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Scaling of greenhouse crop production in low sunlight scenarios

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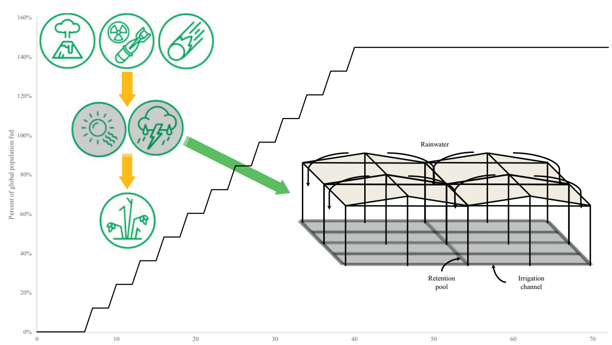
HIGHLIGHTS

- An alternative food production solution in a low sunlight catastrophe is greenhouse agriculture.
- Required current global markets for timber, polymer film, steel nails, and gravel are analyzed.
- The scaling rate considers the possibility of crop transplantation.
- Rapid scaling of greenhouses could be useful in a range of scenarios from nuclear winter to abrupt climate change.
- The economic analysis shows far lower cost for greenhouses than artificial light.

GRAPHICAL ABSTRACT



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ABSTRACT

Purpose: 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. 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.
Methods: A nuclear winter climate model is used to determine conditions for which greenhouses would need to compensate. The greenhouse structures are designed to utilize global markets of timber, polymer film, construction aggregates, and steel nails.
Results: The limiting market that determines the growth rate of the greenhouses is the rate at which polymer film and sheet are currently extruded. Conditions under low-tech greenhouses in the tropics would feasibly accommodate the production of nearly all crops. Some supplemental lighting would be required for long day crops.
Conclusions: The analysis shows that the added cost of low-tech greenhouses is about 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 costs; for instance, a 160% retail cost increase for rice. According to the proposed scaling method, the greenhouses will provide 36% of food requirements for everyone by the end of the first year, and feed everyone after 30 months.

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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 (Denkenberger and 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; Marshall, 1987; Robock et al., 2007). Disturbingly, two quantitative models have the probability of full-scale nuclear war at about 1% per annum (Barrett et al., 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 (Pearce and Denkenberger, 2018). Either a small regional nuclear war such as India vs Pakistan (Mills et al., 2008; Robock and Toon, 2010) or a minor one-sided nuclear assault on population centers (Pearce and Denkenberger, 2018) could catalyze a global nuclear autumn, which would starve millions of people (Mills et al., 2008; Pearce and Denkenberger, 2018; Robock and Toon, 2010, 2012; Toon et al., 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 and Cirkovic, 2011; Donovan and Oppenheimer, 2018; Newhall et al., 2018). A GCR event might destabilize aspects of society, such as from destruction of critical infrastructure, increased crime, or increased cost in the supply chain of raw materials. This study assumes that after a GCR event the world's nations will continue to cooperate, which is more likely to occur with preparation. A research, development, and planning cost of 10 million–100 million USD, has a 95% credible interval of 9–90% chance of feeding everyone with alternative foods (Denkenberger and Pearce, 2016). The ratio of remaining infrastructure and population is considered constant at current values. A global recession is qualitatively considered in this analysis (see Section 2.3.1). Further work is applying a global equilibrium model to estimate the impacts of a GCR on the global economy. 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 and Kassam, 1979). Crops that rely on flowering require certain temperatures even if the ground does not freeze (Wani and 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 (Denkenberger and Pearce, 2015; Humbird et al., 2011; Kennedy, 1993; Spinosa et al., 2008; Unibio, 2014). It is well-established costs can be reduced (Pearce, 2012; Pearce and Mushtaq, 2009; Zelenika and 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 and 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 et al., 2018; Wittwer and 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. The analysis draws from climate conditions generated by a nuclear winter simulation; however, the general conclusions are applicable to other sun obscuring events. 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 were determined for meeting the need. Specifically, calculations were 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 and Herath, 2018). As a general principle, the most challenging crop category, which are long-day obligate crops, representing roughly 0.7% of current global crop production (Cox, 2009; Monfreda et al., 2008), can survive with photoperiods as short as 12 h (Major, 1980). This critical condition represents a threshold for crop survival; however, at this condition they will grow very slowly. For these crops to experience normal growth rates, artificial light will be supplemented in the greenhouses, but it is not fundamentally required.

