SCP. An energy content of 5.56 kWh/kg SCP [38] translates to an efficiency of 14.8-20.7% for HOB.

The energy efficiency of microalgae, more specifically *Spirulina platensis* M2 strain [17], is derived from the electricity produced by the power source which is converted to light with lamps, part of which is absorbed by the microorganisms for photosynthesis. The microorganisms are then centrifuged, which consumes 8 kWh/m^3 for centrifugation to concentrate from 0.4% solid mass [36] to 22%, resulting in 2.0 kWh/kg SCP. Finally, they are dried to a powder. CO_2 capture and spray drying are accounted for using the same values as HOB. The conversion efficiency of sunlight to microalgae biomass is expected to be 3%-9% [39] and the photosynthetically active radiation (PAR) of sunlight is about 50% [40], which means the expected energy efficiency for converting photosynthetically active light to biomass is within the range of 6-18%. The PAR of the lamp that would be used is expected to be between that of an HID lamp (40%) and a state of the art LED lamp (80%) [41]. These values translate to a light to biomass efficiency range of 2.4%-14.4%. The expected energy efficiency of conversion from electricity to light, or wall-plug efficiency, is between 41.4% [42] and 81% [43], from which an electricity to biomass efficiency of 1.0-11.7% can be obtained. Including the energy for water removal and CO_2 capture, the overall efficiency of electricity to microalgae SCP biomass is between 1.0%-7.7%. The lower bound of the photosynthetically active light to biomass value is in agreement with that of an integrated algae production and life support system, known as the Micro Ecological Life Support System Alternative (MELISSA) [44]. MELISSA uses halogen lamps with a notably inefficient expected PAR of 15% and wall-plug efficiency of 5%, to obtain 25.3 g dry/day with an energy use of 7 kW [45], which results in electricity to biomass efficiency of 0.05%. From these, a value of photosynthetically active light to biomass of approximately 6.8% can be back calculated, very close to the expected lower bound of 6%.

Table 3.1: Summary of values used for determining microbial energy efficiencies.[3]

Description	**Value**	**Unit**
Cupriavidus necator		
ISS electrolyzer thermodynamic efficiency	80%	
Specific energy of hydrogen	39.4	kW/kg H_2
Stoichiometric H_2 requirement	0.394	kg H_2/kg SCP
Electrolysis energy requirement	19.4	kWh/kg SCP
Fermentation energy consumption, high end value	4.5	kWh/kg SCP
CO_2 capture efficiency	20%	
Thermodynamic minimum	21	kJ/mol CO_2
Stoichiometric CO_2 requirement	2.2	
Energy requirement	1.45	kWh/kg SCP
Range of solids content at outlet	1%-3%	
Stoichiometric water requirement range	0.03-0.10	m^3 water/kg SCP
Centrifugation power consumption range	0.02-0.76	kWh/kg SCP
Concentrated solids content at outlet	22%	
Spray drying energy consumption range	4,500-11,500	kJ/kg water
Spray drying power consumption range	4.4-10.3	kWh/kg SCP

[3] This table was not included with the submission of this article for peer review.

Table 3.1 continued

Overall power consumption range	26.8-37.5	kWh/kg SCP
Energy content of HOB	5.56	kWh/kg SCP
Overall efficiency of HOB	14.8-20.7%	
Spirulina platensis M2 strain		
Centrifugation power consumption	8	kWh/m^3
Concentrated solids content at outlet	0.4%-22%	
Centrifugation power consumption	2.0	kWh/kg SCP
Efficiency of sunlight to microalgae biomass	3%-9%	
Photosynthetically active radiation (PAR) of sunlight	50%	
Efficiency of PAR to biomass range	6%-18%	
PAR of lamp range, HID to LED	40%-80%	
Efficiency of light to biomass range	2.4%-14.4%	
Wall-plug efficiency	41.4%-81%	
Overall efficiency of electricity to biomass	1.0%-7.7%	

3.2.4 Power generation methods

The prepackaged food alternative requires full use of the ECLSS, which operates at 5.1 kW [22] for 9 ISS crew members [46]. HOB and microalgae require an alternative power system than prepackaged food for providing chemical energy and power for the bioreactor system components, such as for the electrolyzer. Two possible power sources are solar power and nuclear power. Solar power is limited in that it requires sunlight. The ISS, Moon, and Mars are eclipsed for 50% of time. Additionally, Mars experiences sun-blocking dust storms occurring up to several weeks [47], and would have lower solar intensity being further from the sun. Setups could operate in stasis during times when no solar energy is collected to conserve energy and minimize power storage requirements. In view of this, a solar powered setup would require a freezer, batteries, additional solar panels, and a larger setup. Alternatively, nuclear power does not require sunlight to operate; however, it requires more heat rejection per unit mass. The predicted dominant cost was the ESM of each food system, as opposed to the cost of the individual materials. Ancillary equipment for powering the bioreactors was selected by considering the lowest ESM. Mass equivalency factors convert heat rejection ($W_{thermal}$), power ($W_{electrical}$), and pressurized volume (m^3) to unit mass (kg); derived by dividing the mass of the infrastructure by the unit of resource used in the mission scenario [18]. A nuclear reactor was the selected power source for this study considering it has less equivalent mass than a solar powered system.

3.3 Results

A crew of five would require 15.5 million kcal for a three-year mission. The initial mass of prepackaged food would be 3,690 kg. This mass would be reduced as the mission progressed; the apparent mass therefore changes with each segment of the mission. The pressurized volume of prepackaged food was calculated considering the ordinary density of dehydrated food is 1,400 kg/m^3 [48]. The pressurized volume for the bioreactor system is the volume of the setup. The power source was considered to be outside of the pressurized capsule. Further specifications for each bioreactor are listed in Table 1. The energy density for HOB was calculated after removal of nucleic acid content [38].