2. Methods

2.1. Greenhouse design

Design of low-tech greenhouses typically relies on low-cost materials (Baird, 2011; Jha et al., 2013; Marshall, 2006; Von Zabeltitz and Baudoin, 1999). Most commonly used designs for low-tech greenhouses are hoop-houses and A-frames (Osentowski, 2015; Rakow and 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.

The unit cell in Fig. 1a, which has been used in the field (Von Zabeltitz and 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 and 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 should be covered with polymer. The frame should consist of material no smaller than 38-mm diameter, regardless of the material (Von Zabeltitz and 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-

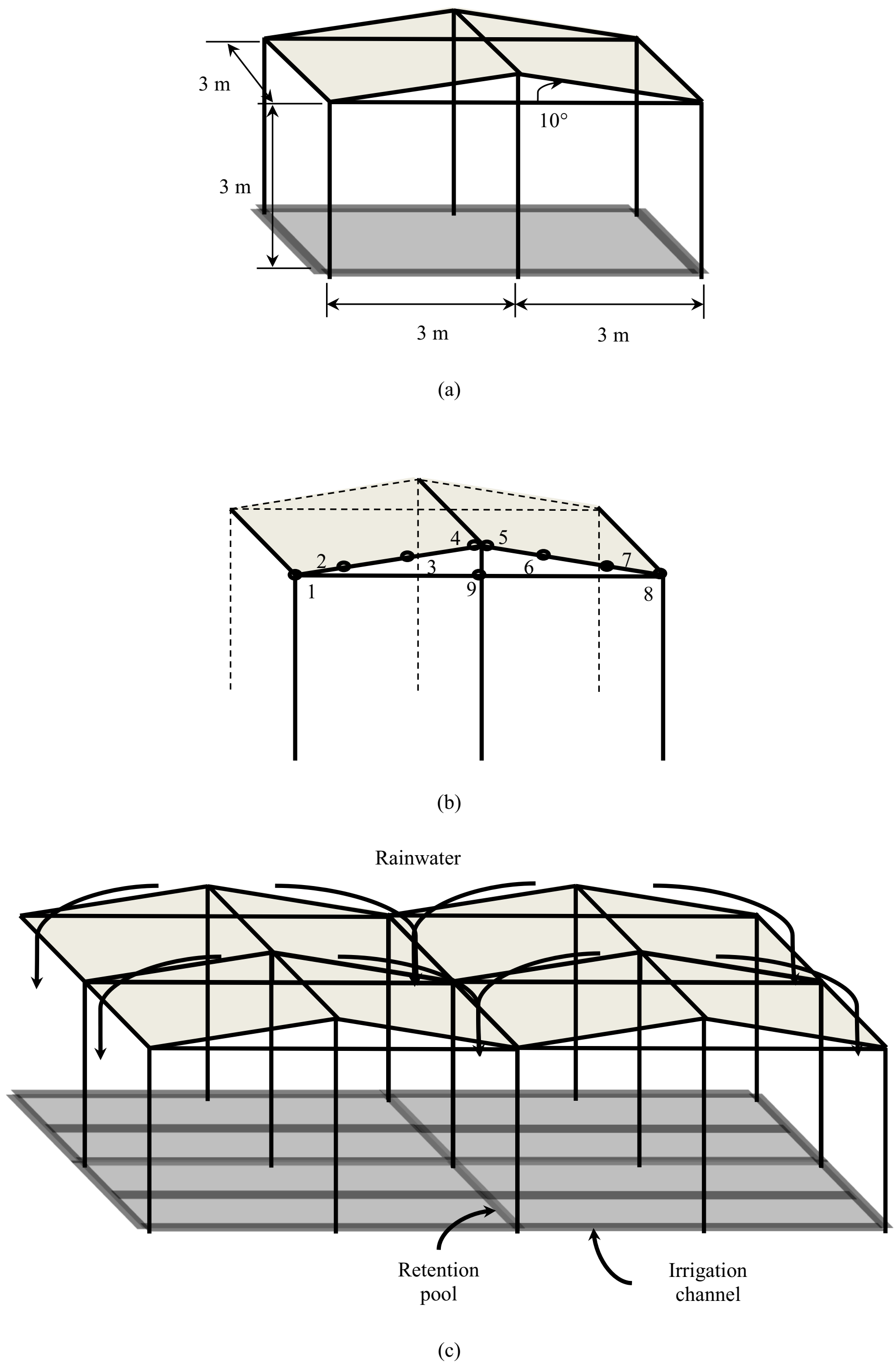


Fig. 1. Low-tech greenhouse design indicating (a) approximate structural dimensions of one unit cell, (b) fastener distribution, and (c) rainwater retention method; the fastener distribution is roughly indexed by the number of nails for frame joints, 1,4,5,8,9, and for polymer cover, 2,3,6,7.