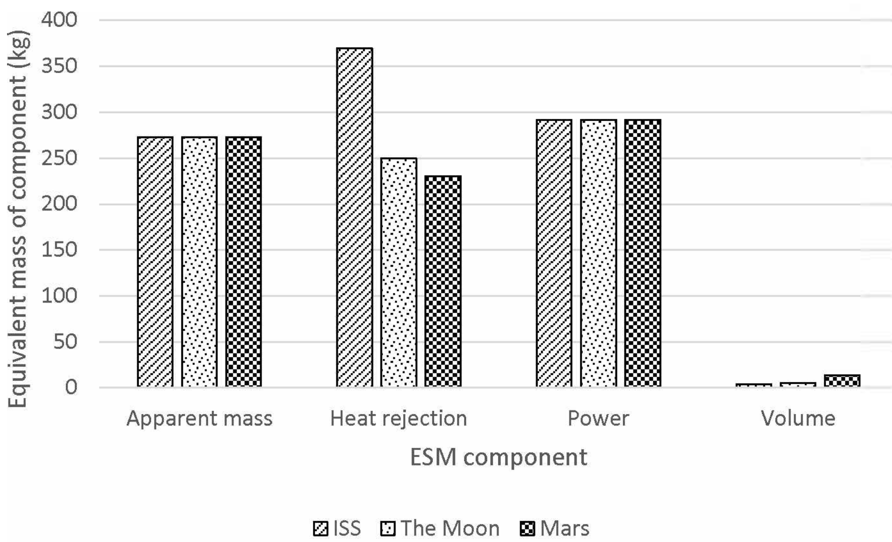
Table 3.2 Specifications of the HOB bioreactor and the microalgae photobioreactor. Values for microalgae and HOB were calculated from estimates in [12], [38].

	HOB	Microalgae
Volumetric productivity (kg dry/m^3/day)	48	3
Energy density (kcal/g dry)	4.78	3.04
Bioreactor volume (L)	62	1,780
Setup mass (kg)	184	1,520
Electrical efficiency to dry food	17.8%	4.0%
Chemical energy requirement of food (kW)	0.684	0.684
Required power for product (kW)	3.8	17.1

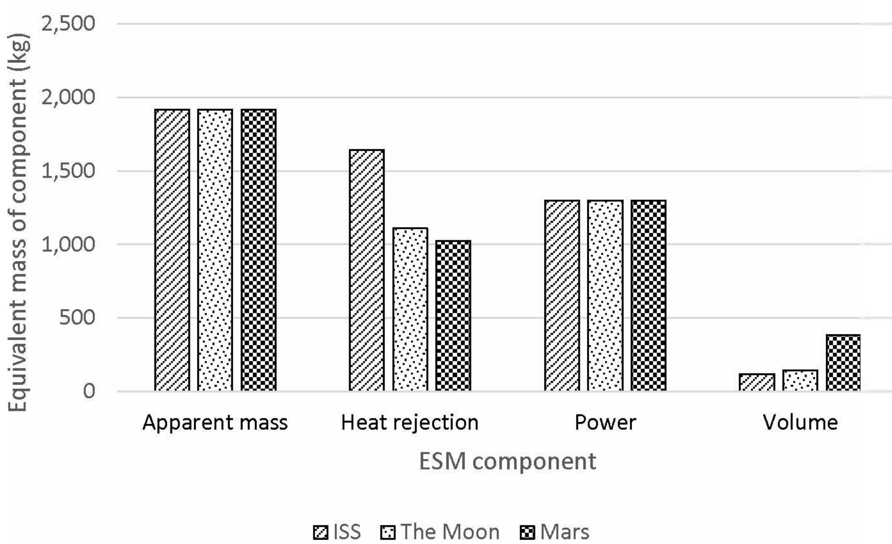
For a conservative analysis comparing prepackaged food with HOB, the crew would begin with exactly enough prepackaged food for a three-year mission which would be depleted (zero mass) upon landing back on Earth. Since these missions are round trips, the apparent mass for prepackaged food was averaged for the entire mission as 1,840 kg. More practically, redundant prepackaged food supply would be carried for the mission. Table 2 summarizes the components of this ESM study.

Table 3.3 Component summary for each mission and food alternative.

	Heat rejection, *C* ($kW_{thermal}$)	Heat rejection equivalency, C_{eq} (kg/ $kW_{thermal}$)	Apparent mass, *M* (kg)	Power, *P* ($kW_{electrical}$)	Power equivalency, P_{eq} (kg/ $kW_{electrical}$)	Pressurized volume, *V* (m^3)	Pressurized volume equivalency, V_{eq} (kg/m^3)	Location factor, L_{eq} (kg/kg)
HOB system								
ISS	3.8	96	273	3.8	76	0.06	66.7	1.0
Moon	3.8	65	273	3.8	76	0.06	80.8	16.6
Mars	3.8	60	273	3.8	76	0.06	215.5	14.1
Microalgae system								
ISS	17.1	96	1,920	17.1	76	1.78	66.7	1.0
Moon	17.1	65	1,920	17.1	76	1.78	80.8	16.6
Mars	17.1	60	1,920	17.1	76	1.78	215.5	14.1
Prepackaged food								
ISS	2.8	96	1,840	2.8	76	1.32	66.7	1.0
Moon	2.8	65	1,840	2.8	76	1.32	80.8	16.6
Mars	2.8	60	1,840	2.8	76	1.32	215.5	14.1