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 (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 and 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 and 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 ha (Aznar-Sánchez et al., 2011), the design of these greenhouses was taken to be 1 ha 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.

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 cost, however it will be economically justified when the demand for crops is high enough. There are risks associated with the supply of each raw material; however, they are generally small. Petrochemicals for all of plastic, which might be the most concerning raw material, represent merely 4% of global fossil fuel production (British Plastics Federation, 2019). Today, greenhouse construction is trending upward (Harrison, 2003) as the state of the art becomes more widely adopted in developed nations (Bernhardt and Milberg, 2011). Technological improvements have reduced labor intensity for growing plants (Janick, 1986) and induce quicker, more fruitful yields (Kitinoja et al., 2011; Tigchelaar and 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.

2.2.1. Forestry products

There are 210 billion tons of aboveground live forest biomass in the tropical and temperate domains (Pan et al., 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. 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 and

Table 1
Bill of materials of a 6-m × 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 × 3 m × 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 et al. (1992).
[b] Chanda et al. (2008).
[c] Sverdrup et al. (2017).

Table 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
2017	Forestry products	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
2017		Industrial roundwood production	1,900,000,000[a]	m^3
2016	Polymer film and sheet	Market volume	46,300,000[b]	tons
2017		Market value	101,000,000,000[c]	USD
2006	Fasteners	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
2019	Construction aggregates	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 (2016).
[g] PRNewswire (2019).

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.

2.2.3. 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 and 2 mm; where flexible (non-rigid) film is generally between 0.002 and 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 and 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.

2.2.4. 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 and Baudoin, 1999).

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 h per day throughout the year in the tropics; civil twilight may constitute another 1 h per day as usable light for crop production (Time and Date, 2019), but this is conservatively ignored. 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 et al., 2019). Rainfall during nuclear winter will likely be concentrated in certain tropical areas of the world. Nuclear war would generally not contaminate water so badly as to be unusable outside target countries. Precipitation would shortly expel radioactive debris from the atmosphere (Denkenberger and Pearce, 2014). The soil becomes radioactive after it undergoes neutron activation (Melissa, 2013), which is why Chernobyl had to be evacuated (Mangalampalli, 2019). However, Hiroshima and Nagasaki were able to be continuously inhabited after nuclear disaster (Mangalampalli, 2019), indicating the radioactivity impact even within target countries is survivable for most. 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. A basic requirement for growing most crops outdoors is about 4 mm/day (Food and Agriculture Organization, 2019). Fig. 2 shows that select regions of the tropics, for example parts of Indonesia, will have 5 mm/day and above of rainfall, meaning precipitation would sufficiently accommodate the needs of crops without additional sources of irrigation such as from rivers or aquifers. 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).

The global reduction of daily sunlight will impact most crops. Long-day obligate crops that require photoperiods of more than 12 h to flower at normal rates, which principally include oats (Hari, 2019), dill, and sweet peas (Cox, 2009), will require supplemental light in the greenhouses. An alternative would be to grow them in windows outside the tropics where day lengths are longer for parts of the year. A minimum of 110 lx light intensity is required for night lighting systems (Cox, 2009), whereas full direct sunlight is 200,000 lx (Nahar et al., 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 1 h 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 and Wheeler, 2009). Eleven crops representing 50% of today's global crop consumption (potato, yam, sweet potato, rice paddy, shell groundnut, wheat, lentil, cassava, maize, sorghum, and soybean) were averaged and used for consideration of food balance and to form a rough crop yield estimate (Food and Agriculture Organization, 2019; Oke et al., 1990). Extrapolating these values suggests that the annual production is roughly 2.4 dry tons/ha/yr. Crop production is reported in relation to dry carbohydrate, with an energy density taken to be 4 kcal/g (Denkenberger and 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 2100 kcal per person daily diet (Kummu et al., 2012).

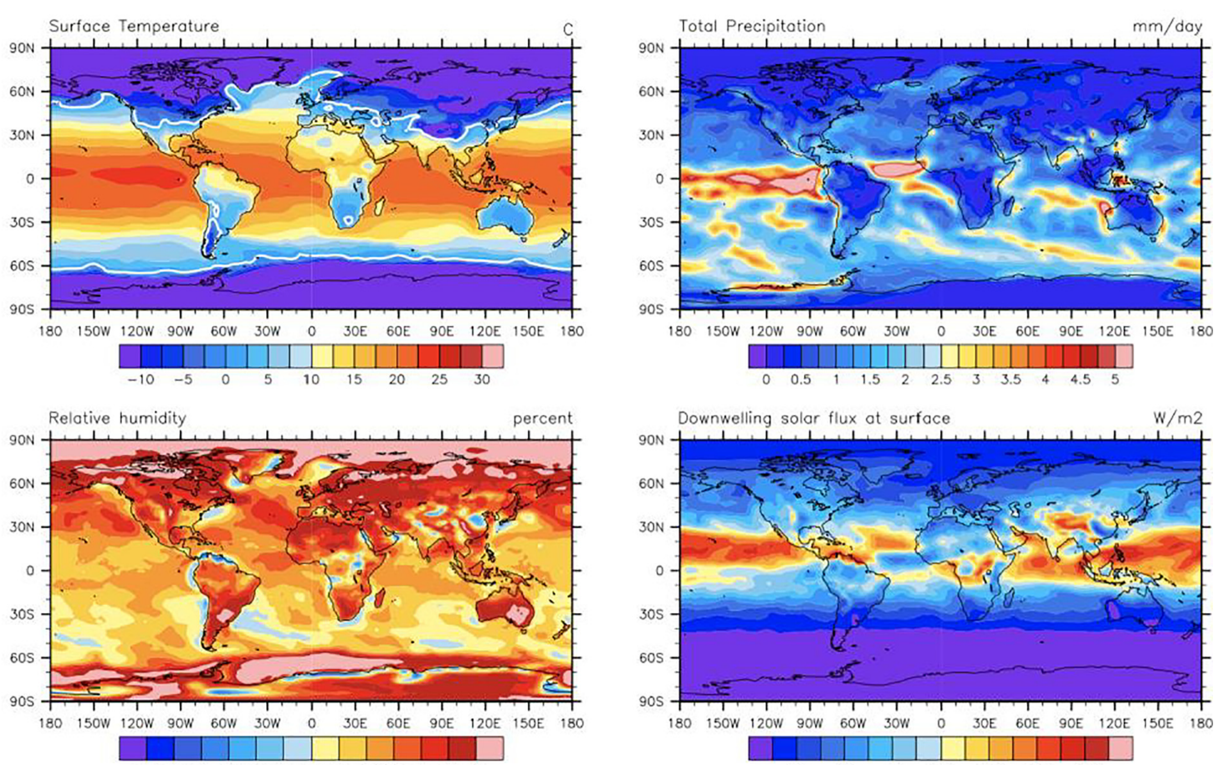


Fig. 2. Global climate predictions during June, July, and August months 12 months after nuclear war; in order to provide high resolution for the climatic variables of interest, very high and low values were truncated, based on (Coupe et al., 2019).

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 24% 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 et al., 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 1160 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. A one-month delay was added to manufacture new extruders, combining two weeks for rapid tooling of specific machine parts (Lü et al., 2001) and an estimated two weeks for assembling the parts. In order to start thus rapid tooling immediately after the catastrophe, planning would be required ahead of time (Denkenberger and Pearce, 2018). 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 cost 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 2700 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 (Marshall, 2006).

Considerations used for determining the values in Table 3 include: no-waste construction, level ground, reallocation of 100% of the supply chain for each material (150% of polymer film supply given more extruders produced), perfect global preparation (i.e. no additional delays), and consistent material dimensions both at raw stage and production.

Table 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

Reasonably, there might be a factor of two uncertainties in any of these values. Therefore, polymer film is not confidently the limiting factor. However, backup plans exist for the framing (such as using sticks and steel) and fasteners (such as using screws and lashing) in addition to the scaling of conventional production that would apply to all the components. These further considerations indicate that polymer extrusion is likely to be the limiting factor.