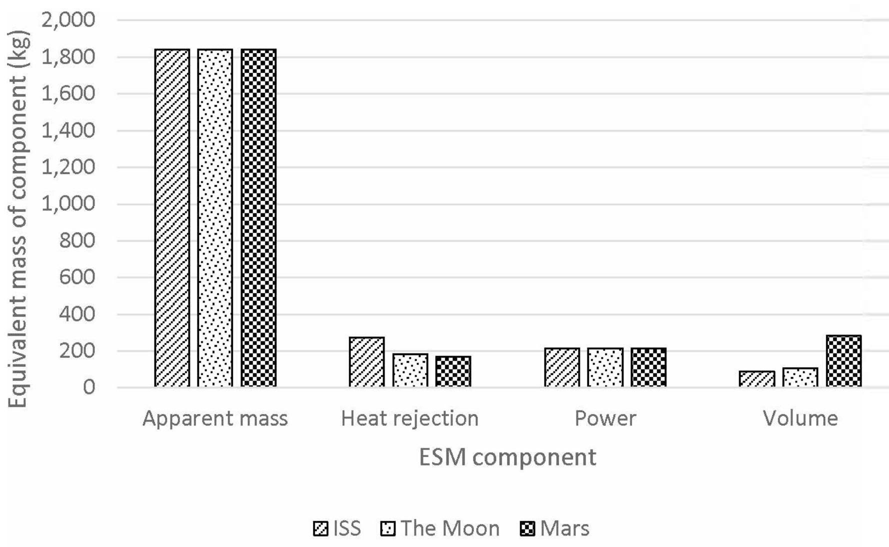
(a)



(b)

Figure 3.1 Graphical representations of the ESM component summaries for (a) the HOB system, (b) the microalgae system.[4] *Figure 3.1 continued next page.*

[4] This figure was not included with the submission of this article for peer review.



(c)

Figure 3.1 continued here. (c) Prepackaged food.

A table of data similar to Table 2 was assembled to calculate the ESM results, displayed in Table 3. Prepackaged food was found to be 2.6, 2.9, and 3.1 times greater in mass than the HOB alternative for ISS, Moon, and Mars missions, respectively; or on average a factor of 2.8. Similarly, the microalgae alternative was found to be 5.3, 5.5, and 5.7 times greater in mass than HOB for each respective mission; or on average a factor of 5.5.

Table 3.4 ESM results (in kg) for each food alternative averaged for three distinct missions.

	HOB	Microalgae	Prepackaged food
ISS	939	4,980	2,150
Moon	13,600	74,200	39,000
Mars	11,400	65,300	35,400

3.4 Discussion

3.4.1 Life support considerations

Table 4 summarizes the considerations made for certain life support components. A net reaction for HOB [49] was used for considering the nutrient and other growing requirements. The net reaction could be reduced (Eq. 2) for the overall system if ideal nutrient recycling occurred and ammonia was the nitrogen source.

$$2.43H_2O + 4.09CO_2 + 0.76NH_3 \rightarrow C_{4.09}H_{7.13}O_{1.89}N_{0.76} + 4.36O_2 \qquad \text{(Eq. 2)}$$

The ammonia can be recycled from urine. The water consumption can be provided by the water production in astronauts' metabolism of the SCP. Life support subsystems for air, water, and waste are currently used to minimally improve resource recovery and recycling [22]. Moreover, if total recycling efficiency of CO_2 is achieved, then the carbon in CO_2 produced by the astronauts' metabolism is consumed by the HOB. The net SCP production can be stable with complete carbon recycling; only a small amount of raw materials would need to be included at the start of a mission. CO_2 and water may also be available from local mission sources, particularly on Mars. All three systems require CO_2 capture to maintain life support, and microalgae is the only system that does not require water electrolysis since the microorganisms directly produce oxygen from water via photosynthesis. The prepackaged food option additionally requires a CO_2 reduction system. The system used by NASA is a Sabatier reactor that combines the CO_2 produced by the crew with H_2 to make CH_4 waste and recycle the oxygen via electrolysis of the water product [50].

Table 3.5 Considerations for components that may add equivalent mass to a food alternative.