2.3.2. Labor requirements

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 and Sukhatme, 1990) allows a builder to cover 725 m^2 per month; needs resulting from a GCR event would justify extended labor requirements. 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 and Sukhatme, 1990), problems in shipping (Weintrit and Neumann, 2011), or material losses inherent in the construction industry (Berge, 2009). Factors that speed up a construction process include expert planning, modular construction (Fawcett et al., 2005), overmanning (more people working at the same time) (Hanna et al., 2007), and continuous construction (around the clock) (Hanna et al., 2008; Ibbs and Vaughan, 2015). 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 vary 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).

3. Solution

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 et al., 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 et al., 1992). Properly implemented, transplantation will yield more greenhouse-occupied time than if not transplanted, as represented by Fig. 3.

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 130 dry MT. By transplanting during each interval listed in Fig. 3b, the cumulative crop output would equal roughly 290 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 lost in overall including waste from harvest, storage, distribution and waste by the consumers, but technical feasibility was estimated at 12% waste (Denkenberger and 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.

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 with some supplemental lighting for some crops. 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

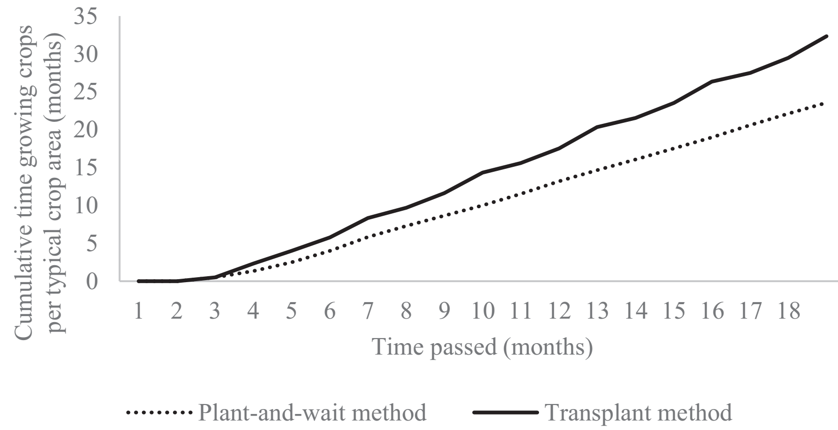
time passed (months)	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
planting density	crop age (months)																	
x1	0	1	2	3	4	5	1	2	3	4	5	1	2	3	4	5	1	2
x1		0	1	2	3	4	5	1	2	3	4	5	1	2	3	4	5	1
x1			0	1	2	3	4	5	1	2	3	4	5	1	2	3	4	5
x1				0	1	2	3	4	5	1	2	3	4	5	1	2	3	4
x1					0	1	2	3	4	5	1	2	3	4	5	1	2	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)

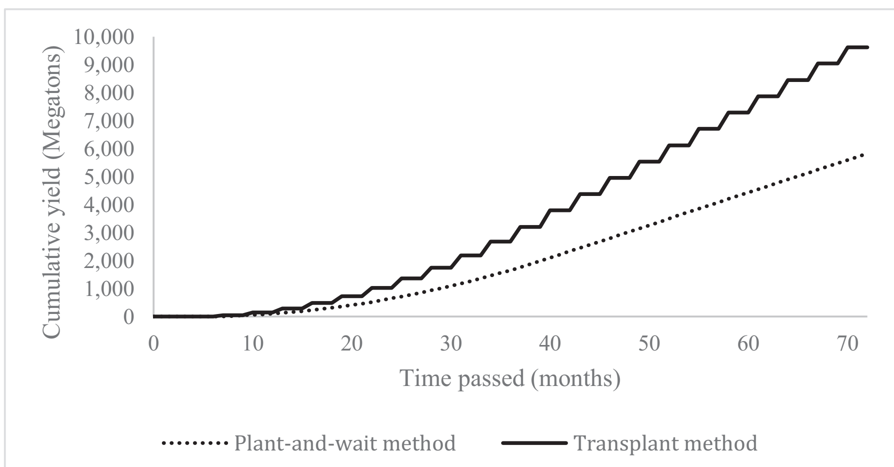
time passed (months)	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
planting density	crop age (months)																	
x3	0	1	2	3	4	5	3	4	5	3	4	5	3	4	5	3	4	5
-		0	2	3	4	5	3	4	5	3	4	5	3	4	5	3	4	5
-			2	3	4	5	3	4	5	3	4	5	3	4	5	3	4	5
x6				0	1	2	3	4	5	3	4	5	3	4	5	3	4	5
-					0	2	3	4	5	3	4	5	3	4	5	3	4	5
-						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)

Fig. 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.