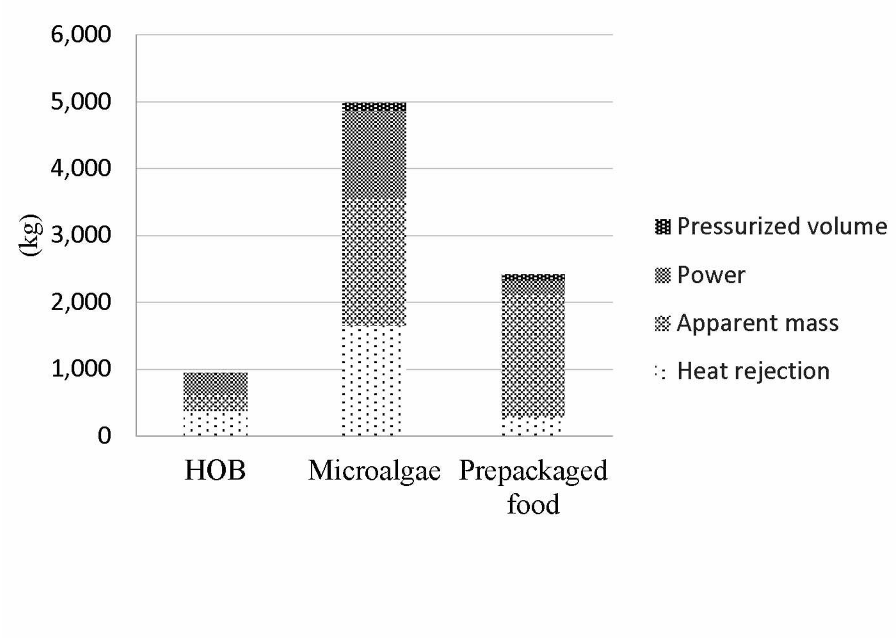
Component	Prepackaged food	HOB	Microalgae
H_2O (liquid)	Consumed in drinking and rehydrating food	Consumed in drinking, electrolysis and microbial growth	Consumed in drinking and by microbial growth
CO_2	Product of crew metabolism, converted to CH_4 waste via the Sabatier system and ejected	Consumed for growing microorganisms for food	Consumed for growing microorganisms for food
O_2	Produced via electrolysis	Product of electrolysis	Product of microbial growth
Food	Prepackaged food	Microbial protein	Microbial protein
Additional infrastructure	-	HOB setup, power supply	Microalgae setup, power supply
Additional power requirements	ECLSS	Bioreactor, drying and processing of SCP	Bioreactor, drying and processing of SCP
Additional thermal control	ECLSS	Bioreactor cooling, heat exchangers, power supply cooling	Bioreactor cooling, heat exchangers, power supply cooling
Crew time	-	Operating, maintenance, cleaning (neglected)	Operating, maintenance, cleaning (neglected)
Waste	Food packaging, human waste and contaminants, methane gas	Non recyclable waste from spent media (if any)	Non recyclable waste from spent media (if any)

3.4.2 Equivalent system mass contributions

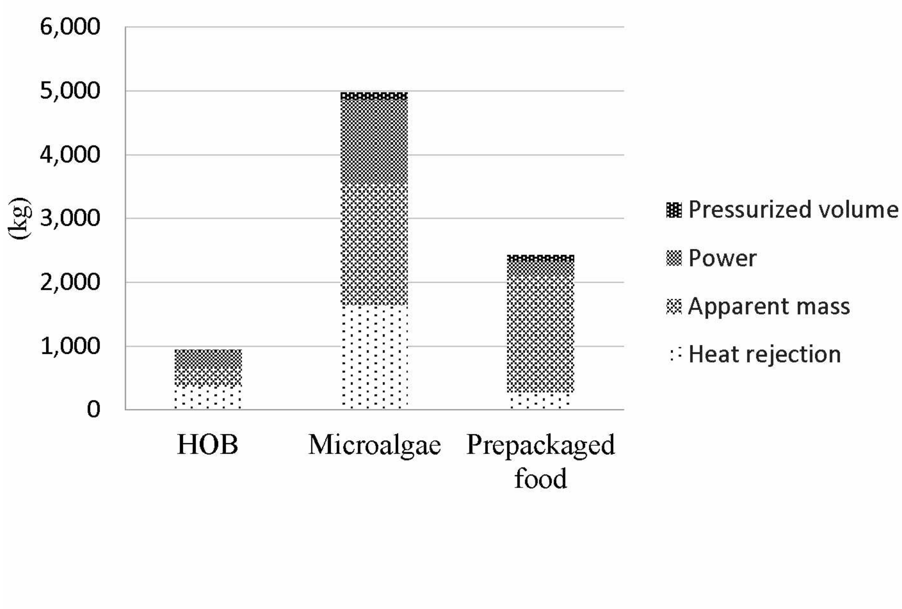
Parameters that did not impact results of the equivalent mass system calculations (Eq 1) were the time- or event-dependent mass M_{TD}, volume V_{TD}, and mass stowage factor SF_{TD} (such as rack structure needed for the subsystem), and crew time CT and mass equivalency factor CT_{eq}. This is because there would be no time or event-dependent mass produced since all waste would be jettisoned periodically (which makes the estimate of the advantage of the HOB conservative compared to the scenario of retaining some waste). Additionally, crew time requirements were ignored since the crew would have excess time during long duration missions [22]; or because a mission's segment length was negligible. Thus, the contributing variables were apparent mass M_I, mass stowage factor SF_I (for known documented masses, SF_I is 1.0), pressurized volume V_I and mass equivalency factor V_{eq}, power P and mass equivalency factor P_{eq}, heat rejection C and mass equivalency factor C_{eq}. Mass equivalency factors vary with each mission and are derived from factors such as the resource used, location, infrastructure, processing, installation [22].

3.4.3 Alternatives comparison

Growing microalgae has been discussed for developing an ecological life support system for space missions [17]. A significant benefit of growing HOB is its efficiency converting electric energy to food calories. Calculated for space, this efficiency is more than three times higher than that of microalgae, which itself has higher photosynthetic efficiency than crops [11]. Since this is a comparison study, the accuracy of individual location factors does not have a significant impact on the results because they are consistent between food alternatives. Location factors, and therefore ESM results, are lower in value for the Moon mission than for Mars. This is because the ESM results are added mass as opposed to overall mission mass. The location factors for Moon and Mars are based on separate shuttles, propulsion types, and transportation history (i.e. whether payloads are jettisoned during travel). ESM is rarely the exclusive metric for a tradeoff study since it lacks considerations of reliability, safety, and performance, however it is pivotal as a cost metric [18]. Figure 1 illustrates the equivalent mass penalties for each alternative food for a Moon mission. ISS and Mars missions appear similar. The apparent mass of prepackaged food is the most significant penalty in comparison; meaning the other penalties are small for that food alternative. On the other hand, the HOB and microalgae systems have relatively high heat rejection and power requirements, similar to the apparent mass penalty, and a small pressurized volume requirement.