(a)



(b)

Fig. 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.

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 cost was estimated by extrapolating from the global market of each material (see Table 2). Each material was assumed to have a uniform unit cost. 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 1.60 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.

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 (Denkenberger et al., 2019). Adding the cost of supplemental lighting to low-tech greenhouses for long-day obligate crops was calculated using a crop requiring 16 h of light at least 110 lx (Cox, 2009). Considering they might require 4 additional hours of light at 0.28% the intensity of light in the tropics in nuclear winter, this is 0.092% of the total light coming from artificial light. In reality, the plant would likely not require 16 h per day of light over the entire life of the plant. However, relative capital costs would be greater for a system that only operates 4 h a day compared to artificial light growing chambers. Therefore, we estimate that these factors counteract and the $600 per dry kilogram retail applies to the percent of total light that is artificial light for these long day plants in greenhouses. This increases the cost of the long day plants by 0.55 USD/dry kg and this amounts to 0.0037 USD/dry kg average over all crops assuming no reduction in percentage of long-day crops. The final added cost of this study is 2.30 USD/dry kg. This added cost represents a 160% increase from current retail cost of rice (Tridge, 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 et al., 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 and 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). 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 and 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.

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 5000 km^2 globally (ProduceGrower, 2019). Using an average outdoor crop productivity of 2.4 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 360 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 and 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 et al., 2006; Hoxey and Richardson, 1983; Orgaz et al., 2005). This scaling method will feed 36% of global population after 12 months of construction and reach 100% at month 30 (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 88% of this demand, or 140% of the food needed to feed the global population.

This analysis is applicable for any sun obscuring GCR event that experiences climate conditions above the threshold for crop survival detailed in the introduction. Conditions below this threshold would require artificial light in order to grow most crops. Furthermore, if the natural light levels were this low, ambient temperatures would be such that supplemental heating would likely be required (and maybe even a slightly higher light levels). The cost would incrementally increase as crops begin to require supplemental energy sources but would not surpass the cost per dry mass of chambered artificial light growth until the sun is entirely blocked. Additional risks that this research might apply to include scenarios that limit global food production, such as abrupt or extreme climate change (Dietz, 2011; Valdes, 2011), simultaneous extreme weather incidents, resulting in multiple breadbasket failures (Bailey et al., 2015), crop pathogens (Dudley and Woodford, 2002), super weeds (Mann, 1999), super crop pests (Saigo, 1999), or super bacterium (Church, 2009). Ongoing research includes other alternative methods for supplying food quickly during a global catastrophe (Baum, 2015) conducted by Alliance to Feed the Earth in Disasters (ALLFED) (ALLFED, 2019), a nonprofit organization. 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 (Pearce and 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. 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

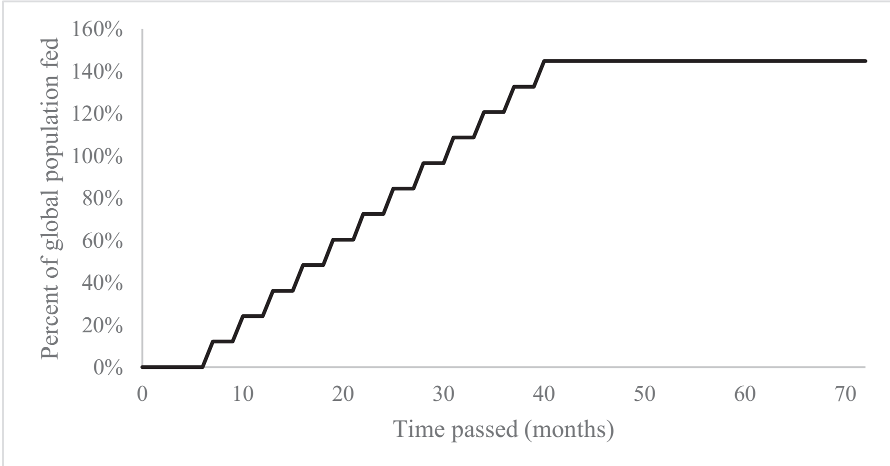


Fig. 5. Percent of global crop need for feeding the human population and meeting current demand using this low-tech greenhouse scaling method; a one-month delay is included after the catastrophe to compensate for attaining global situational awareness.

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.

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 is expected to provide food for 36% of global population. After 30 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.

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Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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