(a)



(b)

Figure 3.2 Overall comparison of equivalent mass penalties for (a) an ISS mission.[5] *Figure 3.2 continued next page.*

[5] Figures 3.2 (a) and (c) were not included with the submission of this article for peer review.

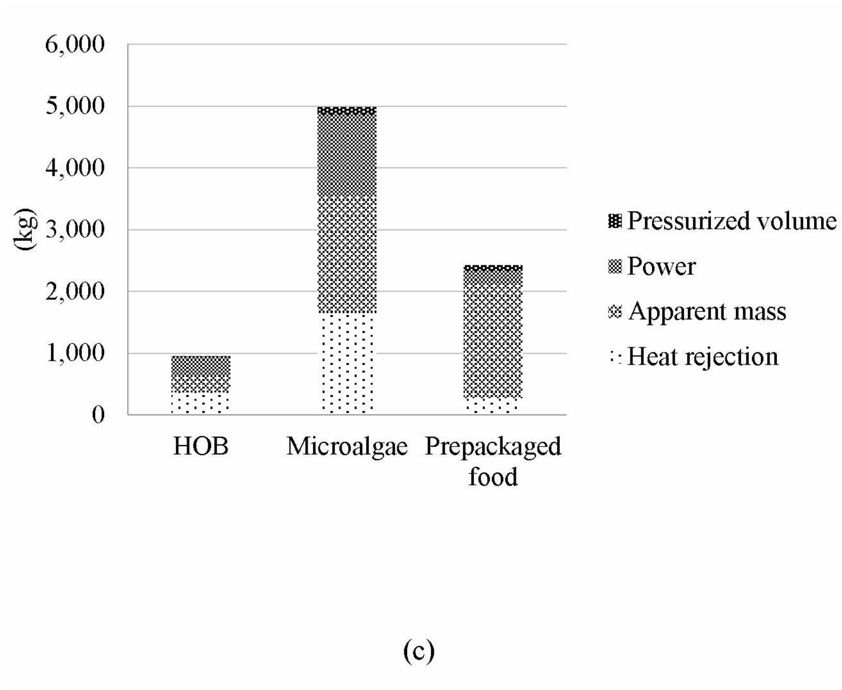


Figure 3.2 continued here. (b) A Moon mission, and (c) a Mars mission.

Although there would theoretically not need to be a chemical ECLSS with either of the bioreactors [17], the infrastructure was kept to ensure a reliable life support system. The mass of the Sabatier reactor could be added but would be negligible in comparison; adding about a 14 mL reactor to a 4-crew unit [50]. All systems would also have a backup chemical ECLSS, including spare parts and smaller or associated systems to substitute its operation during repair, but since the ESMs would be the same, they are not included. The pressure and atmospheric composition of the spacecraft still needs to be controlled. A benefit of the HOB alternative is the recycling of nutrients and waste products. However, the technology for achieving this for these missions needs future work. Additional work should explore feeding a colony of people for a longer period. The growing process for HOB is gaining maturity on Earth for mass production [3–5] and rapid scalability has been investigated [12]. Existential risks that this research might apply to include scenarios that interrupt global food production, such as abrupt or extreme climate change [8,51], simultaneous extreme weather incidents resulting in multiple breadbasket failures [52], eradicative crop pathogens [53], super weeds [54], super crop pests [55], or super bacteria [56]. Common solutions to these risks are artificial light photosynthesis of crops and storage of food. For catastrophes that last several years, a small fraction of people would survive exclusively on the current amount of stored food [57]. Storing sufficient food for the world ahead of time would take years and would be expensive [58]. Artificial light photosynthesis is inherently expensive and energy intensive, and would therefore not be capable of feeding the world [15]. Alternative foods are investigated based on their potential to supply edible biomass; in other words, having low production cost and low energy and resource requirements. Nutrient diversity is also being explored to determine the extent for which the alternative foods should be produced [59].

3.5 Conclusions

The ESM analysis demonstrates that growing HOB as a food source during manned space missions has less equivalent mass, and therefore less cost, than prepackaged food by an average factor of 2.8, as well as growing microalgae by an average factor of 5.5. The electrical to biomass efficiency of HOB in space was calculated to be at least 15%, whereas the highest calculated efficiency for microalgae is 7.0%. It was anticipated that the cost of growing HOB, more specifically *Cupriavidus necator*, would be less than prepackaged food because of the recycling benefits of HOB. Furthermore, it was anticipated that growing HOB would be significantly less expensive than using electricity to grow food with photosynthesis, more specifically from *Spirulina platensis* M2 strain, given the much higher efficiency of HOB. A nuclear reactor was selected to power the bioreactor setups for providing lower equivalent mass than a solar powered system, especially because storage would not be required. The apparent mass of prepackaged food was found to be significantly high in comparison to the ESM penalties for that alternative as well as in comparison to other food alternatives. Similar alternative food studies are being conducted that relate to feeding people on Earth and in space using (i) EAB, wherein direct electricity is used as the energy source to feed bacteria, and (ii) non-biologically synthesized food, wherein food is chemically constructed without the use of living components. These studies will be compared to the results of this HOB study. Benefits of growing bacteria as a food source include its waste recycling, relatively high electrical to chemical efficiency, and reduced need for life support systems such as environmental control. Thus, HOB should be given consideration on future space missions as an important nutritional component.

Acknowledgements: Authors would like to acknowledge discussions with Dr. John A. Hogan, NASA Ames Research Center. Dr. Silvio Matassa is funded as a postdoctoral researcher by the Biofeedstock project, financed under the National Operation Program (PON Italy) 2014-2020. Authors would like to thank Alec Froese, Cullen Chandler, and De Jour Reed for conducting an initial scope.

3.6 References

[1] H.G. Schlegel, R. Lafferty, Growth of 'Knallgas' Bacteria (*Hydrogenomonas*) using Direct Electrolysis of the Culture Medium, Nature. 205 (1965) 308–309. https://doi.org/10.1038/205308b0.

[2] R.I. Mateles, J.N. Baruah, S.R. Tannenbaum, Growth of a thermophilic bacterium on hydrocarbons: a new source of single-cell protein, Science. 157 (1967) 1322–1323.

[3] B.A. Sefton, W.J. Coleman, Novel Microbial Biomass Based Feed Products, 2019.

[4] G. Monbiot, Lab-grown food will soon destroy farming–and save the planet, The Guardian. (2020). https://www.agricanto.org/uploads/5/2/6/3/52634281/lab_grown_food_will_replace_agriculture_monbiot.pdf.

[5] S.W. Jones, A. Karpol, S. Friedman, B.T. Maru, B.P. Tracy, Recent advances in single cell protein use as a feed ingredient in aquaculture, Current Opinion in Biotechnology. 61 (2020) 189–197. https://doi.org/10.1016/j.copbio.2019.12.026.

[6] T.G. Volova, V.A. Barashkov, Characteristics of proteins synthesized by hydrogen-oxidizing microorganisms, Applied Biochemistry and Microbiology. 46 (2010) 574–579.

[7] A. Ritala, S.T. Häkkinen, M. Toivari, M.G. Wiebe, Single Cell Protein—State-of-the-Art, Industrial Landscape and Patents 2001–2016, Frontiers in Microbiology. 8 (2017). https://doi.org/10.3389/fmicb.2017.02009.

[8] S. Dietz, High impact, low probability? An empirical analysis of risk in the economics of climate change, Climatic Change. 108 (2011) 519–541. https://doi.org/10.1007/s10584-010-9993-4.

[9] H. Smith, Finnish Company Uses NASA's Concept to Create Food from Thin Air, Nature World News. (2019). https://www.natureworldnews.com/articles/41847/20190725/finnish-company-uses-nasa-s-concept-to-create-food-from-thin-air.htm (accessed September 29, 2020).

[10] SolarFoods, Solein Q&A, (2019). https://solarfoods.fi/wp-content/uploads/2019/11/Solein-Q_and-A_FULL.pdf.

[11] D. Denkenberger, J.M. Pearce, Feeding Everyone No Matter What: Managing Food Security After Global Catastrophe, Academic Press, 2014.

[12] J.B. García Martínez, J. Egbejimba, J. Throup, S. Matassa, J.M. Pearce, D.C. Denkenberger, Potential of microbial protein from hydrogen for preventing mass starvation in catastrophic scenarios, Sustainable Production and Consumption. 25 (2021) 234–247. https://doi.org/10.1016/j.spc.2020.08.011.

[13] S.D. Baum, D.C. Denkenberger, J. Haqq-Misra, Isolated refuges for surviving global catastrophes, Futures. 72 (2015) 45–56. https://doi.org/10.1016/j.futures.2015.03.009.

[14] A. Turchin, B.P. Green, Aquatic refuges for surviving a global catastrophe, Futures. 89 (2017) 26–37. https://doi.org/10.1016/j.futures.2017.03.010.

[15] K.A. Alvarado, A. Mill, J.M. Pearce, A. Vocaet, D. Denkenberger, Scaling of greenhouse crop production in low sunlight scenarios, Science of The Total Environment. (2019) 136012. https://doi.org/10.1016/j.scitotenv.2019.136012.

[16] D. Denkenberger, J. Pearce, Micronutrient availability in alternative foods during agricultural catastrophes, Agriculture. 8 (2018) 169.

[17] W. Ai, S. Guo, L. Qin, Y. Tang, Development of a ground-based space micro-algae photo-bioreactor, Advances in Space Research. 41 (2008) 742–747. https://doi.org/10.1016/j.asr.2007.06.060.

[18] J.A. Levri, A.R. Centel, M. Field, A.E. Drysdale, M.K. Ewert, J.S. Centel, Advanced Life Support Equivalent System Mass Guidelines Document, National Aeronautics and Space Administration. (2003) 47.

[19] G. Ehrenhaft, R.L. Lehrman, F. Obrecht, A. Mundsack, How to Prepare for the ACT Assessment, Barron's Educational Series, 2004. https://books.google.com/books/about/_.html?id=AOo8ZFo4zlQC (accessed May 29, 2020).

[20] National Aeronautics and Space Administration, Food for Space Flight, NASA. (2004). http://www.nasa.gov/audience/forstudents/postsecondary/features/F_Food_for_Space_Flight.html (accessed May 20, 2020).

[21] M. Ansdell, P. Ehrenfreund, C. McKay, Stepping stones toward global space exploration, Acta Astronautica. 68 (2011) 2098–2113. https://doi.org/10.1016/j.actaastro.2010.10.025.

[22] M.S. Anderson, M.K. Ewert, J.F. Keener, S.A. Wagner, Life Support Baseline Values and Assumptions Document, Life Support. (2015) 220.

[23] Boeing, Active Thermal Control System (ATCS) Overview, (2020). https://www.nasa.gov/pdf/473486main_iss_atcs_overview.pdf.

[24] A.A. Casaburri, C.A. Gardner, Space food and Nutrition, (1999). https://www.nasa.gov/pdf/143163main_Space.Food.and.Nutrition.pdf.

[25] N. Clark, The power of protein, The Physician and Sportsmedicine. 24 (1996) 11–12.

[26] C. Robb-Nicholson, By the way, doctor: Is spirulina good for you?, Harvard Health. (2019). https://www.health.harvard.edu/staying-healthy/by_the_way_doctor_is_spirulina_good_for_you (accessed September 29, 2020).

[27] M. Płaczek, A. Patyna, S. Witczak, Technical evaluation of photobioreactors for microalgae cultivation, in: E3S Web of Conferences, EDP Sciences, 2017: p. 02032.

[28] Q. Huang, F. Jiang, L. Wang, C. Yang, Design of Photobioreactors for Mass Cultivation of Photosynthetic Organisms, Engineering. 3 (2017) 318–329. https://doi.org/10.1016/J.ENG.2017.03.020.

[29] R. Roy, Making Space Safer with Electrolysis, (2011). /topics-resources/content/Making-Space-Safer-with-Electrolysis (accessed May 22, 2020).

[30] C. Ramos, G. Buitrón, I. Moreno-Andrade, R. Chamy, Effect of the initial total solids concentration and initial pH on the bio-hydrogen production from cafeteria food waste, International Journal of Hydrogen Energy. 37 (2012) 13288–13295. https://doi.org/10.1016/j.ijhydene.2012.06.051.

[31] NovoNutrients, NOVONUTRIENTS Food from CO2, (2018). http://nas-sites.org/dels/files/2018/02/2-2-SEFTON-NovoNutrients-NAS.pdf.

[32] I. Pikaar, S. Matassa, B.L. Bodirsky, I. Weindl, F. Humpenöder, K. Rabaey, N. Boon, M. Bruschi, Z. Yuan, H. van Zanten, M. Herrero, W. Verstraete, A. Popp, Decoupling Livestock from Land Use through Industrial Feed Production Pathways, Environ. Sci. Technol. 52 (2018) 7351–7359. https://doi.org/10.1021/acs.est.8b00216.

[33] W. Gellett, Solid State Air Purification System, (2012).

[34] N.R. Council, D. on E. and L. Studies, O.S. Board, B. on A.S. and Climate, C. on G.C.T.E. and D. of Impacts, Climate Intervention: Carbon Dioxide Removal and Reliable Sequestration, National Academies Press, 2015.

[35] S. Szepessy, P. Thorwid, Low Energy Consumption of High-Speed Centrifuges, Chemical Engineering & Technology. 41 (2018) 2375–2384. https://doi.org/10.1002/ceat.201800292.

[36] K. Gayen, T.K. Bhowmick, S.K. Maity, Sustainable Downstream Processing of Microalgae for Industrial Application, CRC Press, 2019.

[37] C.G.J. Baker, K.A. McKenzie, Energy consumption of industrial spray dryers, Drying Technology. 23 (2005) 365–386.

[38] Unibio, What Is Uniprotein®?, (2014). http://www.unibio.dk/?page_id=47.

[39] R.H. Wijffels, M.J. Barbosa, An outlook on microalgal biofuels, Sci. 329 (2010) 796–799.

[40] A.J. Haverkort, Potato crop response to radiation and daylength, in: Potato Biology and Biotechnology, Elsevier, 2007: pp. 353–365.

[41] E. Darko, P. Heydarizadeh, B. Schoefs, M.R. Sabzalian, Photosynthesis under artificial light: the shift in primary and secondary metabolism, Philos Trans R Soc Lond B Biol Sci. 369 (2014). https://doi.org/10.1098/rstb.2013.0243.

[42] R. Blakey, Advantages of LED Lighting in Horticultural Applications, (2018).

[43] M. Wright, Cree royal blue LED delivers 81% wall plug efficiency (UPDATED), LEDs Magazine. (2017). https://www.ledsmagazine.com/specialty-ssl/automotive-vehicles/article/16700708/cree-royal-blue-led-delivers-81-wall-plug-efficiency-updated (accessed May 22, 2020).

[44] F. Godia, J. Albiol, J.L. Montesinos, J. Pérez, N. Creus, F. Cabello, X. Mengual, A. Montras, C. Lasseur, MELISSA: a loop of interconnected bioreactors to develop life support in space, Journal of Biotechnology. 99 (2002) 319–330.

[45] A. Vernerey, J. Albiol, C. Lasseur, F. Godia, Scale-up and design of a pilot-plant photobioreactor for the continuous culture of Spirulina platensis, Biotechnology Progress. 17 (2001) 431–438.

[46] D.E. Urrutia, Crowded Space Station: There Are 9 People from 4 Different Space Agencies in Orbit Right Now, Space.Com. (2019). https://www.space.com/space-station-crowded-nine-crewmembers-expedition-60.html (accessed May 23, 2020).

[47] K. Hille, The Fact and Fiction of Martian Dust Storms, NASA. (2015). http://www.nasa.gov/feature/goddard/the-fact-and-fiction-of-martian-dust-storms (accessed May 20, 2020).

[48] J. Qiu, S. Khalloufi, A. Martynenko, G. Dalen, M. Schutyser, C. Almeida-Rivera, Porosity, Bulk Density, and Volume Reduction During Drying: Review of Measurement Methods and Coefficient Determinations, Drying Technology. 33 (2015). https://doi.org/10.1080/07373937.2015.1036289.

[49] A. Ishizaki, K. Tanaka, Batch culture of Alcaligenes eutrophus ATCC 17697T using recycled gas closed circuit culture system, Journal of Fermentation and Bioengineering. 69 (1990) 170–174. https://doi.org/10.1016/0922-338X(90)90041-T.

[50] C. Junaedi, K. Hawley, D. Walsh, S. Roychoudhury, M. Abney, J. Perry, Compact and Lightweight Sabatier Reactor for Carbon Dioxide Reduction, in: 41st International Conference on Environmental Systems, American Institute of Aeronautics and Astronautics, Portland, Oregon, 2011. https://doi.org/10.2514/6.2011-5033.

[51] P. Valdes, Built for stability, Nat. Geosci. 4 (2011) 414–416. https://doi.org/10.1038/ngeo1200.

[52] R. Bailey, T.G. Benton, A. Challinor, J. Elliott, D. Gustafson, B. Hiller, A. Jones, C. Kent, K. Lewis, T. Meacham, M. Rivington, R. Tiffin, D.J. Wuebbles, Extreme weather and resilience of the global food system: Final Project Report from the UK-US Taskforce on Extreme Weather and Global Food System Resilience, The Global Food Security programme, UK, 2015.

[53] J.P. Dudley, M.H. Woodford, Bioweapons, Biodiversity, and Ecocide: Potential Effects of Biological Weapons on Biological Diversity, BioScience. 52 (2002) 583. https://doi.org/10.1641/0006-3568(2002)052[0583:BBAEPE]2.0.CO;2.

[54] C.C. Mann, Genetic engineers aim to soup up crop photosynthesis, Sci. 283 (1999) 314–316.

[55] H. Saigo, Agricultural Biotechnology and the Negotiation of the Biosafety Protocol, Geo. Int'l Envtl. L. Rev. 12 (1999) 779.

[56] G. Church, Safeguarding biology, Seed. 20 (2009) 84–86.

[57] D. Denkenberger, J. Pearce, A.R. Taylor, R. Black, Food without sun: Price and life-saving potential, Foresight. 21 (2019) 118–129.

[58] S.D. Baum, D.C. Denkenberger, J.M. Pearce, A. Robock, R. Winkler, Resilience to global food supply catastrophes, Environment Systems and Decisions. (2015) 1–13.

[59] D.C. Denkenberger, J.M. Pearce, Feeding everyone: Solving the food crisis in event of global catastrophes that kill crops or obscure the sun, Futures. 72 (2015) 57–68.

Chapter 4 General Conclusions

This research contributes to the security of food production in scenarios where the sun is obscured. When crops are unable to grow outdoors in their current locations using solar photosynthesis, alternative foods may be required to feed people. On Earth during a GCR event, the solution described here is a low-tech greenhouse scaling method, adding about $2.30 /kg dry to current food costs at retail. In other words, this would increase the cost of rice by 160%.

In small scale applications for space or Earth refuges, the solution described here is HOB SCP. Results of this study showed that growing HOB for a group of five people during three years was on average 2.8 times lower ESM (relative to cost) than storing prepackaged food and 5.5 times less than growing microalgae with artificial light. For longer duration space missions, the benefit of HOB would become increasingly apparent. The components of the ESM included the food system's apparent mass, power requirement, heat rejection, and pressurized volume (i.e. the occupied volume that is pressurized for space).

Both solutions eliminate the need for exclusive use of artificial light photosynthesis by determining viable methods of producing calories at significantly lower cost and energy consumption. Some artificial light may be required for long day obligate crops that require more than 12 hours of daylight to flower.

The anaerobic autotroph HOB species was selected in view to its ability to use CO_2 to make its food, and thus become human food, and its exceptional volumetric productivity. However, there are plenty of other applicable species of bacteria that use other forms of waste to produce useful byproducts.

More research on alternative foods is being conducted at the Alliance to Feed the Earth in Disasters (ALLFED). The principal research focus at ALLFED is estimating the cost of alternative food production methods and comparing them. Further research should compare all currently researched alternative foods to develop the logistics of deploying alternative foods in the event of a GCR. This would ensure nutritional diversity and redundancy in the event of multiple GCRs or industrial collapse. Small-scale foods should also be considered for this multiple breadbasket failure scenario so individual communities can independently sustain themselves.

It has not been analyzed yet, but this research may also relate to feeding rural communities, such as those in Alaska. In rural Alaska, the cost of energy is high and, in some cases, the sun is absent or ineffective for photosynthesis. Therefore, alternative foods having low energy consumption would be beneficial. There are heated greenhouses in some remote communities of Alaska, where the application of lower cost, low-tech greenhouses, such as those found in this study, may apply. Additionally, in some communities, there are artificial light greenhouses, where HOB would be a potential solution to reducing costs. However, HOB SCP is not as appetizing as freshly grown greenhouse food, so it would have trouble gaining acceptance in non-catastrophic conditions. This food source may also be impractically expensive and high tech for rural communities.

The competency of these studies was ensured by Dr. David Denkenberger's expertise on general engineering and mechanical engineering concepts, alternative foods, and GCRs, Dr. Meriam Karlsson's discussions on greenhouse operations, and a graduate biotechnology course from Dr. Silke Schiewer. These studies were aimed at developing cost estimates that were better than simply being within an order of magnitude. Furthermore, having been scoping projects, future work is needed on testing the implementation of these alternative food methods. Some of these foods, for example HOB SCP from Finnish food company, Solar Foods, and leaf protein extract by Dr. Joshua Pearce at Michigan Institute of Technology, are being tested on both a large, industrial scale and on a small, non-industrial scale. Testing for a large and quick deployment is still necessary. Global awareness and global cooperation should be emphasized to ensure the deployment of alternative foods results similarly to the results from this greenhouse study, therefore being as effective as possible.